Optical Performance Monitoring in WDM Network: A Review

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Abstract—**The rapid growth of optical networks and huge data traffics being carried by the network has made it critical to monitor the system at different locations between source to destination nodes. The output of the amplifier can be used to control the magnitude of disparaging effects through amplifiers, compensators etc. This paper reviews the different optical performance monitoring techniques proposed in the literature so far based on electrical post processing techniques. These methods implements FIR filters, eye diagrams, delay tap sample plots, constellation diagrams, histograms etc for performing OPM on optical network. The need to build efficient OPM is outlined.**

Keywords—WDM Networks, optical performance, optical layer.

I. Introduction

During the past decade, optical transport has enabled the rapid growth of data traffic in the network backbone. Because of such an enormous amount of data traffic carried by each fiber, even a brief service disruption could result in disastrous problems in every sector of society. Thus, for the proper operation and management of such dynamic networks, it is indispensable to have the capability of monitoring the parameters affecting network's performances directly in the optical layer. Examples of functions that require performance monitoring include amplifier control, channel identification and signal health assessment. It involves assessing the quality of data channel by measuring its optical characteristics without directly looking at the transmitted sequence of bits. It is a potential mechanism to improve control of transmission and physical layer fault management in optical transmission systems. In optical communications, typical roles for optical performance monitoring include ensuring correct switching in reconfigurable optical add-drop multiplexers, setting levels for dynamic equalization of the gain of optical amplifiers, and providing system alarms and error warning for lost or out of specification optical channels. Component alarms include monitoring of parameters such as amplifier pump laser power or temperature controller limits. 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 optical component used for this purpose the networks is known as optical performance monitor (OPM) or optical channel monitor (OCM), which measures channel power, wavelength, amplifier noise, optical signal-to-noise ratio (OSNR), chromatic dispersion, polarization-mode dispersion, fiber nonlinearity induced distortion and crosstalk, etc. Techniques such as Q-factor monitoring are perhaps the closest optical analog of the electronic performance monitor. In order to achieve long link lengths, optical impairments such as amplifier noise, chromatic dispersion, and polarization mode dispersion are carefully controlled. Prediction, monitoring, and control of nonlinear impairments are complicated by interactions between impairments [1-3].

OPM can be performed by measuring changes to the data and determining "real-time" changes resulting from various impairments, such that a change in a particular effect will change a measured parameter. This can employ:

(i) Optical techniques to monitor changes in a radio frequency (RF) tone power or in the spectral channel power distribution

(ii) Electrical post-processing techniques in the specific case of coherent detection

As we know, the network electronics have the equipments that monitor signal quality by checking for bit errors or other signs of signal degradation. This function remains in the optoelectronic regenerators typically spaced about every 500 km in terrestrial fiber networks. However, electronic performance monitoring is possible only where signals are in electronic form, not on fiber spans between switching and regeneration nodes where signal is optical in nature (Fig. 1).

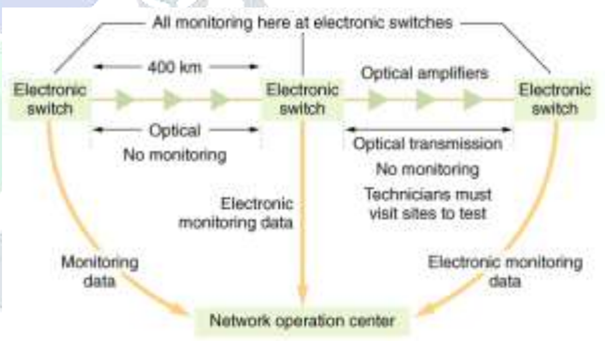

Fig. 1. : System performance monitored electronically at switches that transmit data back to the network operation center to monitor outages between switches. [4]

Optics are needed to monitor performance along those spans, which can include amplifiers, optical switches, and optical add/drops. Because electronic monitoring is not possible on the fiber spans between switches, technicians must go to the site to locate faults. This approach is labor intensive, but carriers find it cost-effective because sophisticated test equipment requires a large capital investment, reaching $100,000 for some units.

The monitoring 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 can be subdivided further into either time domain methods or spectral methods. Time domain monitoring includes eye diagram measurements and spectral methods include optical spectrum and amplitude power spectrum measurements.

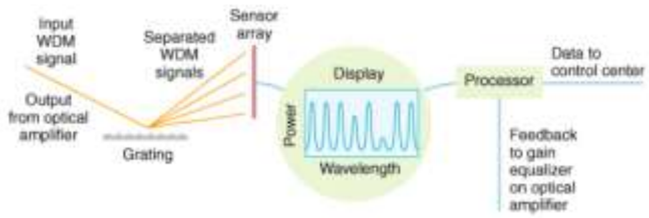

Fig. 2. : An optical spectrum analyzer spectrum showing optical channels in use. [4]

In the simple unit demonstrating OMS is shown in Fig. 2, where a diffraction grating spreads out the spectrum onto a linear sensor array, so each element measures the power over a small range of wavelengths. With proper calibration this gives the intensity on each standard optical channel.

There has been considerable theoretical work done in the field of optical performance monitoring [5-7], where different authors have reported different conclusions employing different techniques. Few of the prominent findings have been reported in brief according to the input element used by them.

Performance monitoring traditionally refers to monitoring for bit 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 may also be used to realize new methods of managing traffic like routing decisions can be taken based on capacity and priority [8], and traffic can be dynamically tuned to high-performance optical channels. In optical transport systems, the system performance is more closely tied to fault management and control applications than digital Quality of service applications. The primary control application is amplifier gain balancing. Also, by monitoring physical signal impairment the monitored signal is used for active compensation for gain ripple in long-haul transmission, dispersion compensation [9].

1.1 Performance monitoring using filter coefficients:

Various methods to monitor the signal are known. In general, they require cost-intensive external devices evaluating the optical spectrum. They monitor the optical signal, neglecting filters and electric distortions that are crucial for the signal quality at the decision point. In addition, they tap the optical signal reducing the effective receive power. Optical performance monitoring technique from FIR filter coefficients in coherent receivers with digital equalization is presented in [10].Residual chromatic dispersion; DGD and OSNR are simultaneously estimated from measured 111Gbit/s data. In [11] a state based OPM with simultaneous estimation of CD, OSNR and non-linearity is designed, which could be cost-effectively realized as a by-product in direct detection receivers with equalization by MLSE. Recently an increased demand on bandwidth efficiency and flexible impairment mitigation lead to an intensified research in coherent demodulation. Coherent demodulation gives a representative of the optical field in the electrical domain. This allows equalization by a complex valued FIR butterfly structure, where the filter coefficients relate to the inverse channel impulse response. This enables us to simultaneously estimate the parameters of CD, DGD and OSNR from FIR filter coefficients.

A complex butterfly structure is used to compensate for PMD, where each filter block is realized by a real butterfly structure to represent the digital filter. The recursive LMS algorithm continuously updates the tap weight coefficients, which guarantees initial convergence and tracking of time variant channel distortions. In steady state, the complex butterfly structure is a digital, real representation of the inverse impulse response defined by the tap coefficients. The received inverse impulse response obtained by blind convergence is transformed into the frequency domain to derive the channel parameters for CD and DGD from the filter coefficients directly. The channel transfer function of the filter can be written as follows:

$$H^{-1}(f) = \boldsymbol{U}(f) \cdot D(f) = \begin{bmatrix} u(f).D(f) & v(f).D(f) \\ -v^{*}(f).D(f) & -u^{*}(f).D(f) \end{bmatrix}$$

…(1)

Where ***U***(f) accounts for the inverse PMD matrix and D(f) contains the inverse linear transfer function. Operating in the linear regime, chromatic dispersion (CD) is the dominating effect. From Eq. 1, if we apply crosswise multiplication of the matrix elements,

$$u(f)D(f) \cdot u^{*}(f)D(f) - v(f)D(f) \cdot (-v(f)^{*})D(f) = D(f)^{2}$$

...(2)

We can easily separate D(f). The phase of D(f) will follow a quadratic function, which makes it easy to unwrap the 2π-ambivalence [12]. With the aid of a quadratic fit we estimate the value of CD giving $\widehat{D}(f)$. Now by eliminating the effect of CD from the transfer function, inverse PMD matrix is calculated. It can be derived that the components of ***U*** (f) satisfy

$$|u(f)|^{2} = (1 + 2(1 - \gamma) \cdot (cos(2\pi f\tau + \emptyset) - 1))$$

Where γ is the power splitting ratio, Φ is an arbitrary phase shift between the PSPs, and τ is the DGD. The same applies for v(f) with a negative sign. So after removing some bias, induced by the windowing effect of limited bandwidth of the filter, the value of the DGD with a sinusoidal fit is calculated. Finally the OSNR value is estimated by the variance of the update signal. This applies to steady state operation, where the mean value of the update signal is constantly zero. Given a sufficient tap length, which is equal or longer than the channel memory length, the variance of the update signal becomes a function of the noise power of the received signal. With a reference measurement or normalization, the noise power or the OSNR is estimated.

As we know, the information available from equalization filters of coherent receivers can be used to determine CD, PMD etc. For this, the frequency dependence Jones Matrix, *H*(ω) = *A*(ω)*U*(ω)*D*(ω), extracted from the filter is decomposed in to three factors where the PMD element is described by a unitary matrix *U*(ω), the Polarization dependent loss element by *A*(ω), and a scalar function *D*(ω) contains information on amplitude filtering and CD. This technique was demonstrated on a 43 Gb/s polarization multiplexed QPSK system [13].

1.2 Performance monitoring using asynchronous delay tap sampling:

Although these results are impressive, and come at no additional hardware cost at the receiver, the real time sampling requirements make them practical only for end to end monitoring. For distributed applications a lower cost application like Asynchronous delay-tap sampling can be implemented. Trevor Anderson and S. D. Dods in [14-15] represents a multi-impairment monitoring system using asynchronous delay tap technique. Asynchronous delay-tap sampling uses the joint probability density function of a signal *x* (*t*), and its delayed version *x* (*t*+Δ*t*) to characterize the signal. To generate the phase portrait, the waveform is sampled in pairs separated by a known delay Δt, as shown for the NRZ signal in Fig. 3 below.

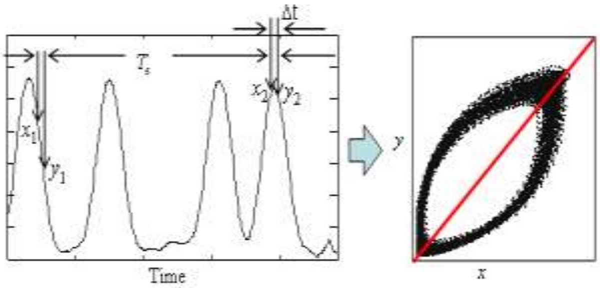

Fig. 3. : Phase portrait generation of 10Gbit/s NRZ with ¼ bit delay.

The phase portraits contain unique impairment signatures that can be discovered using statistical pattern recognition techniques and hence signal can be quantitatively monitored for simultaneous combinations like OSNR, CD, DGD, crosstalk and optical filter detuning, Self phase modulation, Q-factor etc. A key advantage of the technique is that a simple direct detection receiver can be used to monitor both amplitude and phase modulated formats without the need for demodulation of the signal or modification of the receiver bandwidth. The ¼ bit phase portrait shown in Fig. 3 provides a convenient monitor of signal quality. The width of the minor axis is a measure of the slope of the waveform whilst the distribution along the major axis, (corresponding to zero slope) provides an approximate measure of the Q factor. This Q estimate is used to monitor OSNR and the width is used to monitor CD. Alternatively, to capture the behavior of these plots, the plot is divided into four quadrants, Q1-Q4. It is observed that quadrant 4 contains data that is the mirror image of quadrant 2. So quadrant 4 is not used. For quadrants 1 and 3, the means and standard deviations of the magnitudes (r1, σ *r*1, *r*3, σ *r*3) are calculated and for quadrant 2, the means and standard deviations of the *x*'s and *y*'s are calculated separately. The parameter similar to the Q-factor, which is define as Q31 = (*r*3 − *r*1) /(σ *r*1 +σ *r*3) is also used. Using this approach a correlation coefficient between input and output predictions of 0.97 was obtained for a simulated 10 Gb/s NRZ system with relatively few (140) training cases. A key advantage of this approach is that it can be used for any format or tap delay without the need for fine tuning of the algorithm. The kernel based regression technique is used to model the impairments.

As optical networks become more complex, the need for in-line monitoring of more than just channel wavelength, power and OSNR becomes compelling. Another technique for simultaneous measurement of CD and 1st order PMD on a 40 Gb/s NRZ-DPSK signal is presented in [16-17]. It implement asynchronous delay tap sampling technique coupled with statistical machine learning that enables a single monitor to measure multiple simultaneous impairments on multiple formats. Optical performance monitoring of optical signal-to-noise ratio, chromatic dispersion, and polarization-mode dispersion in return-to-zero differential quadrature phase-shift keying signals is demonstrated using asynchronous delay-tap sampling and pattern recognition algorithms in [18]. Precise estimation of parameters over a broad range of impairment levels and good degradation isolation is shown by means of numerical simulation. [19] also represents a multi-impairment monitoring technique, with the added advantage that it can be used with any modulation format. Similar technique of monitoring a 10 Gb/s NRZ channel from a commercial transponder with randomly aligned first-order PMD used in a long-haul WDM test-bed with 50-GHz channel spacing is demonstrated in [20]. To take into account both the differential group delay (DGD) and the power split γ, an effective DGD (DGD_{eff}) is defined proportional to first-order string length and is a measure of first-order PMD system penalty. Independent of the OSNR, author has successfully measured DGD_{eff} and CD simultaneously with standard errors of ±3.1 ps and ±17 ps/nm, respectively. Asynchronous delay-tap sampling is used to create phase portraits. To analyze the phase portraits, the sample pairs are first binned into two-dimensional histograms. Pattern recognition techniques are then used to extract the impairment signatures and develop prediction models from the phase portraits. The training set included varying CD, DGD and γ, where the latter denotes the fraction of signal power in one of the PSPs, as well as a range of OSNR values. The advantages of using DGD_{eff} are that it is directly related to the induced signal distortion and thus the 1st order PMD-induced system penalty, and it provides a dynamic measure for feedback for PMD compensation.

1.3 Performance monitoring using eye diagram:

Author in [21-22] demonstrated powerful new technique for identifying the optical impairments causing the degradation of an optical channel. Machine learning and pattern classification techniques are implemented on eye diagrams to identify the optical impairments. These capabilities can enable the development of low-cost optical performance monitors having significant diagnostic capabilities. The performance measurement e.g. bit error ratio can be taken from the network interface points that do optical to electrical conversion (e.g., client interfaces, domain interconnection points, etc.). The function of the OPMs will be to identify the cause (e.g., type of impairment) of performance degradations, and multiple OPMs will be needed to sectionalize and locate the faulty equipment. An automated technique for analyzing the eye diagram of a monitored optical signal and identifying its optical impairments is proposed. For obtaining the needed training data, commercial optical communication system simulation packages are used to generate eye diagrams with different types and level of impairment and measured data from real optical signals is used for testing to get a reliable indication of the OPM classifier's true performance. For processing the eye diagrams for recognition, lower order Zernike moments are used. To compute the Zernike moments, the eye diagrams are scaled to fit within a unit disk. The moment set is determined by a chosen upper vector, which produced 23 independent moments (23-dimensional feature vector) to be used for classification, and ac as a feature vector input to pattern recognition system. Support vector machine (SVM) machine is used for pattern classification. The aim of SVM classification system is to classify test samples into one of classes. In this letter, we consider optical signals with a single impairment, and the impairment classes are chromatic dispersion (CD), first-order polarization mode dispersion (PMD), non-coherent crosstalk, and no impairment (normal eye). A similar approach implementing eye diagram measurement by asynchronous sampling is presented in [23]. Simple bit error rate (BER) estimation from eye diagrams is performed. The use of high-speed asynchronous opto-electrical (OE) sampling enables the monitoring of fixed timing Q-factors to be performed simply.

1.4 Performance monitoring using amplitude histogram:

Another novel method for monitoring optical signal quality is proposed by [24] for use in optical transmission systems. This method measures the amplitude histograms of optical signals by utilizing the optical sampling technique, and so can monitor the averaged quality of optical signals in an optical network with any bit rate or coding scheme. The paper demonstrates a method to monitor the signal quality or signal-to-noise ratio (SNR) of a digital signal regardless of its bit rate, frame format or even modulation format. Averaged Q-factor monitoring of RZ or NRZ 1OGb/s optical signals using the sum-frequency-generation (SFG) optical sampling method with a temporal resolution of 1ps s demonstrated. The optical signal and optical sampling pulses are combined and injected into an SFG crystal in order to generate the cross-correlation signals (the SF lights). These signals are detected and the sampled values are processed to obtain an amplitude histogram. The amplitude histogram exhibits amplitude distributions in both mark and space levels. The Q-factor(t_o) is estimated from the amplitude histogram which is generally made at a fixed timing phase (t_o) in the pattern. However, the data obtained by optical sampling include unwanted cross-point data in the eye diagram, which decreases the measured value of the averaged Q-factor. Thus, it is necessary to remove the cross-point data before hand [25].

1.5 Performance monitoring using constellation pattern:

In [26] a method using asynchronously generated constellation pattern to simultaneously monitor CD and first order PMD in DQPSK systems is presented. Being asynchronous, does not require exact clocked timing. In general, the eye diagram that can be generated by an oscilloscope after detection is a powerful diagnostic tool for evaluating system performance. It has been shown a clever adaptation of the eye diagram to asynchronously generate a new type of

diagram [27-28]. This asynchronous diagram is fairly straightforward to generate and will deform in generally predictable ways by different types of impairments, i.e., chromatic dispersion, polarization mode dispersion (PMD), optical signal-to-noise-ratio (OSNR). In QPSK, a generically valuable way of portraying the signal is to plot the data constellation on the I(in-phase) and Q (quadrature-phase) planes. A key challenge might be tailoring the constellation in order to monitor data impairments for phase modulated signals. In [29] we presented a method to monitor CD or first order PMD in DQPSK systems based on the constellation diagram using synchronous samples of the received signal, which was so sensitive to sampling time. In this paper we propose asynchronously generated constellation evolution of a DQPSK data stream. The optical part of the system was simulated in OptSim and the constellation plotting was done in MATLAB. In order to measure the effects of CD and DGD on the constellation pattern, some image processing techniques have been used to extract required features.

II. Conclusion

Key features of any optical performance monitors are simplicity in implementation and the ability to accommodate different modulation formats and impairments. As optical networks are now-a-days evolving from closed systems to open systems, in which the optical layer is designed to allow transmitter/receiver add and drop without affecting the current structure. To maintain system performance, agile optical performance monitoring (OPM) and automatic system control become increasingly important. As bit rates increase, it becomes more difficult to predict the data degradation mechanisms in optical networks. The required parameters, that are monitored, are required to be 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. 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 and the system design and the issue needs to be addressed in the nearby future.

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