Optical performance monitoring in phase-modulated transmission systems

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Abstract
Techniques of optical performance monitoring in optical phase-modulated transmission systems are presented. The monitoring requirements are listed and, through comparison of recently developed approaches, it is shown that the sampling-based monitoring offers the highest functionality.

Introduction
In recent years, optical communication systems have evolved towards transparent transmission, leading to end-to-end provisioning of high capacity optical channels. This trend has been accompanied by the introduction of high-spectral efficiency (SE) modulation formats [1]. In particular, the differential (quadrature) phase-shift keying (D(Q)PSK) formats have gained attention due to their resilience to nonlinear transmission impairments as well as reduced influence of chromatic dispersion (CD) and polarization mode dispersion (PMD). Despite the excellent transmission properties, unregenerated D(Q)PSK signals propagated exclusively in the optical domain are affected by accumulated optical impairments. Linear impairments such as the accumulation of amplified spontaneous emission (ASE) noise, CD and PMD and the influence of nonlinear phenomena are expected to limit the transmission reach. Moreover, both CD and PMD fluctuate in time due to temperature changes and vibration. Finally, in a dynamic, wavelength-routed network, signal path will change due to switching upon a connection request and so will the accumulated impairments. In order to ensure the quality of offered service in the network despite the influence of the optical impairments, it is necessary to monitor the quality of transmitted channels. Optical performance monitoring (OPM) can fulfill this role as OPM equipment will be deployed along the transmission path of the signal (Fig. 1) [2]. Several OPM techniques have been proposed in the literature [3]. Although the techniques take different approaches to analyzing the performance, few address monitoring of multiple impairments in phase-modulated systems. In this paper we give an outline of the OPM techniques that have been proved effective in monitoring the phase modulated transmission systems. We present a comparison of the existing approaches and draw conclusions about the development directions of future OPM techniques.

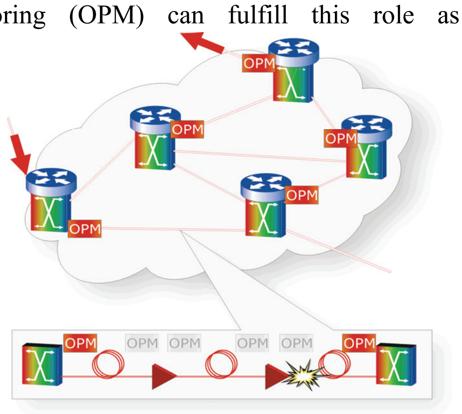

Fig. 1. Deployment of OPM equipment in transparent network.

Monitoring requirements and techniques
In order to realize the monitoring functionality, the OPM equipment must fulfill a number of requirements. The desired characteristics of an OPM system are:

- Transparency
- Asynchronous operation
- Multi-impairment monitoring
- Sensitivity
- Wide dynamic range
- Repeatability
- Affordable design

The basic OPM techniques are the power monitoring and the monitoring of optical spectrum. Although they have not been demonstrated specifically for the DPSK signals, these methods are used as a general reference. However, measuring of OSNR through optical spectrum is not suited to high SE networks [4] as the noise level between the channels cannot be observed. Furthermore, optical filters distort the spectrum of noise. Therefore, signal properties must be measured directly within the bandwidth of the optical channel.
The method, which has been proposed for monitoring of signal parameters on a per-channel basis is the pilot-tone method [5]. This method requires a modification to the transmitter as a low frequency RF-modulated tone is added to the bias of the laser diode. At the receiver, the tone can be filtered from the signal using a bandpass filter after the photodiode (PD) and analyzed using an RF spectrum analyzer. The pilot-tone technique allows monitoring of signal power, wavelength and path for DPSK signals; however, monitoring of transmission impairments has not been realized due to the low frequency of the tone. Another technique for monitoring of DPSK signals analyzes the RF clock power at the outputs of an unbalanced delay interferometer (DI). The clock components are used to independently analyze CD

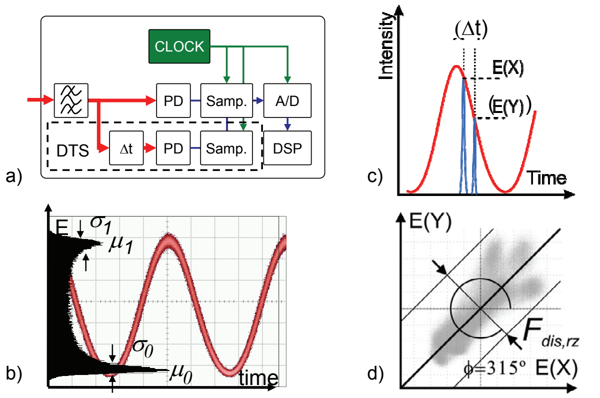

Fig. 2.Asynchronous sampling monitoring: a) monitor components; b) AAH and histogram parameters; c) waveform sampling with delay Δt; d) DTP with 1 symbol delay for monitoring CD.

and PMD. Although flexible, this method is limited to the NRZ-DPSK format and is fixed in terms of bit rate due to the use of a DI. Clock tone monitoring has also been demonstrated for evaluation of CD in NRZ-DPSK and RZ-DPSK signals [7]. The same study used the state of polarization (SOP) for measuring the impairment due to PMD. Finally, the RF signal spectrum has been employed to evaluate the level of OSNR [8].

A more flexible monitoring approach is provided by the techniques which sample the signal using an independent clock and employ digital signal processing (DSP) to evaluate signal degradation, as shown in Fig. 2 (a). Samples can be acquired using a high-speed PD and electronic sampling or optical gating and a slow PD. Sample values correspond to the instantaneous intensity of signal waveform. An example of the technique based on sampling is the asynchronous amplitude histogram (AAH) [9,10]. The histogram is created by sorting the samples by their value and counting the number of amplitude samples falling into each value bin (Fig. 2 (b)). Statistical parameters of the histogram reflect the properties of signal waveform and enable the evaluation of the level of impairments affecting the optical signal. AAH OPM technique enables monitoring of impairments due to CD, PMD and reduced OSNR for both RZ- and NRZ-DPSK signals. This technique also enables monitoring of DQPSK signals.

Another OPM technique developed for DPSK and DQPSK signals is delay-tap sampling (DTS). It is an asynchronous method employing pairs of signal samples (E(X), E(Y)) separated by a fixed delay Δt (Fig. 2. (c)) to analyze transmission impairments [11]. The samples can be obtained using two PDs and an optical delay (the lower branch in Fig 2. (a)) followed by two samplers. Alternatively an electrical delay line can be used. The exact choice of delay depends on which property of the signal is analyzed. The sample pairs serve as Cartesian coordinates which are overlapped to construct the delay-tap plot (DTP) (Fig. 2 (d)). The DTP allows graphically decomposing the waveform. The shape of the plot depends on the delay Δt and is influenced by the changes of signal waveform due to transmission impairments. Subsequent analysis of the DTP allows evaluating the level of signal degradation due to residual CD, PMD and reduced OSNR [12].

	OSNR	CD (ps/nm)	PMD (ps)
Spectral monitoring	Reference	n/a	n/a
Pilot tone	n/a	n/a	n/a
Partial-delay clock	n/a	0~600	0~50
Clock tone			
NRZ-DPSK	n/a	0~600	n/a
RZ-DPSK	n/a	0~900	n/a
SOP	n/a	n/a	0~100
RF spectrum	15~35	n/a	n/a
AAH	17~38	0~600	0~50
DTS	9~32	0~600	0~50

Tab. 1. Comparison of OPM techniques for D(Q)PSK signals (values corresponding to 10 Gsymbol/s signals).

Table 1 summarizes the monitoring techniques developed for D(Q)PSK signals. It considers the evaluation ranges for three impairments: OSNR, CD and PMD, equivalent to monitoring of a 10 Gsymbol/s signal. Clearly, the former techniques cannot realize the multi-impairment monitoring, whereas the asynchronous sampling-based techniques in the form of AAH and DTS have been shown to provide flexibility in terms of both monitored impairment and modulation format.

The presented methods have been verified for systems with symbol rates of up to 20 Gsymbol/s. The techniques will require adaptation and verification as the symbol rates per channel increase and new modulation formats, like optical frequency-division multiplexing (OFDM) or 8PSK/16PSK find their way into the commercial systems. Also new techniques relying on coherent detection and digital signal processing are likely to play a role in monitoring of future optical networks [13].

Conclusions

In this contribution we compared the OPM techniques for supervision of phase-modulated transmission systems. Among the time-averaged and time-resolved monitoring methods, those based upon asynchronous sampling have been shown to provide the highest flexibility of monitoring parameters for currently deployed systems.

Acknowledgements

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