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Optical Performance Monitoring: A Review of Current and Future Technologies

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Abstract—**Optical Performance Monitoring (OPM) is the estimation and acquisition of different physical parameters of transmitted signals and various components of an optical network. OPM functionalities are indispensable in ensuring robust network operation and plays a key role in enabling flexibility and improve overall network efficiency. We review the development of various OPM techniques for direct-detection systems and digital coherent systems and discuss future OPM challenges in flexible and elastic optical networks.**

Index Terms—**chromatic dispersion, coherent detection, digital signal processing, monitoring, noise measurement, optical communication, signal to noise ratio.**

I. Introduction

FIBER-optic communications has seen tremendous growth over the last decade fueled mainly by the incessant and relentless demand for high capacity. This insatiable demand is spurred by the Internet traffic growth both in terms of number of users and the bandwidth consumed by each user. In order to comply with the enormous bandwidth requirements posed by the growth in data traffic, fiber-optic communication networks have evolved drastically. For example, advanced optical modulation formats offering high spectral efficiencies have been successfully employed in conjunction with digital coherent receivers [1]. Furthermore, complex network architectures utilizing reconfigurable optical add-drop multiplexers (ROADMs), flexible grid, modulation format and bandwidth [2] have been incorporated in order to promote dynamicity, flexibility and better utilization of available transmission capacity [3].

The performance of optical networks operating at ultra-high data rates and over long transmission distances strongly depends on the extent of link impairments such as chromatic dispersion (CD) and polarization-mode dispersion (PMD) introduced into the signals by the optical fiber as well as other network elements such as noise from inline optical amplifiers. Traditionally for direct detection links, the deleterious channel effects are handled by either introducing some safety margins in initial network design or by making attempts to compensate some of these impairments manually. Unfortunately, due to stochastic nature of some of these impairments, it is difficult if not impossible to compensate them entirely. The advent of ROADMs makes the situation overwhelmingly more complicated since it allows the signal path to change dynamically, thereby making the impairments in reconfigurable fiber-optic networks become path dependent, dynamic and hence, random in nature [4]. Unlike wireless networks where all the necessary networking issues such as link setup, optimization and testing are performed automatically, such tasks are currently handled manually in optical networks requiring substantial manual intervention, human resources and time. This is due to the fact that the existing fiber-optic networks are not capable of acquiring real-time information about the physical state of the network and the health of the signals propagating through the network. The price paid for this lacking of vital information is that the network designers are forced to keep considerable safety margins in order to provide reasonable level of reliability, resulting in wastage of precious network resources. Network operators may also be compelled to use more aggressive components specifications.

In order to reduce the operating costs, ensure optimum resources utilization and guarantee adequate operation and management of dynamic optical networks, it is essential to be able to continuously monitor various network performance parameters [4], and this is collectively referred to as Optical Performance Monitoring (OPM). The rest of the paper is organized as follows: the background, motivation and objectives of OPM will be given in Section II. This will be followed by an overview of OPM techniques in direct-detection systems in Section III. Section IV discusses OPM developments in digital coherent systems. The role of OPM in enabling flexible and elastic optical network operations and commercialization status of OPM devices are highlighted in Sections V and VI respectively.

II. Background

The capacity of optical communication systems is increasing unremittingly and the architectures of optical networks are continuously becoming more complex, transparent and

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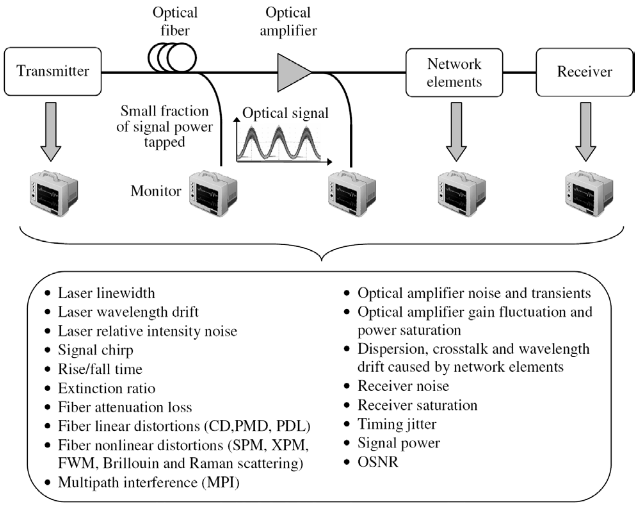

Fig. 1. A fiber-optic network equipped with OPM capability to monitor several possible transmission parameters.

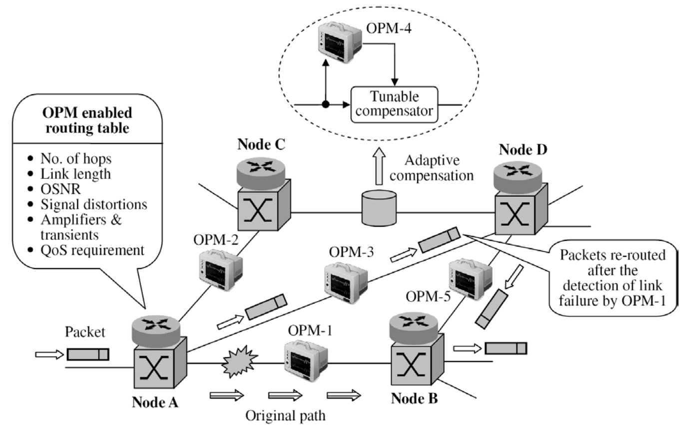

Fig. 2. Adaptive impairments compensation, reliable network operation, and impairment-aware routing enabled through the incorporation of OPM in optical networks.

dynamic in nature. These high-capacity fiber-optic networks are vulnerable to several transmission impairments which can alter over time due to dynamic nature of these networks [5]. Since each fiber carries an enormous amount of data traffic, even a brief disruption of services may result in disastrous consequences. This is because the carriers have to provide a certain set of guarantees called service-level agreements (SLAs) to their customers regarding the system availability and performance and the violation of these guarantees may lead to severe penalties._Therefore, it is imperative to incorporate effective monitoring mechanisms across the whole fiber-optic network which can provide precise and real-time information about the health of each individual DWDM channel. Performance monitoring has been a part of fiber-optic transmission systems from the very beginning for e.g., bit/block-error-rate (BER) monitoring and other quality-of-service (QoS) measurements. However, such monitoring has fundamentally been conducted in the electronic domain i.e. after optical-to-electronic (O/E) conversion of the signal being monitored. For the efficient operation of dynamic DWDM networks, it is crucial to monitor the key performance parameters directly in the optical domain. Quintessentially, OPM is a set of measurements performed on an optical signal at the intermediate network nodes or inside the receiver itself so as to estimate the performance of a transmission network. As one don't want to disturb the traffic (and intermediate nodes won't know much about the original signal anyways), OPM is preferred to be done without having a priori knowledge of the transmitted information as shown in Fig. 1.

A. Network functionalities enabled by OPM

The installation of monitoring mechanisms across the whole optical network can enable several important and advanced network functionalities, including:

Adaptive impairments compensation: The transmission impairments in dynamic optical network are inherently time-variant in nature because the paths traversed by the optical signals change continuously due to network reconfiguration. This implies that the compensation techniques used in dynamic optical networks must be adaptive in nature. OPM can effectively assess the degradations caused by an optical link and this information can then be utilized to provide feedback signals for the adaptive compensation of these impairments as shown in Fig. 2. Note that in case of digital coherent receivers, complete information of the optical signal properties can directly be obtained in the electrical domain which allows for the adaptive compensation of various linear channel impairments such as CD or PMD. During the compensation process, the receiver systematically becomes aware of various channel parameters and thus it also functions as a comprehensive OPM system. However, OPM in coherent detection systems is commonly referred to as channel estimation.

Reliable network operation: OPM can provide continuous and real-time information about the physical condition of an optical network and is thus capable of identifying the faults locations and their causes. Furthermore, the extent of individual impairments contributed by the network as well as their distribution can be determined. This allows the network providers to know when the data signals are beginning to deteriorate. Therefore, preventive measures can be taken at right time to fix the problem before it starts to cause serious degradation to system performance, thereby ensuring reliable network operation [6] as shown in Fig. 2

Efficient resources allocation, impairment-aware routing and elastic optical networks (EONs): OPM can facilitate efficient utilization of available network resources. For example, if the link quality is very good in a dynamic optical network, the transmitted power of signal can be reduced (and hence, decrease the optical signal-to-noise ratio (OSNR)) while still meeting the desired BER requirements or alternatively, the higher modulation formats can be used to increase the data rate. Also, the data routing algorithms used in existing static optical networks either route traffic on shortest paths (i.e. fewest hops) or on paths that satisfy certain minimum QoS constraints (for e.g., delay, packet loss and data rate) [7],[8]. However, such routing algorithms will perform far from optimum in dynamic optical networks since they do not take the variable physical state of the network and traffic patterns into account. Therefore, in order to have better routing capabilities, the routing tables must be updated by also considering optical layer parameters (for e.g., fiber length, signal distortion, amplifier noise and transients) as shown in Fig. 2 [4],[9]-[11]. The valuable information available through OPM can be provided to the network controllers which can make routing decisions considering several different parameters. OPM is also a key enabling technology for EONs which have received considerable attention recently. EONs strongly rely on OPM to become aware of the network conditions and then adaptively adjust various transceiver and network elements' parameters in order to optimize the transmission performance. The vital role of OPM in the realization of various functionalities in EONs will be discussed in Section V.

B. Network parameters requiring OPM

Apart from optical fiber, other network components may also contribute several degradations. The impairments in optical networks can generally be categorized as catastrophic and non-catastrophic in nature. Catastrophic impairments result in loss of optical power and include fiber breaks, network components failures and inappropriately installed network equipment etc. Non-catastrophic impairments do not necessarily decrease the optical signal power but they may severely distort the signal. Such distortions may be linear or nonlinear in nature and must be minimized or properly compensated so as to guarantee the desired network performance [4].

Optical power: The most fundamental parameter to be monitored in an optical network is the optical power. The optical power may decrease substantially due to fiber attenuation and losses encountered at the fiber connectors, splices and couplers [12] or fiber breaks. In wavelength-division multiplexed (WDM) systems, the information about each channel's power is required so as to dynamically equalize the power through a feedback mechanism, thus ensuring a stable system performance [13].

OSNR: Optical amplifiers like erbium-doped fiber amplifiers (EDFAs) are normally employed in optical networks to compensate for the transmission losses over long distances. However, besides providing optical gain, EDFAs also add unwanted amplified spontaneous emission (ASE) noise into the optical signals. Furthermore, the cascading of EDFAs results in accumulation of ASE noise [14]. ASE noise is typically quantified by OSNR and is one of the most important parameters to be monitored in optical networks since the BER is directly related to the signal OSNR [15]. Furthermore, it also plays a pivotal role in fault diagnosis and as a measure of general health of links in an optical network.

Chromatic dispersion and polarization-mode dispersion: CD and PMD belong to the category of dispersive impairments and are crucial parameters to be monitored in dynamic optical networks. In reconfigurable optical networks, changes in path lengths for a given channel (due to switching) may result in variable amounts of accumulated CD. Therefore, fixed CD compensation techniques are less effective in such scenarios [16]. For robust high-speed systems, it is essential to compensate CD adaptively within tight tolerances, making CD monitoring imperative in such systems. PMD also needs to be effectively monitored since it is a major limitation in fiber-optic networks operating at data rates in excess of 40 Gbps [15]. PMD effects are stochastic, time-variant, and temperature and data rate dependent [17].

Fiber nonlinearity: The nonlinear effects arise in an optical fiber due to the power dependence of refractive index and result in interference and crosstalk between different WDM channels when the transmitted power surpasses a certain limit. Since fiber nonlinearities deteriorate the performance of high-speed WDM systems employing advanced modulation formats [15],[18], they need to be well managed and for that objective their monitoring is mandatory.

BER and quality-factor (Q-factor): BER and Q-factor are two important parameters to assess the overall performance of an optical network. The BER monitoring has traditionally been used as a preferable tool to characterize the quality of an optical link. However, BER is merely a number and does not provide any insight into the individual contributions of different impairments towards the degradation of system performance. In addition, BER monitoring requires expensive equipment (such as clock and data recovery systems etc.). Q-factor is used to analyze the performance of transmission systems for which direct measurement of BER is impractical. Q-factor is an indicator of the quality of an optical signal due to strong correlation between Q-factor and BER [15]. It can be used to evaluate the effects of channel degradations such as ASE noise, CD, PMD, fiber nonlinearities as well as the impairments introduced by the transmitter and receiver, thus allowing effective BER estimation. Factors including non-Gaussian nature of noise, crosstalk and signal distortions may culminate in an inaccurate BER estimation using Q-factor [19].

Apart from the aforementioned parameters, other factors such as wavelength shift of optical components, optical amplifier gain and distortions, crosstalk and interference effects, SOP and polarization dependent effects, pulse shape and timing jitter are also useful to be monitored in optical networks [4],[14],[19],[20].

C. Desirable features of OPM techniques

The features which a given OPM technique is expected to demonstrate are determined by several factors such as the nature of the optical network in which the OPM module is anticipated to be deployed, types and extents of impairments prevalent in the network, data rates, implementation cost and the degree of intelligence sought to be incorporated with the inclusion of OPM modules. Some common features expected from the OPM techniques are the following [4],[20].

Accuracy, sensitivity, dynamic range, and low power operation: The precise compensation of impairments in dynamic optical networks depends on the degree of accuracy of the monitoring technique being used. Therefore, the monitoring techniques are expected to meet the desired accuracy requirements. The techniques are also anticipated to show good sensitivities in the whole monitoring range. In addition, the techniques are expected to have broad monitoring ranges in order to enable appropriate compensation of network impairments with wide dynamic ranges. The accuracy, sensitivity and dynamic range of a monitoring technique may rely on a number of factors such as the methodology being employed in the OPM module, the amount of signal power tapped from the optical link for monitoring purposes etc. The OPM module should be able to perform its operation by exploiting only a small fraction of the signal power while still meeting the accuracy, sensitivity and dynamic range requirements. A general rule of thumb is that the power used for monitoring must not exceed a small percentage of the total signal power.

Multi-channel operation: Since fiber-optic networks encompass multiple data channels by incorporating WDM, the OPM techniques used must be capable of monitoring several data channels. This can be achieved by either using a parallel bank of monitoring devices or a tunable optical filter to select a particular channel for sequential monitoring. The parallel operation requires more number of devices and thus involves higher hardware costs. On the other hand, the sequential operation may introduce measurement latency, especially in systems with large number of data channels.

Multi-impairment monitoring: As discussed in previous section, several impairments may coexist in an optical network. If different techniques are employed for the monitoring of individual impairments then it will increase the monitoring costs immensely. Therefore, the techniques must be capable of monitoring multiple network impairments simultaneously and independently.

Data rate and modulation format transparency: The future optical networks are envisioned to contain data traffic with different modulation formats and data rates in individual channels. Therefore, the developed OPM techniques must be transparent to data rates and modulation formats, thus avoiding the need for the modification of monitoring modules.

Cost-effectiveness: Since OPM may be needed at multiple locations in an optical network, a general requirement is that its cost must be relatively lower than that of conventional testing equipment. The cost of an OPM module may depend on the complexity of the technique being used for monitoring. A reduction in cost can be achieved by using techniques which can monitor multiple network impairments for several data channels and for various data rates and modulation formats.

Fast response time: In static optical networks, the response time of the OPM technique can be of the same order of magnitude as the network restoration time of 50 ms [20]. However, in case of dynamic optical networks, the response time must be much smaller than the network reconfiguration interval. A general rule of thumb is that the monitoring time must be in the range of a few ms.

Non-invasiveness: An OPM technique must not have an adverse effect on the normal operation of an optical network. This requires the OPM technique to not modify the network components while it performs the monitoring task. Also, it should not insert additional monitoring signals into the network, which may interfere with the data signal resulting in the degradation of data signal quality.

III. OPM TECHNIQUES FOR DIRECT DETECTION SYSTEMS

The receivers in direct detection systems employ simple photodetectors to detect the intensity of the optical signal or use delay interferometers (DI) in conjunction with photodetectors to transform the differential phase information into amplitude information in the electrical domain. Due to square-law detection nature of the direct detection receivers, only limited information can be retrieved from the optical signals.

The crucial parameters to be monitored in networks employing direct detection include residual CD, total power (i.e. signal plus noise power), OSNR, PMD, polarization-dependent loss (PDL), and fiber nonlinearities. The OPM techniques developed for existing direct detection systems are preferred to utilize simple direct detection. However, the adverse effect of using direct detection in these techniques is that the accurate estimation of various network parameters becomes quite challenging due to the unavailability of sufficient information.

Direct detection fiber-optic transmission systems are typically dispersion compensated. However, due to temperature and other physical effects, there is always some residual CD present. Furthermore, most of the currently deployed optical fibers have reasonably high PMD coefficient values, i.e. of the order of 0.5 ps/km$^{1/2}$ [20]. Therefore, the optical signals are also affected by polarization-related distortions. Finally, the optical signals are also subjected to degradations caused by the ASE noise of EDFAs as well as fiber nonlinearities. Since all the abovementioned deleterious channel effects may coexist, the OPM techniques developed for direct detection optical networks must be capable of monitoring these parameters independently. However, the availability of limited information in the OPM devices makes the simultaneous and independent monitoring of multiple performance parameters overwhelming complicated in direct detection fiber-optic networks.

A. Overview of OPM techniques for existing direct detection systems

Over the past decade, a plethora of OPM techniques for direct detection optical networks have been proposed. A general classification of these techniques is shown in Fig. 3. The existing OPM techniques can be classified as either digital or analog in nature. Digital techniques exploit the digital information content of the signal waveform in the electrical domain. Digital OPM methods e.g. BER monitoring provide information about the overall degradation in signal quality caused by the network impairments but are unable to isolate their individual contributions. Analog monitoring techniques analyze specific characteristics of the analog signal waveform

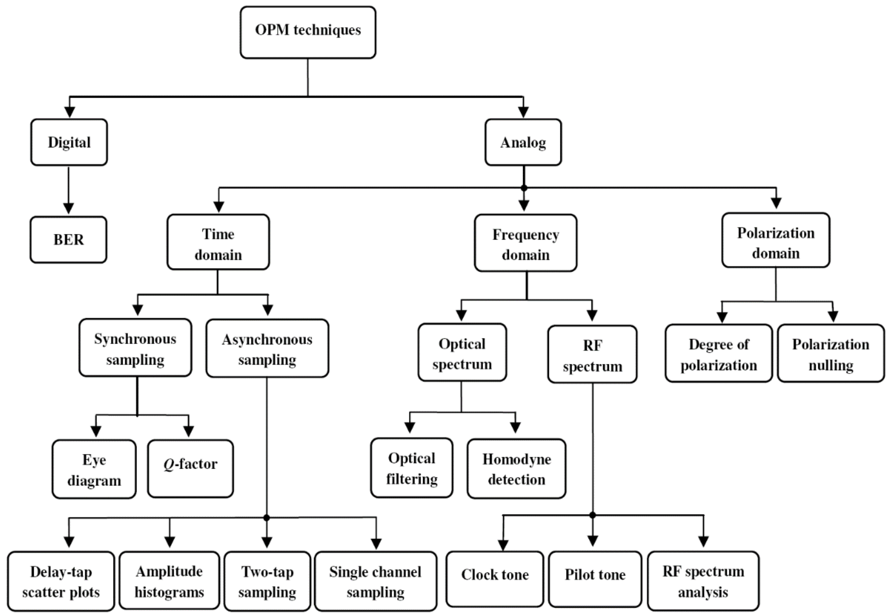

Fig. 3. Classification of existing OPM techniques for direct detection systems.

to extract information about the channel impairments [4]. These techniques can be further subdivided into time domain, frequency domain and polarization domain techniques depending upon whether the monitoring information is extracted from the signal waveform, signal spectrum or the signal polarization, respectively.

Time domain monitoring techniques can be categorized into synchronous and asynchronous sampling based techniques depending upon whether the sampling rate is synchronized with the symbol rate or not. Synchronous sampling techniques require clock recovery, which is a relatively complex operation especially in networks supporting multiple data rates. Eye-diagram is a popular synchronous sampling-based technique, which qualitatively reflects the effects of all impairments on the signal quality. However, it is unable to quantify the effects of individual impairments [4]. Similarly, Q-factor monitoring is another synchronous sampling-based technique which is commonly used in practice due to its strong correlation with BER. Asynchronous sampling-based techniques for e.g. asynchronous amplitude histograms (AAHs) [21]-[28], asynchronous delay-tap plots (ADTPs) [29]-[38], asynchronous two-tap plots (ATTPs) [39],[40], and asynchronous single channel sampling (ASCS) [41], are considered attractive since they do not require clock information and they are also capable of monitoring multiple impairments simultaneously, thus being cost-effective.

Frequency domain monitoring techniques can be subdivided into optical and radio frequency (RF) spectrum based techniques. The optical spectrum analysis techniques can make use of an optical filter which is tuned over the channel bandwidth and the optical power is recorded [4]. The spectral resolution in this case is determined by the filter's bandwidth. Alternatively, optical spectrum can be analyzed by performing homodyne detection, where a tunable LO laser signal is mixed with the monitored signal and the interference signal is then analyzed for spectral analysis [42]. The LO laser is swept across the channel bandwidth. The spectral resolution in this case is determined by the linewidth of the LO laser and is several orders of magnitude higher than that of tunable optical filter. The optical spectrum-based techniques are capable of monitoring out-of-band OSNR, total optical power, and wavelength drift but they can not monitor CD and PMD. These techniques can be used to monitor multiple WDM channels. Since the optical filter or the LO laser needs to be tuned for scanning the whole WDM spectrum, such techniques can introduce measurement latency.

Radio frequency spectrum-based techniques can provide better estimation of signal quality as compared to optical spectrum-based techniques because they analyze the spectrum of the signal that is encoded on the optical carrier. These techniques either make use of clock tones present inherently in the spectrum of various modulation formats or insert pilot tones of different frequencies in each channel at the transmitter. The clock tones-based monitoring techniques can measure CD and PMD and are data rate and modulation format dependent [43]-[46]. On the other hand, pilot tones-based schemes can measure various parameters like wavelength, OSNR, CD, PMD and optical paths of WDM signals by assigning a unique tone frequency to each WDM signal and tracking its path since the tones are bound to follow the same optical paths as their corresponding WDM signals [47]-[50]. These techniques are data rate and modulation format independent. However, the adverse effect of using pilot tones is that they may interfere with the data signal resulting in the deterioration of BER. Apart from monitoring the specific tones (i.e., clock and pilot tones) in the RF spectrum, changes in the spectral distribution of overall RF spectrum, due to various network impairments, may also be analyzed for the monitoring of these impairments [51].

Polarization domain monitoring techniques exploit the alterations in the polarization characteristics of optical signals, caused by various channel degradations, for the effective monitoring of these impairments. These techniques can monitor signal and noise powers (and hence, OSNR), for example, through polarization nulling [52]-[55], as well as PMD of the fiber link, for example, by measuring the

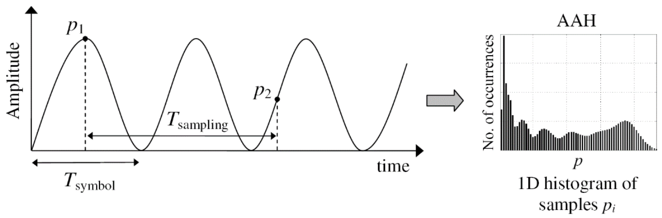

Fig. 4. Conceptual diagram of asynchronous amplitude sampling with an AAH on the right. T_{sampling} is the sampling period and T_{symbol} is the symbol period.

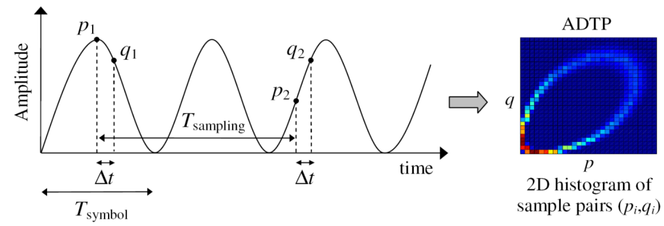

Fig. 5. Conceptual diagram of ADTS technique with an ADTP on the right. Δt is the time delay within each sample pair and T_{sampling} is the sampling period.

degree-of-polarization (DOP) of the received signal [46],[56],[57]. These techniques have the advantage of being transparent to data rates and modulation formats. However, they are not applicable to polarization-multiplexed (PM) signals, which severely limits their use in coherent transmission systems.

B. DSP-based multi-impairment monitoring techniques for direct detection systems

OPM techniques utilizing electronic DSP have gained substantial attention in recent years. These techniques exploit the statistical properties of the data signals after O/E conversion for the estimation of critical signal quality parameters. The reason behind the popularity of DSP-based OPM techniques is that they can facilitate cost-effective monitoring of multiple signal quality parameters simultaneously for several data rates and modulation formats and without necessitating modifications of monitoring hardware. Furthermore, the monitoring of a new parameter as well as monitoring for a different signal type can simply be enabled by downloading the relevant algorithm to the DSP-based monitor, thereby facilitating flexibility and cost-effectiveness. DSP-based monitoring techniques typically perform asynchronous sampling of electrical signal amplitude and then generate one-dimensional (1D) or two-dimensional (2D) histograms of the signal samples. The statistical features of these histograms are then exploited using statistical signal processing, artificial intelligence, and digital image processing techniques for multi-impairment monitoring [20]. Some prominent DSP-based monitoring techniques for direct detection systems include AAH, ADTP, ATTP, and ASCS techniques.

DSP-based techniques using AAHs are attractive due to their remarkable simplicity and flexibility. The concept of AAH is shown in Fig. 4. To obtain an AAH, the electrical signal amplitude is randomly sampled (without any clock information) at a rate much lower than the symbol rate. It is important to note that the sampling period T_{sampling} has no relation with the symbol period T_{symbol}. After the acquisition of numerous amplitude samples p_i, a histogram is generated. The number of samples used for the synthesis of AAH must be sufficient enough to obtain the complete statistics of the signal.

The shape of an AAH reflects the signal properties. Since the signal is distorted by several optical impairments, the statistical features of an AAH also vary accordingly. The variations in AAH's statistical properties can thus be tracked to evaluate the level of various impairments degrading the optical signal. The impairments-sensitive features of AAHs have been successfully exploited using statistical signal processing and machine learning techniques for the monitoring of multiple signal quality parameters in fiber-optic networks [21]-[28].

The advantages of AAH-based monitoring techniques are that they are cost-effective, have less implementation complexity and are transparent to data rates and modulation formats. However, their drawback is that the effects of various impairments are often intermixed, thus prohibiting independent monitoring of these parameters. The monitoring accuracy of AAH-based techniques depends on the number of samples acquired for monitoring purpose. Hence, there is a trade-off between accuracy and monitoring speed.

ADTS-based monitoring techniques are quite interesting since they offer the potential for data rate and modulation format independent multi-impairment monitoring [29]-[38]. Like AAH, ADTS-based techniques also exploit the statistical properties of the asynchronously sampled signal. However, in contrast to AAH which is a 1D histogram of signal amplitudes, ADTS produces a 2D histogram of closely located sample pairs [29]. The concept of ADTS is illustrated in Fig. 5. The electrical signal amplitude after direct detection is asynchronously sampled in pairs (p_i,q_i) with a known constant time delay Δt between them called tap-delay. The sampling period T_{sampling} between the pairs (p_i,q_i) is not related to the symbol period T_{symbol} and can be many orders of magnitude longer. Binning the sample pairs (p_i,q_i) into a 2D histogram generates an ADTP or scatter plot as shown in Fig. 5. An ADTP provides the information richness of an eye-diagram without requiring clock information for its generation. The shape and features of an ADTP depend on the modulation format, bit rate, tap-delay Δt as well as various signal distortions such as ASE noise, CD, PMD, crosstalk etc. The unique signatures of various impairments, reflected in ADTPs, can be exploited for OPM purpose. In addition, the ADTPs can even distinguish between the sign of accumulated CD. Li *et al.* [30] detailed how this property can be effectively used for signed CD monitoring. However, it is important to note that an ADTP is essentially a graphical representation allowing qualitative estimation of signal properties. In order to extract quantitative information from an ADTP, a further analysis is required. Several approaches such as statistical signal processing [31]-[34], image processing [35], artificial intelligence and machine learning [36],[37] etc., have been proposed for the treatment of ADTPs for the purpose of multi-impairment monitoring. The advantage of ADTS-based OPM techniques is that they are capable of monitoring multiple impairments simultaneously and independently. Like AAH-based techniques, they are also transparent to data rates and modulation formats. However, their implementation complexity is higher than that of AAH-based techniques. This is due to the fact that the tap-delay value is a function of symbol period and hence, it needs to be adjusted precisely depending upon the data rate of the signal being monitored. The monitoring accuracy of ADTS-based techniques depends on the number of sample pairs acquired for monitoring purpose as well as on the degree of correlation between the transponders used for the acquisition of calibration curves or for the training of artificial intelligence-based classifiers, and the transponders employed during the actual monitoring process.

In addition to AAH and ADTS based techniques, several other DSP-based OPM schemes have been proposed. These include ASCS, asynchronous two-tap sampling (ATTS), and empirical moments based monitoring techniques [5],[39]-[41],[58]. In ASCS-based technique [41], a 2D scatter plot equivalent to ADTP is produced by utilizing the original and shifted versions of the acquired amplitude samples as sample pairs. Consequently, the implementation complexity and cost of this technique is expected to be lower than ADTS-based techniques. In [40], an ATTS-based technique is proposed which estimates the CD-induced relative group delay between the two vestigial sideband (VSB) signals by computing the differences in the sampled amplitude levels of two VSB signals which are sampled simultaneously but asynchronously. The technique is shown to monitor CD for various modulation formats and data rates without requiring hardware modifications. In [5], the use of empirical moments of asynchronously sampled signal amplitudes in conjunction with artificial neural networks (ANNs) is proposed for multi-impairment monitoring. This technique requires simple hardware for the acquisition of signal samples as compared to ADTP and ATTS based techniques.

The existing OPM techniques for direct detection fiber-optic networks assume either prior information about the signal's bit rate and modulation format or the attainment of this knowledge from the upper layer protocols. However, practically it is not feasible to introduce additional cross-layer communication for OPM purposes at the intermediate network nodes because these nodes can only handle limited complexity. Therefore, it is crucial to have joint bit rate and modulation format identification (BR-MFI) capability at the intermediate network nodes. Recently, Khan *et al.*[59], demonstrated a simple and cost-effective MFI technique utilizing an ANN trained with the features extracted from AAHs. A modification of this technique is presented in [60], whereby joint BR-MFI is demonstrated by using an ANN trained with the bit-rate and modulation format-sensitive features of ADTPs. Tan *et al.* [35], proposed a simple technique for joint BR-MFI as well as simultaneous and independent monitoring of OSNR, CD and DGD by using principal component analysis (PCA)-based pattern recognition on ADTPs.

IV. OPM FOR DIGITAL COHERENT SYSTEMS

Advances in coherent detection and DSP over the past decade together defined the current generation of optical transmission systems and opened up the phase and polarization of an optical carrier for information encoding. High order modulation formats such as PM-QPSK and PM-16QAM enable data transmission rates per channel to move beyond 100Gbit/s. A standard coherent receiver with typical DSP algorithm blocks is shown in Fig. 6. After coherent detection, the baseband electrical signals are first sampled by the ADCs and then processed by the following DSP algorithms: 1) CD compensation, 2) adaptive equalization for residual CD, PMD, polarization de-multiplexing and timing errors using constant modulus algorithm (CMA) or pilot-symbol based algorithms, 3) frequency offset compensation, 4) carrier phase estimation (CPE) and symbol decision followed by decoding (for hard-decision forward error correction (HD-FEC)) or decoding followed by symbol decision (for soft-decision forward error correction (SD-FEC)) [61].

The fundamental technology shift brought about by digital coherent communications also impacted the roles, functionalities and research direction of OPM in optical networks. At a first glance, many commonly used OPM techniques proposed for direct detection systems, such as interpolation based out-band OSNR monitoring or polarization nulling based in-band OSNR monitoring techniques [62], [63], are no longer suitable for coherent detection with very tight channel spacing, Nyquist pulse shaping and polarization multiplexing. As a result, new OPM is needed for digital coherent systems. Besides, in polarization-multiplexed coherent systems,

1) CD and PMD are linear transmission impairments that can be fully compensated by linear filters at the receiver [64], and can be essentially monitored simply by reading the filter taps [65],[66]. Additionally, other impairments such as laser frequency offset and carrier phase are estimated and compensated in a digital coherent receiver. It is once thought that OPM became largely unnecessary with coherent detection and DSP, but it should be noted that acquisition of channel parameters in general are still inherent and integral in the receiver. The difference is just that these impairments won't necessarily degrade transmission performance like in direct detection systems as long as they are appropriately estimated. This is more commonly known as channel estimation in wireless communications literature but it shares the same objectives as OPM in a general sense. For channel estimation in coherent receivers, recent research efforts focus on higher performance and/or lower complexity algorithms to estimate various channel parameters as well as joint channel estimation/data detection.

2) Since all the linear impairments can be fully compensated, transmission performance is largely determined by the OSNR and hence OSNR monitoring is especially vital for coherent links. OSNR monitoring is commonly realized by DSP as a by-product of the digital coherent receiver.

3) OSNR and power monitors are still needed ubiquitously across the network including intermediate nodes. However, using full digital coherent receivers with symbol-rate bandwidth is simply too costly and impractical for this purpose. Low-cost monitoring solutions utilizing reduced-complexity and low-speed hardware are still highly desirable.

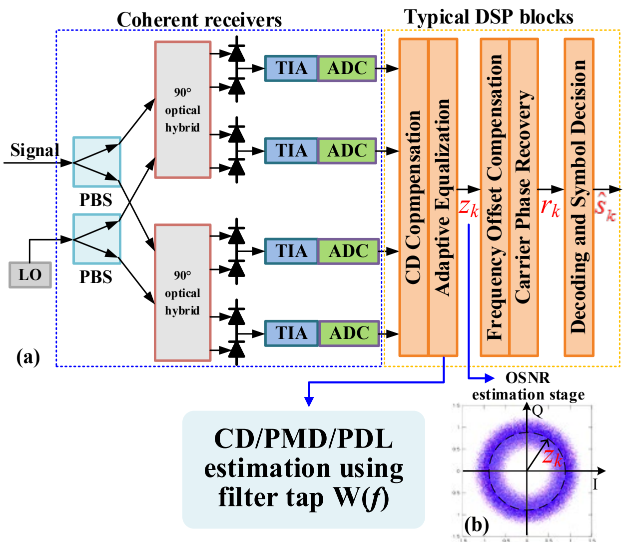

Fig. 6. Schematic of a standard coherent optical receiver with typical DSP algorithms for data recovery (a). Adaptive equalizer outputs are used for OSNR monitoring (b). (LO: local oscillator, PBS: polarization-beam splitter, TIA: trans-impedance amplifier, ADC: analog-to-digital converter).

4) Optical network design is evolving from fixed grid static point to point links to flexible and elastic optical networks with flexible grid, dynamically reconfigurable mesh networks and heterogeneous traffic patterns. Impairment-aware routing has long been a goal for OPM, but it was not until the introduction of digital coherent transmissions that modulation formats, bandwidth and bit rate can be made adaptive according to real-time link impairments and traffic demands. OPM needs to take a more active role in acquiring real-time channel state information and possibly feedback to a centralized network management unit for routing decisions or choosing a right modulation format. In addition, OPM functionalities applicable to different pulse shapes and modulation formats are in its own right non-trivial and challenging.

TABLE I compares the roles of various OPM functionalities in direct-detection with coherent systems. We will discuss such issues in greater detail in the following sections.

A. CD, PMD monitoring and polarization state estimation for digital coherent receivers

Coherent detection with DSP algorithms for various impairment compensation define this current generation of optical transceivers and a general review can be found at [61],[67]. In this case, the optical channel is linear with the channel transfer matrix H(*f*) and equalization filter W(*f*) obtained through the zero-forcing (ZF) solution or minimum mean square estimation (MMSE) solution is the inverse impulse response of the channel, expressed as [66]

$$W(f)=H^{-1}(f)=D^{-1}(f)\prod_{i=N,-1}^{1}U_i^{-1}(f)E_i^{-1} \tag{1}$$

where H(*f*) is composed of the transfer function *D*(*f*) and concatenated elements E_i and $U_i(f)$ accounting for PDL and higher-order PMD. After some algebraic manipulations, the following equations can be obtained

$$\arg(\hat{H}_{CD}^{-1})=\arg(\sqrt{\det(W(f))})=-f^2\varphi \tag{2}$$

$$\hat{H}_{PDL}(f)=\left|\sqrt{\det(W(f))}\right|=\left|H_{AF}(f)\right|^{-1}\prod_{i=1}^{N}(k_i)^{-1/2} \tag{3}$$

TABLE I
COMPARISON OF VARIOUS OPM FUNCTIONALITIES IN NON-COHERENT AND COHERENT SYSTEMS

	Direct-detection systems	Digital Coherent Systems
CD/PMD	Required	Inherent in DSP
OSNR	Required	Required
Power	Required	Required
Nonlinearity	Required for avoidance	Required for avoidance or nonlinearity compensation algorithms
OPM at Intermediate nodes	Power, OSNR, CD, PMD	Power, OSNR in presence of large inline uncompensated CDs

$$W_{UE}(f)=\frac{W(f)}{\sqrt{\det(W(f))}}=\prod_i\begin{pmatrix}u_i^* & -v_i\\ v_i^* & u_i\end{pmatrix}\begin{pmatrix}k_i^{1/2} & 0\\ 0 & k_i^{-1/2}\end{pmatrix} \tag{4}$$

which are responsible for residual CD, PDL and PMD. $W_{UE}(f)$ is the normalized W(*f*) by the square root of its determinant. u_i and v_i form the PMD matrices and k_i is the attenuation factor accounting for PDL.

However, the monitoring range of the CD estimation method by reading the coefficients of adaptive filer is up to around several hundred ps/nm that is limited by the length of filter taps. For coherent long-haul optical transmission systems there is usually no CD compensation modules deployed in the links and the accumulated CD may be up to tens of thousands ps/nm at the intermediate nodes. Therefore a CD monitoring that can monitor large amount CD is still in demand. Since 2011, several scanning-free CD estimation techniques for single carrier systems have emerged [68]-[73]. Zweck *et al.* proposed a modulation-format-independent technique for estimating CD up to 3000 ps/nm from the phase of a coherently-received signal at four frequencies [68]. Wang *et al.* proposed a polynomial fitting based CD estimation for single carrier coherent optical system and it can estimate CD up to 12800ps/nm with an accuracy of better than 200ps/nm [69]. The techniques proposed in [70]-[73], although apparently look different, essentially rely on examining the delay τ_{CD} between the upper and lower sideband with a frequency interval $f = 1/T_s$, where T_s is the symbol period, and τ_{CD} can be easily calculated by examining the location of the correlation peak, facilitated by the FFT/IFFT operators embedded in the coherent receiver. The final CD estimate is given by

$$CD=\frac{\tau_{CD}T_s c}{\lambda^2} \tag{5}$$

where λ is the carrier wavelength and c is the speed of light. Such correlation based CD estimation technologies can estimate CD values up to 50,000 ps/nm with a maximum error of 186 ps/nm under first-order PMD of up to 80 ps [71] and are insensitive to ASE noise, laser frequency offset and laser phase noise. As a linear scan of a preset range of CD is not needed, the number of symbols of the proposed technique is dramatically reduced to hundreds to thousands of symbols.

In [74], a polarization state estimation technique based on Stokes space analysis is proposed. Considering the general case of polarization-multiplexed signals of arbitrary modulation format that is normalized to fit into a unit circle, they can be represented by the following Jones vector:

$$\mathrm{J} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ re^{j\varphi} \end{pmatrix}, \tag{6}$$

where r represents the amplitude and φ represents the phase. Using (6), the expression for the Stokes vector is

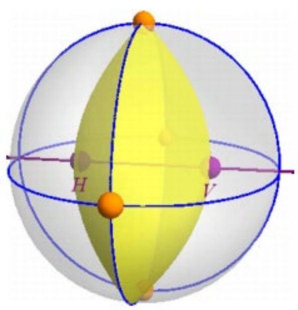

Fig. 7. Characteristic lens-like object in Stokes space is defined by mapping the circle bounded constellations to 3-D Stokes space. The lens axis uniquely locates polarization states of transmission, in this case, *H* and *V*. This provides a means for polarization state alignment [74].

$$\mathrm{S} = \frac{1}{2}\begin{pmatrix} 1+r^2 \\ 1-r^2 \\ 2r\cos\varphi \\ 2r\sin\varphi \end{pmatrix}. \tag{7}$$

The last three components of this Stokes vector parametrically describe one of the paraboloidal surfaces shown in Fig. 7. The other paraboliodal surface results from selecting 1 for the *V* polarization state and considering the full circle in the complex plane for the *H* polarization state. Together the two paraboloids define a lens-like object or a lens. The axis of the lens uniquely identifies the polarization states and thus the identification of the orientation of the lens and of its axis can be seen as the estimation of the signal polarization states. It has the advantage that it is independent on the modulation format and can be applied before CD compensation as it does not require the demodulation of the optical signal [74].

B. OSNR monitoring for digital coherent receivers

Although OSNR monitoring is not as easy as reading off filter taps, ASE-noise-induced distortions can be separated from all the other linear transmission impairments in a digital coherent receiver and reliable OSNR can still be estimated with further processing of the received signals. One simple approach is to utilize the statistical moments of the equalized signal [75]-[78]. The signal used to estimate the OSNR is taken from just after the adaptive equalization, before the carrier phase recovery stage (as shown in Fig. 6). The adaptive equalization can either utilize "blind" non-data-aided channel acquisition by gradient algorithms like CMA or data-aided channel acquisition based on a periodically transmitted training sequence. Data-aided channel acquisition gives high estimation accuracy and instantaneous filter acquisition that enables faster OPM with the trade-off of reduced bandwidth efficiency compared to non-data-aided acquisition [79][80].

After adaptive equalization, the linear distortions such as CD and PMD ideally can be fully compensated, and thus the variations of the equalized signal envelope are mainly caused by the ASE noise. We use z_k to represent the envelope of the k^{th} received signal in one particular polarization from the adaptive filter (as shown in Fig. 6(b)). In a practical system, the second- and fourth-order moments from a received data block of L symbols can be calculated as

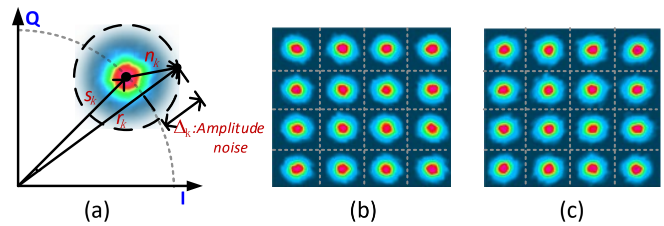

Fig. 8. (a) Graphical illustration of distributions of fully equalized signal and amplitude noise; Received 16-QAM distributions with (b) -4 dBm signal launched power and 18 dB OSNR (c) 4 dBm signal launched power and 26 dB OSNR over an 800-km link. As evident from the figures, amplifier noise and fiber nonlinearity effects will induce similar distortions to the received signal distributions and therefore it is not easy to distinguish between them for accurate OSNR monitoring [83].

$$\mu_2 \approx \mathbf{E}(|z_k|^2), \tag{8}$$

$$\mu_4 \approx \mathbf{E}(|z_k|^4), \tag{9}$$

respectively. $\mathbf{E}(\cdot)$ denotes expectation and the carrier-to-noise ratio (CNR) for QPSK and 16-QAM are expressed as

$$CNR_{QPSK} = \sqrt{2\mu_2^2 - \mu_4}\Big/\left(\mu_2 - \sqrt{2\mu_2^2 - \mu_4}\right) \tag{10}$$

and

$$CNR_{16-QAM} = \sqrt{2\mu_2^2 - \mu_4}\Big/(\mu_2\sqrt{0.68} - \sqrt{2\mu_2^2 - \mu_4}) \tag{11}$$

respectively. When the launched power is so low that fiber nonlinear effects can be neglected, the OSNR value in dB can be estimated from the CNR value as

$$OSNR_{dB} = 10\log_{10}(CNR) + 10\log_{10}(\frac{R_s}{B_{ref}}), \tag{12}$$

where R_s is the symbol rate and R_s/B_{ref} is a scaling factor adjusting the measured noise bandwidth to the reference bandwidth B_{ref}. The bandwidth B_{ref} is usually set to 12.5 GHz, which is equivalent to the 0.1-nm OSA resolution bandwidth. As shown in (8) and (9), measuring second- and fourth-order moments does not include any effect of the phase noise and thus the proposed scheme operates phase insensitively.

Another approach is to utilize the error vector magnitude (EVM) of fully equalized signals as an OSNR estimator [80]-[83]. In this approach, the k^{th} received symbol in one particular polarization r_k is taken before decoding and symbol decision stage where frequency offset compensation and carrier phase estimation are applied to z_k. In this case, r_k is fully equalized and can be represented as

$$r_k = \hat{s}_k + n_k, \tag{13}$$

where $\hat{s}_k$ is the symbol after decoding and symbol decision stage that is the estimate of transmitted 16-QAM symbol s_k and n_k models the collective ASE noise generated by inline optical amplifiers which is a band-limited complex circularly symmetric zero-mean Gaussian random process with covariance matrix $\sigma^2 I$ (Shown as in Fig. 8(a)). The OSNR can be estimated through an EVM-based approach [83]

$$OSNR_{Estimated} = \frac{P_{in}}{P_{ASE}} = \frac{\mathbf{E}(|\hat{s}_k|^2)}{\mathbf{E}(|n_k|^2)}, \quad (14)$$

where P_{in} is the signal power, P_{ASE} accounts for the ASE noise power. However, since the signals used for estimation are taken after carrier-phase recovery, the accuracy of the estimation may be affected by the frequency offset and phase noise. Furthermore, it should be noted that both the statistical-moment-based and the EVM-based OSNR estimator are affected by the ISI caused by cascaded-WSS-filtering since it is regarded as additional ASE noise. A filtering-effect-insensitive OSNR monitoring method [84] will be introduced in the next section.

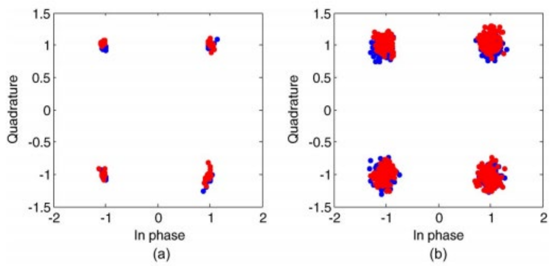

Fig. 9. Constellation of equalized TS (QPSK) with (a) no filtering and (b) channel filtering [79].

In [79], a method is proposed to employ a moving average filter based on the estimated channel transfer function to reserve the noise information in the received training sequences (TS), and then OSNR can then be estimated through the SNR from the training sequences. Fig. 9 shows a constellation plot of the equalized training sequences for QPSK system before and after channel filtering using Golay sequences with OSNR = 22 dB. In case of no channel filtering, small variations in the equalized training sequences are due to misalignment between the overlap-cut equalizer and the training blocks, while it can be seen that, with estimation filtering, the noise information is reserved and can be used for SNR estimation. After the equalization of the training sequences using the estimated channel information with filtering, the added noise can then be subtracted from the signal and the SNR is measured from the EVM of the equalized TSs by(14). Finally, the OSNR is estimated by first measuring the electrical RF noise SNR_{RF} at a reference OSNR point. This is done by measuring the reference point in a back to back configuration and without any added ASE and then the OSNR is calculated as:

$$OSNR_{dB} = 10\log_{10}(\frac{B_{ref}}{R_s}) - 10\log_{10}(SNR^{-1} - SNR_{RF}^{-1}), \quad (15)$$

where SNR_{RF} is the measured system SNR without any added ASE noise. This method is modulation-format independent as it only utilizes the properties of the equalized TSs and the modulation format can be altered arbitrarily in between the fixed training patterns. Another data-aided joint PDL and OSNR Monitoring method is proposed in [80], where frequency-domain (FD) equalization combined with periodically transmitted training sequence is used for better filter acquisition. The OSNR is monitored using the EVM method and the PDL is obtained from the coefficients of the adaptive filter.

All the OSNR monitoring techniques discussed above are under the assumption that the optical transmission channel is linear. However, in order to attain the best performance, most of the currently deployed long-haul optical communication systems are operating in the weakly nonlinear regime which is a tradeoff between mitigating the effect of ASE noise and fiber nonlinearities. Nonlinear distortions are typically treated as noise and are indistinguishable from amplifier noise (as shown in Fig. 8(b)-(c)) by the standard DSP platform since fiber nonlinearity compensation algorithms such as digital back-propagation [85] is too complex to be realized at present. Therefore, those abovementioned OSNR estimation techniques based on the SNR of equalized signal or TSs will considerably under-estimate the OSNR for long-haul transmission systems. In [83], the fiber nonlinearity induced amplitude noise correlation among neighboring symbols is characterized as a quantitative measure of nonlinear distortions which is shown to only depend on signal launched power but not OSNR and hence fiber nonlinear distortions can be isolated from ASE noise. In this case, nonlinearity-insensitive OSNR monitoring is achieved by incorporating/calibrating such amplitude noise correlations into an EVM-based OSNR estimator. Since nonlinear distortions can be modeled as complex circularly symmetric additive Gaussian noise with zero-mean for long-haul coherent transmission links without in-line dispersion compensation, (13) can be re-written as

$$r_k = s_k + n'_k = s_k + n_k + v_k \quad (16)$$

where $n'_k = n_k + v_k$ consists of ASE noise n_k and nonlinearity-induced distortions v_k. With the EVM methodology, v_k become addition distortions and thus if we naively use the EVM method by simply measuring the 'size' of the 'clouds' in the received signal distributions, the OSNR estimates in (14) can be re-written as

$$\begin{aligned} OSNR_{Estimated} &= \frac{\mathbf{E}(|\hat{s}_k|^2)}{\mathbf{E}(|n'_k|^2)} \\ &= \frac{\mathbf{E}(|\hat{s}_k|^2)}{\mathbf{E}(|n_k|^2) + \underbrace{\mathbf{E}(|v_k|^2) + \mathbf{E}(n_k v_k^*) + \mathbf{E}(n_k^* v_k)}_{P_{NL}}} = \frac{P_{in}}{P_{ASE} + P_{NL}}, \end{aligned} \quad (17)$$

which can significantly under-estimate the true OSNR. The interaction of fiber nonlinearity, CD and ASE noise will produce distortions such as IFWM that are shown to be correlated across neighboring symbols even after appropriate linear impairment compensation [86]. Denoting Δ_k as the amplitude noise of the k^{th} received symbol, let the autocorrelation function (ACF) of amplitude noise across neighboring symbols be

$$R_\Delta(m) = \mathbf{E}[\Delta_k \Delta_{k+m}] \quad (18)$$

It is shown in [86] that the amplitude noise is correlated across neighboring symbols and $|R_\Delta(1)|$ can be used by multiplied by a calibration factor ξ as a measure/estimate of the amount of nonlinear distortions P_{NL} in the received signal r_k. The calibration factor ξ only depends on the transmission distance L. Incorporate the term $|R_\Delta(1)|\times\xi$ in the OSNR estimator in (17) and thus a nonlinearity-insensitive OSNR monitor can be obtained by

$$OSNR_{Estimated} = \frac{\mathbf{E}(|\hat{s}_k|^2)}{\mathbf{E}(|n_k'|^2) - |R_\Delta(1)|\times\xi}. \qquad (19)$$

With the calibration based on $|R_\Delta(1)|\times\xi$, it achieves <1 dB accuracy for both PM-QPSK and PM-16-QAM signals for a transmission link up to 1600 km with 2 dBm signal launched power [83].

Since this method only use the amplitude noise correlation across neighboring symbols mainly to characterize the intra-channel nonlinearities, it may not work accurately in WDM systems where inter-channel nonlinearities also occur. In [87], Choi *et al.* propose to use the autocorrelation between two polarizations at the same time slot, $R_{XY}(0)$, to characterize inter-channel nonlinearities such as cross phase modulation (XPM), together with the amplitude noise autocorrelation across neighboring symbols of both polarizations $R_{XX}(1)$ and $R_{YY}(1)$, to achieve a nonlinearity-tolerant OSNR monitor in WDM systems. The total autocorrelation function R_{NID} for nonlinearity-induced distortion (NID) is written as

$$R_{NID} = [R_{XX}(1) + R_{YY}(1)] + aR_{XY}(0), \qquad (20)$$

where a is a weighting factor. This method can achieve <1.3 dB OSNR monitoring accuracy regardless of the transmission distances, number of WDM channels, signal launched powers, and PMD.

In [88], an in-band OSNR monitor with large nonlinear tolerance is proposed based on transmitting differential pilot sequence at transmitter side together with DSP algorithms after coherent detection. When the nonlinearity is absence, in the pilot period the signal spectrum is composed by one single spectrum component which denotes pilot and a flat pedestal which is ASE noise. As the noise spectrum density can be easily measured by the spectrum components different from dedicated pilot frequencies, together with the total power of the equalized payload, OSNR value can be obtained. However, in the presence of fiber nonlinearity, the spectrum will be broadened and the ASE noise cannot be easily measured from the spectrum components different from dedicated pilot frequencies. Dou *et al.* [88] propose to generate QPSK constellation points in the pilot sequences in clockwise and counter-clockwise directions in horizontal (H) and vertical (V) polarizations, respectively. With such design, the ASE noise can be isolated from intra-channel and inter-channel nonlinear noise in frequency domain and taken for OSNR calculations. Experimental results showed a high monitoring accuracy of less than 0.5 dB monitoring error regardless of different pulse shapes and the amount of nonlinearities (1dB error after 4dBm 2700km transmission).

In [89], a technique is introduced to measure the OSNR for systems operating under linear and nonlinear conditions, by taking into account nonlinear-induced signal spectral deformation. By comparing the transmitted optical spectrum with the reference spectrum obtained at the transmitter side and with some deformation, the OSNR can be obtained even in the non-linear regime. Measurements on five representative 100G system configurations with multiple test channels and OSAs showed that a typical monitoring error below 0.5 dB can be achieved over a wide range of conditions.

In [90], an in-band optical signal-to-noise ratio (OSNR) monitor using a high-speed Stokes polarimeter and based on the analysis of instantaneous polarization state distributions for polarization multiplexed signals is proposed. The principle of the proposed OSNR monitor is that the thickness of the lens-like shape of data scattered distributions in Stokes space (as shown in Fig. 7) highly depends on the ASE noise power, especially for PSK signals of constant amplitude and it can therefore be used as a measure of the OSNR. However, it requires a high detection bandwidth of the order of the signal

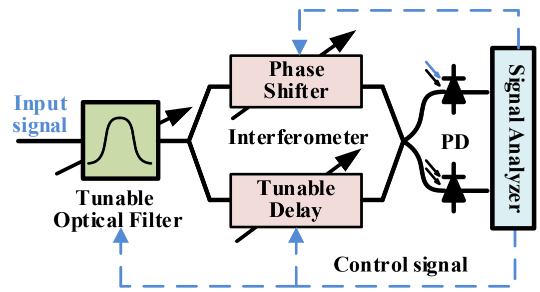

Fig. 10. Block diagram of delay-line interferometer (DLI) based OSNR monitor for WDM channels [92].

symbol rate and is sensitive to chromatic dispersion. Lundberg *et al.* [91] propose to use a setup based on a polarization beam splitter, a 90◦ hybrid and balanced detectors, similar to a coherent receiver but with relatively low-speed electronics (sampling rate is 50 MHz), to obtain the Stokes parameters. Then, the ratio between the diameter and the thickness of the lens can be used as a measure of the OSNR. This ratio, Γ, can be written in terms of the variances of the Stokes parameters as [91]

$$\Gamma = \frac{\mathrm{var}(s_2)+\mathrm{var}(s_3)}{2\,\mathrm{var}(s_1)} = \frac{k_{22}OSNR^2 + k_1 OSNR + k_0}{k_{21}OSNR^2 + k_1 OSNR + k_0}, \qquad (21)$$

where k_{ij} are the coefficients depended on the modulation format. It is shown that by applying low-pass filtering, the method is robust to large amounts of accumulated CD and also can apply in Nyquist-WDM systems.

C. OPM at the intermediate network nodes using low-cost structures

A typical low-cost OSNR monitor for intermediate nodes is based on a delay-line interferometer (DLI) [92] which is shown in Fig. 10. Since the signal is coherent and experiences constructive and destructive interference in the DLI whereas in-band noise is noncoherent and insensitive to constructive and destructive interference, the power splitting ratio of signal and noise between the constructive and the destructive ports of the DLI are different. Therefore, by measuring the optical power of the constructive and destructive output ports using simple, low-speed photodiodes, the power associated with the signal and the noise can be determined and thus the OSNR can be obtained as,

$$OSNR(dB)=10\log_{10}\left(\frac{(\alpha+1)\times(\delta-\beta)}{(\beta+1)\times(\alpha-\beta)}\times\frac{\text{NEB}}{0.1\text{nm}}\right),\qquad(22)$$

where $\alpha=P_{\text{Const, Signal}}/P_{\text{Dest, Signal}}$, $\beta=P_{\text{Const, Noise}}/P_{\text{Dest, Noise}}$, $\delta=P_{\text{Const, Channel}}/P_{\text{Dest, Channel}}$. In the above equation, α, β, and δ are the signal, noise, and channel under test distribution factors, respectively. The NEB is defined as the noise equivalent bandwidth for the filter. In the series paper [93]-[96], some practical application issues of DLI-based OSNR monitor were investigated. Reference [93] gives design guidelines of DLI-based OSNR monitor to achieve a desired level of monitoring accuracy. Reference [94] shows its robustness and accuracy to the transmitter parameters drift in a various reconfigurable networking conditions is investigated for 25-Gbaud PM-QPSK and PM-16-QAM signals. Reference [95] demonstrates its format transparency and baud rate tunability and gives an operating guidelines for a desired level of monitoring accuracy for coherent data channels including the shape of the filter spectrum, the bandwidth of the filter, DLI delay, and DLI phase-detuning. In [96], the monitor accuracy is experimentally examined when the initially measured calibration parameters of the DLI-based monitor for a 25-Gbaud PM-QPSK signal are kept fixed without updating in the presence of various systems changes by modifying the transmitter and link parameters. Additionally, by tuning the optical filter to an offset frequency of the target optical signal and adjusting the phase shift of the DLI, it succeed in monitoring the OSNR of Nyquist-Shaped superchannels with <1dB accuracy [97]. Also, Ahsan *et al.* [98] demonstrate a pilot tone-aided DLI-based OSNR monitor for cross-layer impairment-aware routing in a mixed signal environment. Pilot tones have been shown to be an effective means of labeling signals and for providing signal presence and power information in the past [50]. In their proposed solution, the pilot tone is added to each type of signal at the transmitter to act as an identification code, which can assists the DLI-based OSNR monitor to autonomously change its calibration parameters to adaptive to various data rates and modulation formats of the signal under test. It is a key step towards realizing intelligent impairment aware networks. However, the monitoring accuracy of the DLI-based OSNR monitor is affected by the spectral narrowing introduced by cascaded WSSs as the calibration parameters α and β depends on the spectral shape of the signal which will be changed along transmission in the presence of WSS filtering.

Another simple OSNR monitoring scheme using tunable optical band pass filter with optical power measurements on an offset frequency is reported in [99],[100]. Its working principle is based on the fact that the ASE noise can be modeled as additive white Gaussian noise (AWGN) and its power P_{ASE} around center frequency f_{CF} and offset frequency f_{OF1} within a given band can be assumed to be the same, while the signal power P_{SIG} within the two bands are determined by the signal pulse shape which normally are not the same (as shown in Fig. 11). The relationship between P_{CF}, P_{OF1}, P_{SIG} and P_{ASE} can be described as [99]

$$P_{\text{CF}}=P_{\text{SIG}}+P_{\text{ASE}},\quad P_{\text{OF1}}=R_1P_{\text{SIG}}+P_{\text{ASE}}.\qquad(23)$$

The calibration parameter R_1 can be obtained by placing the monitor at the transmitter (Tx) side and performing a back-to-back measurement where the ASE noise is negligible, i.e. $R_1=P_{\text{OF1-Tx}}/P_{\text{CF-Tx}}$. The OSNR can then be calculated by the CPU as

$$\text{OSNR[dB]}=10\log_{10}\gamma\frac{1-P_{\text{CF}}/P_{\text{OF1}}}{(P_{\text{CF}}/P_{\text{OF1}})R_1-1},\qquad(24)$$

where the calibration parameter γ is determined by the electrical filter bandwidth and signal bandwidth. However, the monitoring accuracy relies on the bandwidth of the optical filter and a very narrow bandwidth (several GHz, expensive and not commercially available at present) is needed to guarantee a good monitoring accuracy [99]. Besides, it may also suffer from WSS induced spectral narrowing.

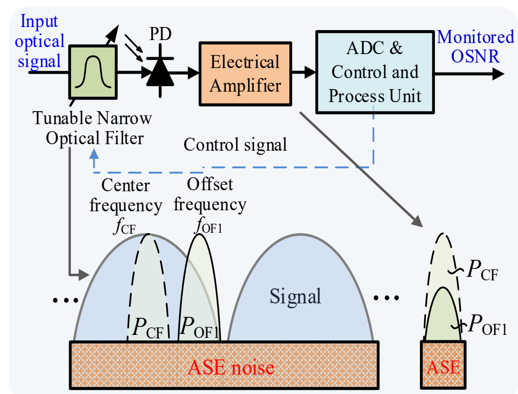

Fig. 11. Schematic diagram of proposed in-band OSNR monitor based on offset optical filtering and the optical spectra after filtering at center frequency and offset frequency. ASE noise spectrum is assumed to be constant within a given band, whereas P_{CF} and P_{OF1} represent the power of central filtering and offset filtering.

Alternatively, the OSNR monitoring technique based on offset filtering and power measurement can also be implemented in electrical domain by coherent detections where electrical filters with a bandwidth of hundreds of MHz can be used instead of the optical filter and thus the monitoring accuracy is increased [84]. Fig. 12 (a) shows the schematic diagram of the monitor. It consists of a tunable laser that functions as a local oscillator (LO), a 3dB coupler, a low-speed balanced detector (several GHz), a low-pass electrical filter, an RF power meter and a control and process unit (CPU). The incoming optical signals tapped from the transmission link firstly go into a 3dB coupler, where the signals beat with the light of tunable laser. Since no phase or polarization information is required for the monitoring, a 3 dB coupler rather than a polarization diversity optical quadrature front-end (2×4 90° hybrid) is used to coherently detect the signals. After balance detection, the resulting baseband RF signals then go into an electrical low-pass filter. All devices used in the monitor are commercially available that implements it in a low-cost fashion. The monitoring principle is similar to that in the optical domain. By tuning the frequency of the tunable laser to the center frequency f_{CF} and an offset frequency f_{OF1} of the target optical signal, the signal components around f_{CF} and f_{OF1} falls into the passband of the electrical filter and are measured by the RF power meter as P_{CF} and P_{OF1} respectively. By performing a back to back measurement that gives the power ratio R_1 of the pure signals at frequencies f_{CF} and f_{OF1}, the OSNR can be obtained by using (24). However, the calibration parameter R_1 depends on the signal spectral shape and remain unchanged only when there is no additional filtering effect. In practical transmission systems, WSSs in ROADMs are essential parts of present optical networks and cascaded filtering effects by WSSs during signal transmission are known to affect spectral shapes. Fig. 11(b) shows the spectral narrowing effect for a 25-Gbaud signal by cascaded WSSs. The shape of the sideband is obviously changed and thus the relationship in (23) will no longer hold which may lead to unacceptable OSNR monitoring errors. In order to cope with spectral narrowing in the OSNR monitoring, Dong *et al.* [84] proposed to take another RF power measurement P_{OF2} at a second offset frequency f_{OF2} and define a calibration parameter R_2 similar to R_1. Additionally, two more

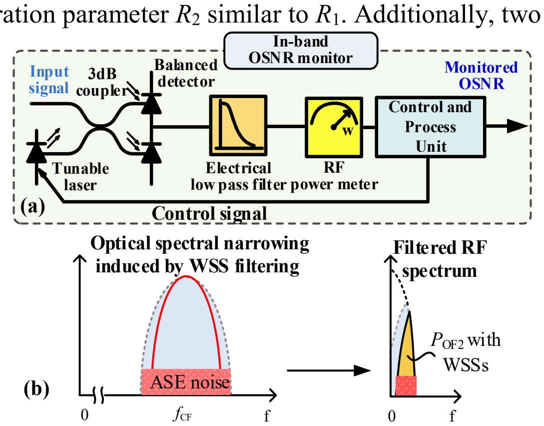

Fig. 12. (a) Schematic diagram of proposed OSNR monitor; (b) WSS filtering induced optical spectral narrowing and RF spectral narrowing.

parameters α and β are defined to characterize the effect of a WSS on the spectral shape at f_{OF1} and f_{OF2} respectively, which can be obtained by placing a WSS between the transmitter and the monitor and performing a back-to-back measurement. In the presence of N cascaded WSSs in the transmission link, the measured power can be re-written as

$$\begin{cases} P_{CF} = P_{SIG} + P_{ASE}, \\ P_{OF1} = R_1 \alpha^N P_{SIG} + P_{ASE}, \\ P_{OF2} = R_2 \beta^N P_{SIG} + P_{ASE}. \end{cases} \tag{25}$$

By solving the three equations above, we can obtain N, P_{SIG} and P_{ASE} and thus calculate the OSNR. OSNR monitoring is experimentally demonstrated in [84] for different data formats over various distances. The accuracy of the monitoring results show that the OSNR monitor can perform accurately independent of the data format and insensitive to the WSS filtering. The proposed technique is also shown to be robust to the fiber nonlinearities, calibration parameter mismatches and random variations of WSS parameters within a certain range.

Data-aided DSP with low-speed coherent receivers also can be implemented in the intermediate nodes for the low-cost OSNR monitoring purpose. In [101], Golay sequences are used as the training sequences since they are a pair of complimentary sequences $S_1[k]$ and $S_2[k]$ that satisfy the power spectrum property:

$$G[k] = |S_1[k]|^2 + |S_2[k]|^2 = L, \tag{26}$$

where $S_1[k]$ and $S_2[k]$ are the discrete Fourier transform of the original S_1 and S_2 sequence, respectively, and L is a constant related to the length of each sequence. Neglecting the effect of linear impairments, considering Gaussian distributed noise with zero mean and after some mathematical manipulation and simplification, it is shown that the variance of Golay power spectrum of the received TSs $G[k]$, is proportional to the expected value of noise power spectral density and thus is related to the system SNR as shown in Fig. 13. Since the proposed technique utilizes spectral property in frequency domain, SNR can be estimated by using a low sampling speed and low-bandwidth receiver. Experimental verification is demonstrated to monitoring the OSNR of 10 Gbaud PM-QPSK and PM-16-QAM signals utilizing a low-bandwidth receiver

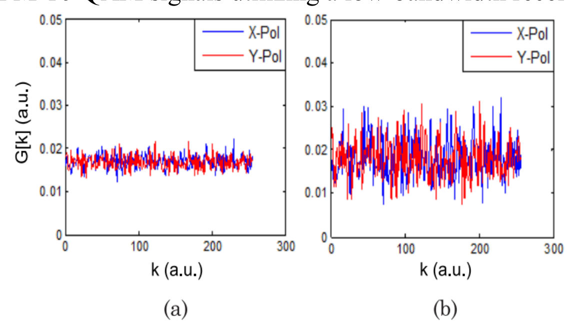

Fig. 13. Frequency spectrum $G[k]$ of Golay pair on both polarizations with (a) OSNR = 22 dB and (b) OSNR = 12 dB [101].

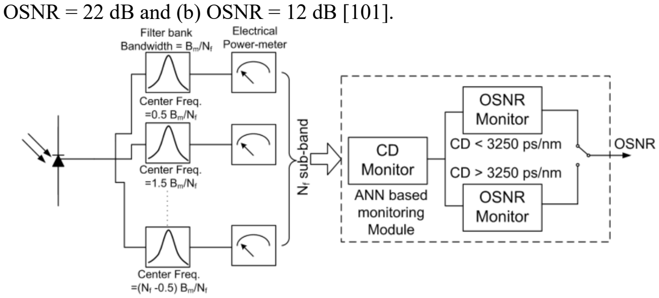

Fig. 14. OSNR monitoring setup for 112 Gbps PM-RZ-QPSK systems with large inline CD using a bank of electrical filters and power meters covering an overall bandwidth of several GHz. An ANN based-CD monitor is used to determine whether the CD exceeds 3250 ps/nm followed by two separate OSNR monitors covering the low and high CD ranges [102].

with 800-MHz filter working at 2.5 GHz sampling rate. A wide OSNR monitoring range with accuracy within 1 dB for up to 1000-km transmission is achieved.

Shen *et al.* [102] utilized the artificial neural network (ANN) to directly detect polarization multiplexed return-to-zero QPSK (PM-RZ-QPSK) signals and use part of its RF spectrum as an input to an ANN for OSNR monitoring in presence of a large range of CD values. This is motivated by the fact that new coherent transmissions links will not have inline dispersion compensation and hence OSNR monitoring in presence of a wide range of unknown CD become a new and unprecedented challenge in OPM research. The input to the ANN is part of the RF spectrum power which can be measured in practice by simple power meters and only direct detection is used as shown in Fig. 14. Therefore, this proposed technique is low-cost and may serve as a key step towards practical realization of ubiquitous OSNR monitors for coherent links.

The comparison of in-band OSNR monitoring techniques discussed above in terms of their monitoring domain, bandwidth requirement, training-symbol requirement, advantages and limitations is presented in TABLE II.

TABLE II
COMPARISON OF OSNR MONITORING TECHNIQUES FOR COHERENT SYSTEMS

Technique	Domain	Bandwidth requirement	Data-aided/ Non-data-aided	Advantages/ Limitations
1.Statistical moments /EVM [75]-[82]	Electrical	High	Either	Nonlinearity- and filtering -sensitive
2.Calibration Tech. 1 with noise ACF [83],[87]	Electrical	High	Either	Nonlinearity-insensitive and filtering -sensitive
3. Stokes parameters [91]	Electrical	Low	Non-data-aided	PMD-sensitive
4. DLI [92]-[98]	Optical	Low	Non-data-aided	Filtering -sensitive
5.Offset frequency filtering [99]-[84]	Optical/ Electrical	Low	Non-data-aided	Filtering -insensitive [84]
6. Golay sequences [101]	Electrical	Low	Data-aided	CD, FO compensation and frame synchronization are needed
7. RF spectrum with ANN [102]	Electrical	Low	Data-aided	Complicated

V. Integrating OPM functionalities in Flexible and Elastic network operations

One defining feature of Elastic optical networks (EONs) is the ability to incorporate real-time network conditions and then plan and adapt different transmission link parameters such as modulation format, data rate, spectrum assignment and FEC codes depending upon those conditions [103]. An EON can automatically scale up or down resources in order to maximize the spectral and energy efficiencies of the network without any manual intervention. The key enabling technologies supporting EON include [104]:

Flexible frequency grid: A flexible-grid configuration allows the usage of multiple spectrum slots with fine granularity in contrast to a fixed-grid case which enables the occupation of only one spectrum slot for each connection.

Adaptive elements: These include flexible bandwidth transmitters and receivers (called bandwidth variable transceivers (BVTs)), bandwidth variable wavelength cross-connects (BV-WXCs) etc., which give the network the capacity to modify its configuration adaptively.

Monitoring mechanisms: The monitoring elements allow the EONs to be fully aware of the current network conditions, which is a prerequisite to be adaptive.

Optical performance monitoring is considered indispensable for the proper functioning of EONs. Through the monitoring devices placed at various strategic locations, an EON can become aware of the current network conditions and can thus adapt itself (with the help of adaptive elements) in order to optimize the network performance. The incorporation of OPM can help realize several key functionalities in EONs such as (i) dynamic and adaptive adjustment of modulation formats (called modulation format switching (MFS)) depending upon the physical layer parameters in order to maximize the spectral efficiency (ii) optimization of routing and wavelength assignment (RWA) algorithms by also considering physical layer impairments (PLIs) (referred to as PLI-aware RWA (PLIA-RWA)) apart from commonly-used metrics i.e. transmission distance and number of traversed nodes (iii) adjustment of powers and symbol rates of different subcarriers based upon actual channel conditions for the maximization of transparent reach (iv) efficient restoration of quality-of-transmission (QoT) through real-time impairments awareness for combating network failures [105],[106].

Since the future EONs operating at 400 Gbps and beyond are anticipated to employ the powerful DSP-based coherent technologies at the transmission end points, OPM techniques implemented within the DSP-based coherent receivers will be preferable for such networks. This is because the DSP-based OPM techniques are supposed to be easily adaptable to continuously varying modulation formats and data rates occurring in an EON. In addition, the DSP-based OPM techniques do not necessitate expensive external devices. Rather, the useful network information can directly be retrieved inside the DSP-based coherent receiver itself. Similarly, by integrating the reduced-complexity and low-cost DSP into the network elements (such as ROADMs and optical amplifiers etc.), real-time information about the network conditions can potentially be acquired at the intermediate network nodes [104].

Since optical orthogonal frequency division multiplexing (OFDM) may play a role in future EON, there is a considerable interest in the development of OPM techniques for OFDM signals. Both coherent- and direct detection- based OPM techniques have been proposed in literature. Coherent detection-based OPM techniques utilize DSP inside the coherent receivers for the simultaneous monitoring of various channel impairments [107]. Chen *et al.* [108] demonstrated the use of low-bandwidth coherent receivers as a cost-effective solution for OPM of OFDM signals at the intermediate network nodes. On the other hand, Bo *et al.* [109] performed monitoring of OFDM signals by inserting coded pilot subcarriers into the signals spectra at the transmitters and analyzing the correlation properties of the directly-detected signals at the intermediate network nodes.

Recently, there have been a few experimental works demonstrating the functionalities of OPM in EONs [110]-[113]. Gesiler *et al.* [110], employed OPM and a real-time adaptive control plane to optimize the network parameters depending upon the PLIs. In their work, signal quality was monitored at various network nodes, equipped with the necessary monitoring mechanisms, and the resulting information was then communicated to the network control plane. Based on the real-time monitoring information, the modulation formats and the centre frequencies of the optical signals were modified dynamically so as to maximize the spectral efficiency while retaining the required QoS and BER performance despite the presence of time-varying impairments.

Similarly, Jin *et al.* [111], demonstrated the use of online performance monitoring for adaptive bit and/or power loading in OFDM systems. Bit/power loading is a technique which is used in multi-carrier communication systems to optimize the bit/power distribution over various subcarriers depending upon the channel's state. In their work, the BER of each individual subcarrier was monitored and this information was then exploited to allocate higher-order modulation formats and/or lesser power to the subcarriers which experienced lower noise/distortion while the subcarriers experiencing deep fade were simply dropped. It is shown that the monitoring-enabled bit/power loading can significantly improve the transmission performance.

In [112], Cai *et al.* have demonstrated an efficient restoration method in EONs based on real-time performance monitoring. In their work, when the OSNR of a particular optical link degrades below an acceptable threshold, the monitoring module present in the relevant node detects and notifies the network control plane about the QoT degradation. The control plane then triggers a combination of MFS and lightpath rerouting (LR) methods to combat impairments and coordinate the simultaneous restoration of all affected connections.

OPM can also help in the realization of PLI-aware routing in EONs in order to improve the overall network efficiency. To this end, Lai *et al.* [113] demonstrated the use of OSNR monitoring for efficient network routing and enabling packet protection for critical data flows. In their work, OSNR information obtained thorough a DLI based OPM module is used to send feedback signals to the higher layers for effective packet rerouting and protection. A low OSNR value detected by the OPM device indicates degraded signal quality and vice versa. Depending upon the measured OSNR and the packet-encoded priority, the optical packets are either discarded and rerouted on the alternate path, or forwarded to the final destination port. This approach helps to reduce the penalties incurred due to re-transmission of critical, high-priority data packets.

VI. Commercial OPM devices and their deployments in Optical Networks

Current commercially available OPM devices are nothing more than a simplified version of optical spectrum analyzers [114]. These devices are capable of monitoring a few parameters such as wavelengths of WDM channels, total optical power, and out-of-band OSNR, and are normally referred to as optical channel monitors (OCM). These devices typically employ a tunable band-pass filter or a diffraction grating combined with a single detector to monitor the abovementioned parameters [4]. The information about the power level of each WDM channel is typically used to balance the optical amplifier gain across the spectrum. Similarly, the wavelength measurement provides information about whether the optical signal is properly placed in its channel. Recently a commercially available high-resolution OCM has been reported in [115]. It is based on the coherent detection technique and has high monitoring speed, 300 MHz high frequency resolution and small package size that is suitable for integration into next-generation ROADMs.

The limited information provided by the current OPM devices can only facilitate the detection of sudden faults and thus enable system alarms and error warnings for lost or out of specification optical channels. These devices are far from achieving the real objectives of OPM i.e., to enable error root cause analysis and to provide early failure identification so that the operators can initiate fast error cancellation. Therefore, to fulfill the ultimate potential of OPM, the commercial OPM devices need to undergo significant improvement in order to be able to constantly monitor the signal dynamics, observe system functionality, detect performance changes, and provide feedback information to the network elements for the optimization of operational performance of the optical networks.

Recently, there have been a few attempts to realize the OPM-enabled functionalities in practical fiber-optic networks. Morgan *et al.* [116], reported the in-service measurement of OSNR, CD and PMD on a live 140 km, 10 Gbps WDM optical link between Bromsgrove and Shrewsbury in Western England without interrupting the actual data traffic. An ADTS-based technique is used for the simultaneous monitoring of abovementioned parameters in a field trial. The real-time information provided by the OPM module is then used to effectively diagnose the underlying system issues. For example, it is revealed that the root cause of the higher than expected pre-FEC BER and reduced system margin of the monitored link is the high amount of residual CD resulting from the use of an incorrect dispersion compensation module. Thus, an in-service diagnosis of underlying network problems, as demonstrated in this work, can facilitate the early identification of root causes and permit the network operators to resolve the issues.

VII. Conclusions and Outlook

OPM continues to be an integral part of optical network operation and imperative for their evolution towards higher speed and improved reliability. As we move towards digital coherent transmissions and beyond, more tools are at our disposal for OPM and their underlying principles inherently merge with other well-researched disciplines such as channel estimation in traditional copper-wire/wireless communications. In addition, the emerging dominance of data centers/cloud computing driven traffic have fueled the need for OPM to not only manage network faults, but also provide information on real-time network conditions for implement impairment-aware routing and elastic optical networks. OPM and related optical network functionalities are expected to play an increasing role in shaping next generation optical networks.

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