Optical Performance Monitoring

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***Abstract*—Progress in optical networking has stimulated interest in optical performance monitoring (OPM), particularly regarding signal quality measures such as optical signal-to-noise ratio (SNR), Q-factor, and dispersion. These advanced monitoring methods have the potential to extend fault management and quality-of-service (QoS) monitoring into the optical domain. This paper reviews OPM applications and techniques, while examining the role of OPM as an enabling technology for advances in high-speed and optically switched networks.**

***Index Terms*—Fault detection, networks, optical fiber communication, optical performance monitoring (OPM).**

I. Introduction

DURING the past decade, optical transport has enabled the rapid growth of data traffic in the network backbone. Further increases in capacity are gained by moving to dense wavelength division multiplexing (DWDM) with large channel counts. Optical performance monitoring (OPM) is essential for managing such high capacity optical transmission and switching systems. Examples of functions that require OPM include amplifier control, channel identification and signal health assessment. Ultralong haul and optically switched networks promise improved operations, reduced footprint and cost. However, these benefits come with the added complication required by managing transparent networks and have stimulated interest in OPM for enhanced fault management applications. The need for fault management capability in the physical layer is also driven by transmission requirements for very high bit rate systems. While clear advantages have been identified for increased transparency and bit rates, these trends place tighter constraints on the engineering rules and transmission margins [1]. OPM is a potential mechanism for relieving this tension both through improved control of transmission and physical layer fault management. New optical layer functionality such as dynamic reconfiguration and link level restoration also introduce a level of complexity that may require advanced OPM capabilities. All of these issues bring focus to OPM as an enabling technology for next generation optical networks.

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The topic of OPM has been discussed in the literature since the early 1990s and the term itself has taken on multiple definitions [2]–[9]. In this paper, we adopt a broad definition of OPM: physical layer monitoring of the signal quality, i.e., for the purpose of determining the health of the signal in the optical domain. Performance monitoring traditionally refers to monitoring at the SONET/SDH layer for bit/block error rates (BERs) and other quality-of-service (QoS) measures. The primary application of performance monitoring is to certify service level agreements between the network operators and their clients. OPM involves the monitoring of physical layer performance, which is not necessarily correlated with digital performance, although much work has gone into identifying OPM techniques that can be used in QoS applications.

An underlying theme in OPM is the notion that for transparent networks, one might envisage service level agreements certified through OPM. As performance monitoring and QoS measures migrate into the physical layer, OPM might be used to realize new methods of managing traffic. Routing decisions based upon OPM is one possibility [2], [3]. High capacity and priority traffic can be dynamically tuned to high-performance optical channels. Interactions between OPM and higher-level element management systems (EMS) and network management systems (NMS) become a critical issue. Questions arise such as what information should be passed around the network in order to keep the network management scalable. These aspects have been addressed in recent OPM drafts within the IETF [10].

In optical transport systems, the physical layer performance is more closely tied to fault management and control applications than digital QoS applications. Control of optical transmission is the first key application area for OPM. Several early field trials used OPM methods for control of transmission [4], [5]. Today the primary application is amplifier gain balancing. In fact, one can argue that if a physical signal impairment can be monitored, then why not use the monitor signal for active compensation or regeneration? Compensating for gain ripple in long-haul transmission using optical channel monitors is an example of this. Polarization mode dispersion (PMD) is another impairment that is perhaps best handled through compensation. Certainly it would be impractical to use maintenance calls to manually tune amplifier settings or dispersion compensators. There is obviously a gray area between monitoring in physical layer control systems to maintain healthy operation and physical layer performance monitoring or OPM. Traditional electronic performance monitoring also finds use in control and fault management applications in addition to QoS, so it is not surprising that OPM is used across these application areas as well.

At present, monitoring of performance in the physical layer (i.e., OPM) primarily involves a combination of individual component alarms, aggregate power, and in some cases optical channel monitoring (OCM). Component alarms include monitoring of parameters such as amplifier pump laser power or temperature controller limits. In this case, OPM is indirectly realized through the assumption that if all of the components are working correctly, then the signal must be good. This is a very powerful technique that largely comes for free, but unfortunately there are signal failures that violate this assumption. OCM includes measurements of channel power, presence, and wavelength. From an OPM perspective, channel monitoring and also aggregate power monitoring is an extension of component alarms in that it indirectly measures signal quality. The term OPM is often applied to OCM devices with the additional capability of monitoring the OSNR as well as other signal quality measures such as chromatic dispersion, PMD, or jitter. In band channel monitors that are sensitive to the per-channel signal-to-noise ratio (SNR) are referred to as signal quality monitors. Techniques such as Q-factor monitoring are perhaps the closest optical analog of the electronic performance monitor.

Prior reviews of OPM are found in [6]–[11]. Early references to OPM were included in the details of several advanced optical networking research initiatives such as NUTEK and MONET [4], [5]. A number of papers focusing on fault management [12], [13] and transparent networks [14]–[16] have dealt with optical layer monitoring. Recent work has examined applications of OPM techniques [9], [17] and system demonstrations [18], [19]. The literature on optical monitoring techniques, however, is extensive and references are given below.

II. OPM Reference Model

OPM can be broken down into three layers, as shown in Fig. 1. The first layer is transport or WDM channel management layer monitoring, which involves a determination of the optical domain characteristics essential for transport and channel management at the WDM layer. For example, real time measurements of channel presence, wavelength registration, power levels and the spectral OSNR are transport layer measurements. The second level is the optical signal or channel quality layer monitoring, which locks onto a single wavelength and performs signal transition sensitive measurements. Examples of features that can be analyzed in the signal quality layer are the analog eye and eye statistics, Q-factor, the electronic SNR, and distortion that occurs within the eye due to dispersion and nonlinear effects. The third level of OPM involves monitoring the data protocol information, protocol performance monitoring (PPM). This includes digital measurements such as the BER, when used to infer properties of the analog optical signal.

There are several methods of implementing OPM in a line system. i) the nondisruptive dedicated monitor: where the signal is tapped on a WDM fiber and the monitor is shared among many wavelengths on a single fiber (either through polling or in parallel); ii) the disruptive shared monitor: this is the case in which one of multiple optical fibers can be switched to a monitor so the monitor is shared, but the monitoring is disruptive as it takes the fiber offline. This case can also be used to poll multiple fibers. Nondisruptive fiber polling can be implemented by combining i) and ii). iii) the in-line monitor: the full optical signal is transmitted through the monitor and a nondestructive measurement is performed. This approach is most effective when the signal is demuxed into single channels and is often integrated with optical regeneration devices [20].

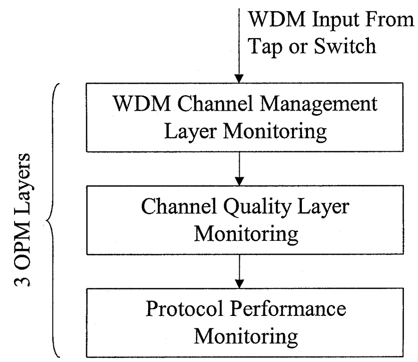

Fig. 1. Three layers of OPM: transport monitoring, signal quality monitoring, and protocol monitoring.

III. Window of Operability

The drive for greater bandwidth and lower cost has led to the rapid technological evolution of optical communications. This growth, which is achieved by transporting more bits/s longer distances, is resisted by the physical and practical limitations of the technology. Chraplyvy and Tkach first developed the notion of a window of operability for a transmission system [21]. As the capacity of a network increases, effects such as gain ripple and dispersion reduce this window. New technology is developed to keep the window open. Ultralong-haul distances and the evolution to transparent mesh networks threaten to close the window of operability due in part to the complexity of managing these networks. The introduction of 40 Gb/s modulation, likewise poses new challenges for optical systems. In this case, however, it is the increased impact of transmission impairments such as chromatic dispersion, PMD, and nonlinearities that tighten the window [22]. OPM is one potential means of widening this window and enabling rapid growth of these new technologies.

IV. Optical Impairments

Optical impairments can be classified into three broad categories: i) noise; 2) distortion; and 3) timing.

1) Noise: random signal fluctuations that are often treated as a Gaussian process and can be signal level dependent.
2) Distortion: modification of the average signal waveform, for example, the average waveform of the marks and spaces taken separately. Distortion may be signal level and pattern dependent and can lead to bursty errors and BER floors.
3) Timing: fluctuations in the time registration of the bits. Timing jitter can occur as quickly as bit-to-bit or accumulate over many bit periods.

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

A. Component Faults

Component faults include individual or multiple component malfunctions, improperly installed or configured equipment, and damage or intrusion to the network. Impairments due to such faults are as diverse as the components and network designs deployed in the field and cannot be comprehensively cataloged. Kartalopoulos recently cataloged the more common component failure modes in DWDM systems [11]. To appreciate the range of possibilities, consider for example optical amplifier failure modes. Failing pump lasers will result in reduced power at particular points in the transmission path or within internal sections of the amplifier. Subsequent amplification can convert these low power levels into excess noise that will show up in the optical spectrum. Unstable pump lasers can also result in excess noise on the signal, but in this case it may not show up in the optical spectrum. If the power control loop on a pump laser fails and it runs high, then the signal levels will be high, which can enhance a host of nonlinear effects in transmission, such as cross-phase (XPM) or self-phase modulation (SPM).

In transparent networks, optical components replace electronic switches, multiplexers, and regenerators, which traditionally include SONET/SDH layer performance monitoring. By introducing the optical components with reduced monitoring capability, one is trading off the additional capital equipment expense of including optical monitoring (to replace the electronic monitoring) against increased operating costs due to more difficult troubleshooting. This tradeoff is acceptable as long as the two costs scale the same. It is not clear how the cost of troubleshooting a network scales. In the past, this tradeoff was required in some sense because optical performance monitoring was prohibitively expensive. More recently critical optical technologies such as tunable filters and spectrometers have become more available and have made many optical monitoring options more economical.

B. Transmission Impairments

In addition to faulty network operation, there are many well-known and perhaps countable disparaging effects of optical transmission that are always present and must be minimized or controlled. The most prevalent effects are given in List 1. The last two effects in List 1 are transmission impairments in networks with transparent switches or add-drop multiplexers. In principle, all of these effects are controlled through the network design. Engineering rules and transmission margins are established to account for the worst-case impact of each impairment on a particular system.

List 1. Notable transmission impairments:

1) amplifier noise;
2) amplifier distortion and transients;
3) chromatic dispersion;
4) polarization-mode dispersion;
5) fiber nonlinearity induced distortion and crosstalk (SPM, XPM, four-wave mixing (FWM), stimulated Rayleigh, and Brillouin scattering);
6) timing jitter;
7) polarization effects;
8) interference effects (MPI);
9) pump laser RIN transfer;
10) optical filter distortion;
11) linear crosstalk.

In order to achieve long link lengths, optical impairments such as amplifier noise, chromatic dispersion, and polarization mode dispersion 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 between impairments. The impact of XPM is dispersion dependent. Therefore the network performance is dependent on the channel configuration and distance.

While distance is a primary driver for increased optical monitoring to mitigate transmission impairments, the use of optical switching elements will affect the way in which different impairments need to be monitored. For example, in static point-to-point systems chromatic dispersion might only be monitored to verify correct network installation or for in-service compensation. In a reconfigurable network, chromatic dispersion may need to be monitored for faults because the accumulated dispersion and its impact will change as the network changes. Furthermore, in an optical switching environment the individual channels will have unique histories and thus performance and accumulated impairments should be measured on a per channel basis. Single-channel impairments are also less likely to be correlated with component alarms, particularly for components that act on the entire WDM band. For these reasons, functions such as wavelength routing and network reconfiguration may require advanced per-channel OPM to assist in the diagnosis of failures.

V. Network Maintenance

Another area that could significantly impact the cost of operating an optical network is the maintenance and troubleshooting procedures. Troubleshooting is often a trial and error process and the cost is likely to scale rapidly with the number of sites visited and components tested. Many intangibles can come into play here such as locked repeater huts or incorrect measurements, both of which would require repeated truck rolls. Long delays can occur because parts are shipped to the wrong place. Troubleshooting will be especially difficult if the maintenance teams cannot obtain accurate information concerning the signal routes and channel configurations. This reality of managing a large network places a greater premium on accurate and automated performance information about a network. The closer such monitoring can put the repair teams toward identifying the problem, the less opportunities will arise for unnecessary expenses.

The impact of active optical components must also be considered. For example, dynamic gain equalization balances the optical power across the optical spectrum. Therefore, the power evolution through the network is a complex function of the state of the system. Excess tilt caused by degraded amplifier performance will be compensated in the next repeater with dynamic gain equalization capability. Therefore the network is self-healing and the degradation may not set off alarms until a complete loss of signal occurs. As components are replaced or removed during troubleshooting, the active components will respond such that the system is no longer the same and the effect of the change is not easily interpreted. Also, nonlinear interactions between the channels will create performance variations that are dependent on the network configuration. While self-healing is certainly beneficial, it makes troubleshooting more difficult without adequate monitoring. A clear view into the network through OPM techniques is a solution to these complications.

Any business case for OPM is complicated by the fact that it results in higher capital expense that must be recovered through savings over time in operational expenses. In the case that OPM is strictly required, clearly this is not an issue—OPM becomes an enabler for the adoption of new technology. If OPM is viewed as a means to reduce operating costs, a strong business case is needed in order to overcome the initial cost of deployment. Even if improved fault management is possible, a given carrier may not be able to realize the full benefit. For example, if a carrier has a blanket service contract or billing structure, then the cost savings will be difficult to identify. On the other hand, if a carrier bills by the truck roll and OPM reduces the number of truck rolls, then the savings are clear and quantifiable.

VI. Fault Management in Optical Networks

Fault management refers to the identification, diagnosis, resolution, and tracking of faults in a network. Here we use a broad definition of fault to include any negative performance due to improper system or component behavior. The fault is recognized when a component or monitor alarm is triggered or a customer report is filed. Many faults are self-healing or can be resolved through software techniques such as remotely rebooting a circuit pack. Bit error alarms at the network end terminals or in the customer equipment are the primary fault indications. Fiber cuts, for example, will result in alarm indication signals and trigger a repair response.

In optical network fault management applications, one typically needs to localize and diagnose a fault that is triggered by an alarm at the end terminal. Ideally, this function is automated through software.

For a monitor to be effective it must be able to detect the fault that caused the end terminal alarm. For this purpose, the monitors must have equal to or better sensitivity than the end terminal receiver, where sensitivity is defined relative to a particular impairment. For a given monitor, the sensitivity requirements will also vary depending on where the monitor is used in the network. Noise builds throughout the network and distortion follows the dispersion map. The combination of both noise and distortion at a given location will determine the sensitivity requirements for that location.

Amplified spontaneous emission (ASE) noise from optical amplifiers is added by a nominally fixed amount in each span. For monitoring near the transmitter side of the network, there will be less noise on the signal and therefore in general a monitor can more easily pick out a noise increase. The opposite is true near the receiver, where more noise has accumulated. ASE noise is often quantified by the optical signal-to-noise ratio (OSNR), which is the ratio of the signal power to the ASE noise power in a 0.1-nm optical bandwidth. Fig. 2 illustrates the monitoring situation for ASE noise. The representative optical network consists of OPM units at various amplifier and OADM sites. For a 30 span network, the OSNR will evolve according to the top curve (squares). This represents the noise level readouts of the OPM units under normal operating conditions. If we consider for example excess noise introduced by a faulty OADM device at the eighth repeater site, the OSNR will then drop as shown in the graph. All monitors along the network after the faulty component will readout values along the bottom curve (circles). Thus, if an alarm is triggered by the transponder unit at the end of the network, then each OPM unit will show a drop in performance back to the OADM unit. The fault is localized at the OADM unit as the first site that registers a performance drop.

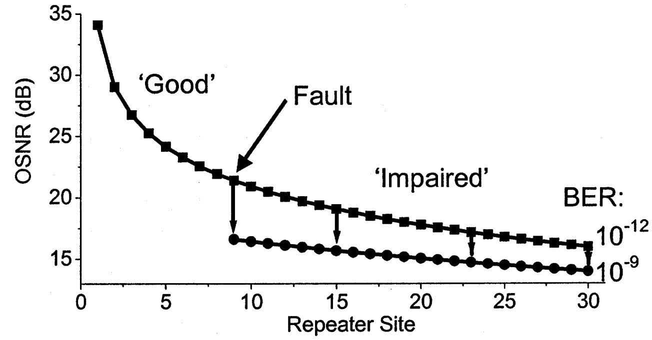

Fig. 2. OSNR versus distance. Fault at the 8th repeater site drops the end terminal BER to 10^{-9} and OSNR after site 8 follows the bottom curve after the onset of the impairment.

Although much research has been directed toward understanding the various optical impairments in a network and what their implications are for the end-to-end performance, very little work has examined the implications on monitoring. Recently the sensitivity requirements for monitoring ASE noise in a 10 Gb/s system were determined [9]. The sensitivity is set by the minimum tolerable performance degradation at the end terminal. This will vary from network to network. If the normal performance variations in a network are quite large over the course of a day, for example, then this will set the desired sensitivity. An impairment that is smaller than these normal fluctuations will be difficult to detect and in general should be negligible. On the other hand, if the network is quite stable, then other considerations may determine the sensitivity requirements such as the desired size of the margin between when the monitoring can detect an impairment and when that impairment becomes service effecting. Kilper and Weingartner introduced a generic metric of one order of magnitude BER degradation at the end terminal. Furthermore, a threshold of 10^{-9} BER was used for determining the error-free condition. Note that this metric provides as much as three to four orders of magnitude advanced warning before the service effecting BER levels are reached when FEC is used.

Sensitivity requirements must be derived for other signal quality measures. Often monitoring techniques are analyzed as test and measurement devices and not as network OPMs. For an OPM device, the network manager needs to know that it has the sensitivity required to localize the root cause of bit errors registered at the end terminal and which impairments are covered by the monitor.

VII. Optical Performance Monitoring Techniques

Interest in optical monitoring first took hold in the early 1990s with the introduction of WDM systems. As people began to think more about optical networks rather than optical transmission systems, it became clear that a solution would be needed for the monitoring problem. This was particularly true of undersea transmission systems because of the high repair costs and larger capital budgets. A major challenge in submarine systems has been to locate amplifier failures. Several techniques were developed including low-frequency modulation of the amplifier pump lasers for supervisory signaling, loop-back methods, and tone modulation [23]–[25]. In terrestrial WDM systems, particularly with the use of optical add-drop multiplexers, there has been interest in measurements of the optical spectrum for managing channel reconfiguration and discovery. Economical techniques for measuring the optical spectrum only became available in the latter half of the 1990s and therefore tone based techniques were the first used for monitoring WDM channels. Advanced OPM or signal quality monitoring, which measures the per channel SNR, has been vigorously pursued in laboratories as a next-generation monitoring technique.

List 2. Physical layer measurements for OPM:

1) average power (per wavelength or aggregate);
2) peak power;
3) pulse/bit shape;
4) eye diagram;
5) intensity/field autocorrelation (including higher order);
6) amplitude power spectrum (RF spectrum);
7) polarization state;
8) optical spectrum (wavelength);
9) amplitude histogram (synchronous and asynchronous);
10) V-curve (Q-factor)/BER;
11) polarization-mode dispersion (DGD, including higher order);
12) chromatic dispersion;
13) phase/optical carrier characteristics.

One strength of electronic monitoring is that the required parameters that are monitored have been standardized. There have been several attempts to identify a standard set of OPM parameters. This is challenging because OPM is physical layer monitoring and therefore the required OPM depends strongly on the physical network design—for all of the reasons described above! Furthermore, all electronic PM measurements can be implemented in a single chip. Different OPM parameters often require different monitors and certain parameters may require costly technology. Therefore OPM is still highly constrained by the available optical monitoring technology. List 2 is a list of many possible measurements that can be made on an optical signal. From these measurements there is an even larger list of signal quality parameters that one might consider for standardization. On the other hand, optical channel monitoring is becoming more common in WDM systems and may be well adapted to standardization. Frequently suggested OPM parameters are given in Table I.

TABLE I
Suggested OPM Parameters

OCM/WDM layer Parameters	**Advanced/Signal Quality Parameters**
Aggregate power	In-band OSNR
Channel power	Q Factor/BER/ESNR
Channel wavelength	PMD (DGD)
Spectral OSNR	Accumulated CD
	Bit Rate
	Jitter

Each of the advanced parameters would be measured using a unique monitoring technique, as described below. One might expect that OPM parameters would be reported in much the same way that electronic monitoring is reported. Average values and high and low tide levels can be periodically recorded and read out. Monitors at network elements can be read by the network management software through an optical supervisory channel.

A. Advanced OPM

Advanced optical performance monitoring techniques are sensitive to the SNR of the optical signals. In general these techniques can either be analog or digital. Digital techniques use high-speed logic to process digital information encoded on the optical waveform. Measurements on the digital signal are used to infer the characteristics of the optical signal. Digital methods have the strongest correlation with the BER, but are usually less effective at isolating the effects of individual impairments.

Analog measurement techniques treat the optical signal as an analog waveform and attempt to measure specific characteristics of this waveform. These measurements are typically protocol independent and can be subdivided further into either time domain methods or spectral methods. Time domain monitoring includes eye diagram measurements and auto- or cross-correlation measurements. Spectral methods must be broken down into optical spectrum and amplitude power spectrum (also referred to as the electrical or RF spectrum) measurements. The optical spectrum is conveniently measured using highly sensitive optical techniques and can provide optical noise information. Unfortunately, the connection between the optical spectrum and the signal quality is not particularly strong. The amplitude power spectrum is a better measure of signal quality because it measures the spectrum of the signal that is encoded on the optical carrier (assuming intensity on-off keying modulation). Noise and distortion on the amplitude power spectrum will usually directly translate to impairments on the signal.

Many monitoring techniques based upon the amplitude power spectrum are facilitated by the use of spectral tones. These narrowband monitor signals are superimposed on the data signal and used as monitoring probes. The most common low-frequency technique involves placing an RF sinusoidal modulation on the optical signal at the transmitter. Because the tone is at a single, low frequency it is easy to generate and process using conventional electronics. Each WDM channel is assigned a different RF frequency tone. The average power in these tones will be proportional to the average optical power in the channel. Thus, the aggregate WDM optical signal on the line can be detected and the tones of all the channels will appear in the RF power spectrum in much the same way they would appear in the optical spectrum. Furthermore, the noise between the tones will be proportional to the optical noise, except in the cases mentioned later. The clear advantage here is that an image of the optical spectrum is encoded on the electrical (or RF power) spectrum for convenient monitoring [4], [8], [26]. Additionally, the monitoring of RF tones can be used for measuring the accumulation of chromatic dispersion and PMD on a digital signal [27]–[29]. An historical difficulty with the tone monitoring techniques is the occurrence of ghost tones. These are tones written from one channel to another through the cross-gain modulation in the optical amplifiers. Thus, even after a channel has been dropped at an OADM, its tone will appear on the optical line because it was transferred to other channels that are still present. High-frequency tones do not have a ghost tone problem because the tones are too fast for the amplifiers to follow [8], [30], [31].

Many spectral techniques have the advantage that they can be implemented with narrowband electronics. Even though high frequencies might be used, the narrow bandwidths will reduce the cost of the electronics. Furthermore, if the detection bandwidth can be narrowed as well, then the sensitivity can be increased. Sensitivity is a critical issue in monitoring because optical power levels are typically below 10 μW without amplification. With optical amplification the optical power levels per channel are still below 1 mW, which is low for many advanced monitoring techniques.

1) OSNR Monitoring: Perhaps the most direct method for implementing advanced optical performance monitoring is to perform OSNR monitoring. Often signal (average) power monitoring is required for gain equalization and other network functions. Common technologies for spectral OCMs are fiber Fabry-Perot filters, fiber Bragg grating filters, free-space and MEMS diffractive optics, and dielectric thin film filters. Several techniques have been developed that do not directly measure the optical spectrum or focus on wavelength monitoring [32]–[35]. Modulation tone techniques have also been used as a low-cost alternative to spectral measurements. In principle, these same techniques that measure signal power can also be used to obtain the optical noise power, which is extrapolated from the power level adjacent to the channel. This approach works well if the optical noise can in fact be obtained from the power level adjacent to the channel. This condition is not true for many important types of optical noise including multi-path interference effects, amplifier pump laser RIN transfer noise, and four wave mixing. Furthermore, there are two general cases in which spectral monitoring becomes problematic: dense WDM channel packing and OADM/OXC networking [36]. Fig. 3 illustrates the difficulty with dense channel packing. Monitoring 10 Gb/s RZ modulated channels on a 50 GHz ITU grid (0.1 nm resolution), there is little spectrum available for monitoring between the channels. The actual noise level shown near 1566 nm, where a channel has been turned off, is very different from the minimum optical power between the channels. In the mesh optical networking situation (with OADMs and OXCs), adjacent channels will have different histories and hence different optical noise powers. Therefore, not only does one need space between the channels, but there needs to be sufficient spectrum to measure two adjacent and independent noise levels. Filtering associated with the optical cross-connect devices will shape this background as well. For 10 Gb/s signals, a spacing of 100 GHz or more is needed for spectral OSNR monitoring, and the success of such monitoring will depend on the filters and modulation format used in a particular system. Despite these limitations on signal quality monitoring, OSNR monitoring is an excellent measure of optical amplifier performance. Even if the noise on individual channels cannot be resolved, the noise level outside the WDM band can be monitored [37], [38]. Amplifier failure or degradation, which is a prevalent source of signal degradation, can be monitored and located within a network through OSNR techniques. In fact, OSNR techniques are frequently used for troubleshooting network faults.

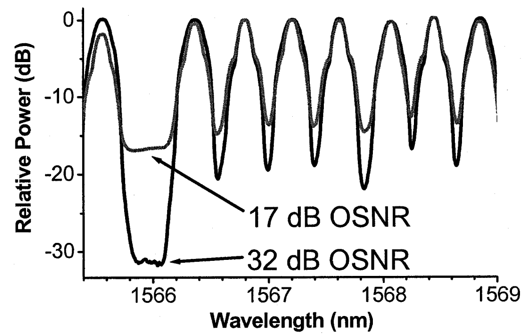

Fig. 3. Optical spectrum of 50 GHz spaced 10 Gb/s RZ modulated DWDM channels with 17 dB and 32 dB OSNR.

Other OSNR monitoring techniques have been developed that measure the noise power within the individual channel optical bandwidth. The challenge in this case is to discriminate between the noise and the signal. This is particularly difficult because a data signal is random and therefore has the appearance of noise by most measures. One approach is to use the optical polarization [39]–[41]. In principle, an optical signal will have a well-defined polarization, whereas optical noise will be unpolarized. Therefore, the polarization extinction ratio is a measure of the optical SNR. Unfortunately, optical signals are not well behaved with respect to polarization. Although PMD effects can be compensated, polarization scattering in ultralong-haul systems results in fast bit-to-bit polarization fluctuations that are impractical to track [42].

Another approach to in-channel OSNR monitoring is to use the amplitude power spectrum of the data and monitor at spectral locations at which the signal is not present. This can involve monitoring at low frequencies, high frequencies, or at special null locations within the spectrum. Optical subcarrier monitoring has been used to directly measure the OSNR and correlate the optical measured value to the electrical SNR seen by the receiver [30]. This approach has an advantage in that it involves monitoring on the actual data signal as it has propagated along the impairment path of the signal itself.

For frequencies above approximately 1/4 of the bit rate, the monitoring signal will be sensitive to both distortion and noise [27].

High- and low-frequency monitoring are essentially out of band techniques in that they measure the electrical noise power at a frequency outside the electrical spectrum of the data. Both methods are often used in conjunction with electrical tones, as described above. Low-frequency monitoring suffers because it is susceptible to low-frequency noise tails. There are low-frequency pattern dependent fluctuations and cross-gain modulation artifacts due to optical amplifiers for example. Furthermore, many noise sources (e.g., MPI noise) have a large low-frequency tail, which would exaggerate the strength of the noise in a low-frequency measurement. At the high-frequency end, these same noise sources are underestimated relative to ASE noise, which is flat with frequency. High-frequency measurements are more sensitive to dispersion effects, due to high-frequency fading. Each of these approaches suffers in fault localization applications, because they do not directly measure the noise on the signal and instead rely on the notion that the noise extrapolates to high or low frequencies.

Electronic spectral measurement techniques that measure the noise within the data spectrum are most promising for fault management applications, because they measure the noise directly on the data. Several approaches have been proposed in this respect, including: framing signal monitoring [43], homodyne signal nulling [44], and 1/2 clock frequency constellation monitoring [45].

2) Dispersion Monitoring: High-bit-rate transmission systems are susceptible to deleterious optical-fiber-based effects, such as chromatic dispersion and PMD. These impairments can create significant signal distortion and lead to BER floors; thus, isolating the accumulation of these effects may be valuable in network management and control. Noise monitoring by itself is only effective for fault localization if distortion and timing jitter are sufficiently controlled that they can be neglected. In today's networks, fibers and other dispersive components are precharacterized for CD and PMD and the transmission link engineered to accommodate or correct for this value. Errors in the network record, failures in dispersive components, and improperly installed network elements are potential sources of dispersion-related faults. These problems are often handled in static networks through offline testing during installation. As bit rates increase and optical switching is employed, more emphasis is placed on embedded dispersion monitoring. Increased sensitivity to environmental effects has driven the development of active compensation devices. In reconfigurable optical networks different signals can traverse different paths at different times and, thus, the target dispersion becomes time dependent. Keeping track of dispersion in a dynamically changing environment can become prohibitively difficult without embedded monitoring. The routing of individual wavelengths requires wavelength selective components, which are often dispersive. The use of these and other dispersive elements introduce a new set of component failure modes that might benefit from monitoring.

Using a dispersion monitor together with noise monitoring provides a highly effective combination for both fault localization and diagnosis (i.e., determining the root cause). Indeed,

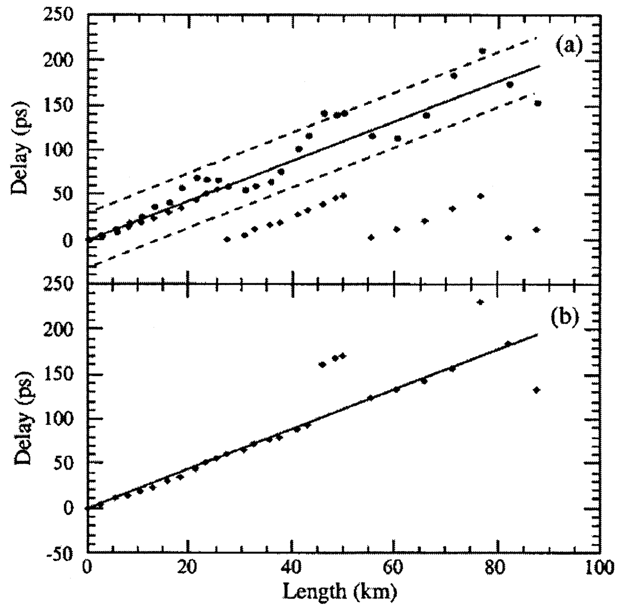

Fig. 4. Chromatic dispersion measurements based on optical subcarrier multiplexing. (a) Course delay measurements and (b) normalized fine delay measurements.

it may be desirable for management systems to mitigate or compensate these degrading effects separately. In a system that utilizes OCM and active dispersion compensation for control of transmission, this OPM combination might be implemented with little additional hardware.

Real time dispersion monitors that can measure the amount of distortion can be used to trigger alarms or feedback to active dispersion compensators [27]. The literature on dispersion monitoring is extensive and readers are directed toward several reviews for a comprehensive treatment of the subject [27], [46]. Here we provide a brief overview of several techniques that are of interest for OPM.

a) Chromatic dispersion monitoring: Chromatic dispersion is a well-understood effect that arises from the frequency-dependent nature of the index of refraction in an optical fiber, and is one of the main impairments that limit the performance of optical fiber systems. For robust high-bit-rate systems, it is essential that dispersion be compensated to within tight tolerances. Several techniques have been demonstrated for real-time chromatic dispersion monitoring to enable dynamic dispersion compensation and may be applied more generally as OPM techniques. One method is to detect the conversion of a phase-modulated signal into an amplitude-modulated signal due to chromatic dispersion [47]. A second method is inserting a subcarrier (RF tone) at the transmitter. The subcarrier approach measures the resulting delay of the subcarrier sidebands relative to the baseband and can be used to measure the accumulated dispersion with fine and medium accuracy without knowledge of the signal transport history (see Fig. 4) [8], [30], [31], [48]. These two methods are simple and applicable to WDM systems, but require modification of the transmitter. Also based on the dispersion-induced RF power fading effect, an alterative technique is extracting the bit-rate frequency component (clock) from photo-detected

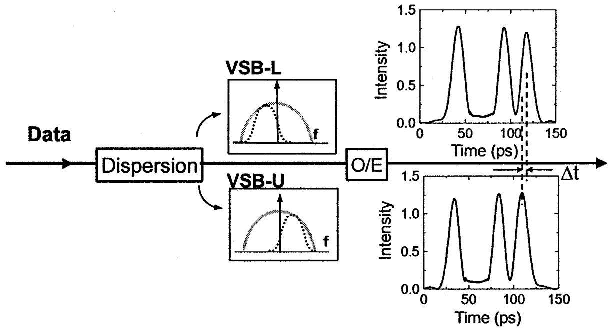

Fig. 5. Chromatic dispersion monitoring using vestigial sideband (VSB) filtering.

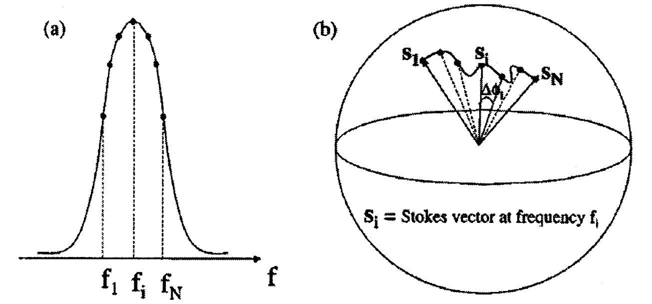

Fig. 6. Technique to monitor PMD: (a) Frequency sweep over the pulse spectrum. (b) Corresponding motion of the Stokes vector on the Poincaré sphere [54].

data and monitoring its RF power [49]. This technique does not require modification of the transmitter, but is bit rate and modulation format dependent. Although this approach cannot isolate chromatic dispersion, like other tone fading techniques it is sensitive to a variety of distortion effects including PMD and pulse carver misalignment, which is advantageous for fault localization.

Another powerful technique is detecting the relative group delay between the upper and lower vestigial-sideband (VSB) signals in transmitted data [50]: the lower and upper vestigial sidebands are obtained by tuning an optical filter away from the optical spectrum center of the double-sideband data (see Fig. 5). Since the two optical sidebands occupy different wavelength ranges, fiber chromatic dispersion induces a relative group delay between the lower and upper VSB signals. This group delay can be measured through clock recovery and phase-sensitive detection. This technique requires no modification at the transmitter, is highly sensitive, is unaffected by PMD, fiber nonlinearity, and transmitter chirp, and can be applied to WDM signals by sweeping the optical filter.

b) Polarization-mode-dispersion monitoring: PMD is a limitation in optical communication systems due to either the PMD of the fiber plant, particularly for high-PMD legacy fiber, or of in-line components [46]. PMD is based on the concept that the same spectral component of optical data splits on two orthogonal states of polarization [i.e., principal states of polarization (PSPs)] within a fiber and these two spectral copies travel down the fiber at slightly different speeds. Deleterious PMD effects are stochastic, time-varying, temperature-dependent, and worsen as the bit rate rises. Moreover, the instantaneous first-order PMD [i.e., differential group delay (DGD)] follows a Maxwellian probability distribution, always with some finite possibility of a network outage.

A number of monitoring techniques have been demonstrated to provide appropriate control signals for PMD mitigation. Several techniques are based on spectral analysis such as RF tones [28], [29], [51]–[53]. A given optical frequency component splits on two orthogonal PSPs and each replica travels down the fiber with a different speed that dephases these replicas. This effect reduces the corresponding spectral component in the detected RF power spectrum through destructive interference. As described earlier, these techniques can be effective as generalized distortion monitors, but cannot isolate a given impairment. By filtering out several spectral slices from the baseband signal and measuring the S-parameters, however, one can isolate the differential group delay as shown in Fig. 6 [54]. This technique can yield real-time measurements of the DGD without knowledge of the signal transport history.

Another technique involves measuring the phase difference between two optical frequency components for the two orthogonal PSPs [55]. This technique requires polarization tracking at the receiver to be able to find the PSPs so the phase can be measured. Monitoring techniques based on measuring the degree of polarization (DOP) of the signal [56], [57] have the advantage of not requiring high-speed circuits and are insensitive to the other degrading effects [58]. However, DOP-based techniques suffer from the following disadvantages: i) a small DGD monitoring range for short pulse RZ signals, ii) a lack of sensitivity for NRZ signals, and iii) they are affected by higher-order PMD. These limitations can potentially be overcome by centering a narrowband optical filter at either the optical central frequency or one of the signal's sidebands [59].

3) Q-Factor/BER: The preferred parameter to use for fault management is the BER. Indeed this is precisely the parameter used in electronic networks. Since it is the same metric that is used at each network end-terminal for QoS, it is sensitive to the same impairments that affect the QoS. In fault localization, one hopes to identify the location of the cause of the BER degradation. In order to implement this in optical networks today, one would effectively need to terminate the optical line with a transponder (O/E/O) on every channel and thus remove all of the advantages of optical networking. An alternative solution is to use polling. Instead of an entire bank of transponders, in this case only the receive side of a single transponder is used and a tunable optical filter sequentially polls each WDM channel and even multiple fibers in a repeater. In order for this approach to be nonintrusive, the monitor either must work off of a 1–2% optical tap or it must be placed at a location in which a larger tap might be tolerated such as mid-stage in an optical amplifier. If a large tap loss is required, an optical preamplifier can be used to overcome this loss. In fact, a 20 dB tap loss is similar to the loss on a single span and therefore the combination of optical tap and filter/preamp front end is roughly equivalent to terminating the line one span farther down and conducting performance monitoring on the full signal.

One difficulty for using this type of BER monitoring in optical networks is that the signal is typically error free within the network. When the BER is monitored at a transponder, error-free signals are not a problem because the signal is regenerated and impairments will not accumulate. For OPM at an amplifier site the signal is only amplified and not fully regenerated, therefore, noise will pass through and continue to accumulate. The result is the situation in Fig. 2. Measurement of the BER at the location of the fault (near site 8) would result in an error free measurement. When the signal reaches the end terminal, however, due to accumulated noise it is not error free and the performance degradation on the BER is observed. In order to detect the degradation within the network, one solution is to use noise loading. In this case, noise is intentionally added to the signal in order to bring the BER to a measurable level and then the additional noise caused by the impairment can be detected.

Another solution to the low sensitivity of BER monitoring is to use Q-factor monitoring [60], [61]. The Q-factor is obtained by adjusting the decision threshold voltage of the monitor receiver away from the optimum level so that errors are recorded. Once an error rate is generated, changes to that rate can be monitored and small degradations become visible. Several such techniques have been developed for measuring the Q-factor [62], [63], one in particular involves comparing the output of a variable decision circuit with a fixed optimized reference decision circuit [62].

The Q-factor is essentially the SNR. If it is measured using a receiver, then it is precisely the electronic SNR. If measured by other means such as optical sampling [64], then it is the in-band optical SNR. It is defined as the difference between the average value of the marks (ones) and of the spaces (zeros) divided by the sum of the standard deviations of the noise distributions around each.

The Q-factor measurements described above require some form of clock recovery. In some cases this may not be desirable either because of the cost of the recovery electronics or the need to support (in a truly transparent sense) an unwieldy number of bit rates. Also, if the eye is heavily impaired within the network, for example due to a strong dispersion map, clock recovery may not be possible. In these situations, asynchronous Q-factor estimation techniques can be used [17], [63], [65], [66]. Asynchronous histograms are generated by simply recording the amplitude histogram without any regard to timing. This histogram will differ from a synchronous histogram because the transition points will fill in the center of the histogram. This additional data makes it difficult to extract both the average values on the marks and spaces, as well as the noise distributions around each. A number of techniques have been devised to extract the parameters in the Q-factor calculation. Asynchronous histograms work best for NRZ format data, in which the rails are well defined.

Because of the strong correlation between Q-factor and BER, this measurement is highly effective for fault management. Q-factor is sensitive to the same impairments that impact the end terminal receiver with the appropriate sensitivity. Although the cost of this approach may be high for many embedded network-monitoring applications, a portable unit can be a valuable tool in troubleshooting faults particularly to target the rare complication that is not identified by embedded OCMs.

4) Timing Jitter: Timing jitter is difficult to monitor and compensate. It is usually left to the regeneration devices to deal with jitter. Timing jitter faults are most commonly associated with the transmitter and can be addressed by monitoring at the transmitter. Generalized SNR monitors such as the Q-factor and BER are indirectly sensitive to jitter and could be used to identify a localized source of jitter.

VIII. Conclusion

Exhaustive monitoring is possible with an unlimited budget. Although the future of optical networks is difficult to predict, the value of OPM increases with increasing transparency. Networks are evolving in ways that make higher levels of OPM desirable if not required. Numerous technologies have been developed to address this OPM need. The challenge going forward will be to apply these techniques with the right balance between monitoring coverage, sensitivity, and cost.

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