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100 Gb/s PM-QPSK 相干光接收系统中改进的带内 OSNR 监测方法

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摘　要:为保证偏分复用正交相移键控(PM-QPSK)相干光通信系统的传输性能,提出了一种改进的基于高阶统计矩的光信噪比监测方案.该方案针对不同调制格式给出了不同的修正值,因此对调制格式透明.在搭建的 100 Gb/s PM-QPSK 相干接收系统中对该方案进行了数值仿真,结果表明:当光信噪比在 5～25 dB 的范围内,不同占空比调制码型的监测误差均小于 0.5 dB;光信噪比参考值为 14 dB 时,在 0.5 dB的监测范围内,色散容忍度为 2 400 ps/nm,对一阶偏振模色散的容忍度为 62 ps.

关键词:光纤通信;监测;偏分复用正交相移键控;色散;偏振模色散;相干接收系统;统计矩

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An Improved In-band OSNR Monitoring Method in 100Gb/s PM-QPSK Optical Coherent Receiving System

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Abstract: For protecting the transmission performance of the Polarization Multiplexed-Quadrature Phase Shift Keying (PM-QPSK) optical transmission system, an improved Optical-Signal-Noise-Ratio(OSNR) monitoring method based on high order statistical moment was proposed. By using different calibrations, this method is transparent for modulation formats. Using numerical simulation the proposed method is verified in 100 Gb/s PM-QPSK coherent receiving system. In the range of 5～25 dB OSNR, the OSNR measurement error is within 0.5 dB for the modulation formats with different duty cycle, and the system has 2 400 ps/nm of chromatic dispersion tolerance and 62 ps of first-order polarization mode dispersion tolerance for 14 dB OSNR with measurement error in 0.5 dB. The improved monitoring method has such advantages of small monitoring error and high tolerance to chromatic dispersion and first-order polarization mode dispersion.

Key words: Optical communication; Monitoring; Polarization multiplexed-quadrature phase shift keying; Chromatic dispersion; Polarization mode dispersion; Coherent receiving system; Statistical moment

OCIS Codes: 060.1660; 060.2330; 060.4510; 060.4080

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0 Introduction

Optical Signal-To-Noise Ratio (OSNR)[1-2] is a key parameter for the fiber link because it is related to the Bit Error Rate (BER) of the terminal end and transparent to the transmission rate and modulation format. In addition, OSNR of the transmission system can be used to manage, configure and optimize dynamic optical networks[3]. Over the past decade, the OSNR monitoring method is out-band measurement[4], which assumes that the Amplified Spontaneous Emission (ASE) noise level out-band can represent the ASE noise level in-band. However, with the widespread application of the Dense Wavelength Division Multiplexing (DWDM) system and Reconfigurable Optical Add-Drop Multiplexer (ROADM), the channel spacing is narrower and the out-band noise level cannot be used to estimate the in-band ASE noise level any more. So the accuracy of the out-band technique is no longer satisfied. In recent years, several in-band OSNR monitoring methods have been proposed. For example, the polarization-nulling method isolates optical signals from the ASE noise using different polarization properties produced by polarizers[5]; the interferometer-based techniques, such as delay interferometer[6], separate the ASE noise from optical signals on the basis of different coherence properties[6]. Both of the two in-band methods are mainly applied in 10G or 40G non-coherent receiver systems.

With the ever-increasing demand for bandwidth, high-speed coherent optical communication system, such as 100G and beyond-100G (B-100G) optical coherent transmission systems have been focused and gradually commercialized[7]. An in-band OSNR monitoring method for the high-speed system using higher-order statistical moment at the coherent receiver end has been proposed[8-10]. It occupies only a small DSP resource and without additional monitoring equipment. However, this method does not take the effect of some noise into account, such as the electrical noise resulted from Balanced Detector (BD) and other electrical devices in the coherent receiver, which leads to the inaccuracy of the OSNR measurement. On the other hand, this method is sensitive to different modulation formats and strict to the linear impairment compensation at the coherent receiver end.

To solve these problems, an improved OSNR measurement method based on statistical moment is proposed. Taking the electrical noises of the coherent receiver into account, measured OSNR vs. real OSNR with and without calibrations for different modulation formats are simulated. Furthermore, numerical simulations for different residual chromatic dispersion (CD) and Polarization Mode Dispersion (PMD) under incomplete linear impairment compensation[11] are carried out. Simulation results show that this modified OSNR monitoring technique suitable for high-speed in 100G Polarization Multiplexed Quadrature Phase Shift Keying[12] (PM-QPSK) coherent optical transmission system with different modulation formats.

1 100 Gb/s PM-QPSK optical coherent receiving simulation system setup

The simulation system setup is depicted as Fig. 1 in which the 100 Gb/s PM-QPSK coherent receiving system is comprised of transmitter, transmission link and coherent receiver. At the receiver end, the electrical signals of x and y polarization state are sampled after coherent receiver, CD and PMD compensation and the polarization demultiplexing. Using statistically processing, the SNR of the sampled signals is obtained and then the OSNR of the optical transmission signals.

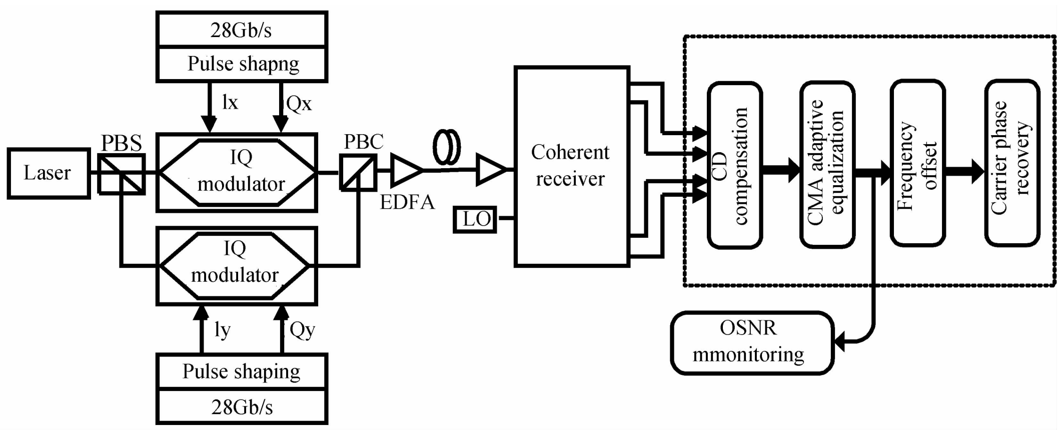


Fig. 1 100Gb/s PM-QPSK coherent receiving system and schematic diagram of OSNR

As an example, the electrical signals in x polarization can be expressed as

$$x_n = k\{\sqrt{P_s}\, e^{-j\varphi_s(t)} + \sqrt{N} n_x e^{-j\varphi_n(t)}\} + i_{sh} \tag{1}$$

where k is a parameter related to the power of local laser and the response of photodiode. P_s and N are the powers of the signal and the noise of x polarization respectively. n_x is normalized noise component. $\varphi_s(t)$ and $\varphi_{nx}(t)$ are the phases of signal and noise respectively. Taking the frequency offset between transmitter laser and the local laser and the phase noise into account, $\varphi_{nx}(t)$ obeys uniformly distribution. The module of signal, for QPSK modulation, is a constant and the noise component is a complex Gaussian noise, whose mean and variance is 0 and $2\sigma^2$ respectively. Consequently, the module of the received signal obeys Rician distribution. In Eq. (1), is the electrical noise of the balance detector, including thermal noise and shot noise, etc.

2 Theory of the improved OSNR monitoring method

According to Ref. [8], the second-order and fourth-order statistical moments of the received signals are as following

$$\begin{cases} E\{x_n x_n^{\dagger}\} = P_s + 2\sigma^2 \\ E\{(x_n x_n^{\dagger})^2\} = P_s^2 + 8P_s\sigma^2 + 8\sigma^4 \end{cases} \tag{2}$$

The powers of signal and noise can be deduced from Eqs. (2) and then the Signal-To-Noise Ratio (SNR) is given by

$$\mathrm{SNR} = P_s / P_{\mathrm{ASE}} = P_s / 2\sigma^2 = \frac{\sqrt{2E\{x_n x_n^{\dagger}\}^2 - E\{(x_n x_n^{\dagger})^2\}}}{E\{x_n x_n^{\dagger}\} - \sqrt{2E\{x_n x_n^{\dagger}\}^2 - E\{(x_n x_n^{\dagger})^2\}}} \tag{3}$$

In Eq. (3), the noise power is obtained based on the assumption that the ASE noise spectrum is flat in the monitored channel. But in practical, the ASE noise spectrum may not be flat because optical signals go through several Wavelength Selective Switches (WSS) and Erbium Doped Fiber Amplifiers (EDFA). We use Gaussian lowpass filter at the receiving end in order to approach the real ASE noise spectrum.

For coherent receiving system, the signals are oversampled by the two-fold symbol rate. The SNR calculated from Eq. (3) is that of sampled signals, which is larger than the real value. Therefore, a calibration value described as Eq. (4) is used to modify the result from Eq. (3)

$$\Delta \mathrm{SNR} = \frac{E\{(x_{\mathrm{samp}} x_{\mathrm{samp}}^{\dagger})\}}{E\{(x_n x_n^{\dagger})\}} \tag{4}$$

where $E\{(x_{\mathrm{samp}} x_{\mathrm{samp}}^{\dagger})\}$ is the average power of the sampled signals, and $E\{(x_n x_n^{\dagger})\}$ is the average power of the whole symbol period, namely the power of un-sampled signals, which can be measured by power meter. The average power of the sampled signals and the calibration value of ΔSNR vary with different modulation formats.

It should be noticed that the electrical noise i_{sh} has not been taken into account. We further modify the calibration value with statistical moments. The back-to-back transmission SNR is

$$\mathrm{SNR}_{\mathrm{RF}} = \frac{P_s}{P_{\mathrm{RF}}} \tag{5}$$

when ASE noise exist, the estimated SNR can be expressed as

$$\mathrm{SNR}_{\mathrm{ASE+RF}} = \frac{P_s}{P_{\mathrm{RF}} + P_{\mathrm{ASE}}} \tag{6}$$

As a result, the SNR calculated in the absence of electrical noise is

$$\mathrm{SNR}_{\mathrm{ASE}} = \frac{P_s}{P_{\mathrm{ASE}}} = \left(\frac{1}{\mathrm{SNR}_{\mathrm{ASE+RF}}} - \frac{1}{\mathrm{SNR}_{\mathrm{RF}}}\right)^{-1} \tag{7}$$

For certain coherent receiver, the calibration can be applied for future SNR monitoring once the electrical noise is estimated.

From Eqs. (4) and (7), the actual SNR after the calibration is as

$$\mathrm{SNR}_{\mathrm{true}}(\mathrm{dB}) = \mathrm{SNR}_{\mathrm{ASE}} - \Delta\mathrm{SNR} \tag{8}$$

The noise in the fiber link mainly derives from the ASE noise of the EDFA. As the noise in reference bandwidth is 0.1 nm, the OSNR can be expressed as

$$\mathrm{OSNR} = 10\lg \mathrm{SNR}_{\mathrm{true}} + 10\lg(B_n / B_r) \tag{9}$$

where B_r and B_n are the noise reference bandwidth (12.5 GHz) and noise equivalent bandwidth respectively.

3 Simulation results

First the simulation setup is back-to-back PM-QPSK transmission system, in which both of the transmitter pulse shaping filter and receiver end lowpass filter are Gaussian filter. The linewidth of the transmitter laser and local laser are 100 kHz, and the frequency offset is set as 500 MHz. Different levels of Gaussian noise are added into the optical signal to emulate particular OSNR. At the receiver end, the actual OSNR is measured by OSA. As mentioned before, the sample rate is 56 G Samps/s.

The OSNR calibrations of different modulations from Eqs. (4) are listed in Table 1. Compared with the real OSNR, the monitoring OSNR without calibration is shown in Fig. 2(a) and the values measured by the proposed method show in Fig. 2(b). As expected, the calibration values increase along with the decrease of the duty cycle of modulation cycle.

Table 1 The calibration of different modulation formats

Modulation format	OSNR calibration
CSRZ	3.2 dB
RZ50	3.4 dB
RZ33	5.1 dB

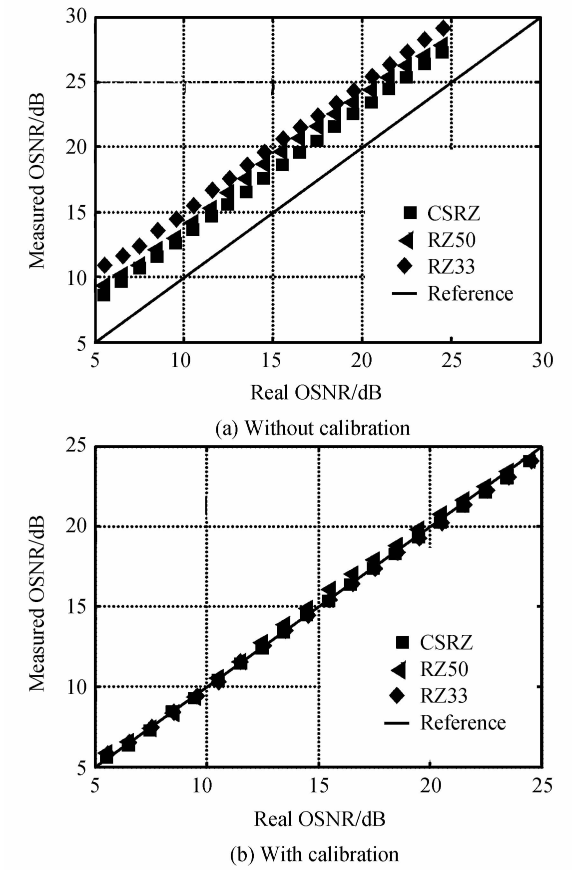


Fig. 2　Measured OSNR vs. real OSNR with and without calibration for different modulation formats

Generally, the equalizer at receiver end cannot completely compensate the linear impairment, such as CD and PMD, especially the first order PMD, i. e. Differential Group Delay (DGD). Then, the following investigation is mainly focused on the tolerance of linear impairment of the proposed method.

In fact, the proposed method based on statistical moments is carried out in time domain and its principle can be approximately explained in constellation diagrams of the received signals. This method performs well as long as the constellation depicting an annulus, whose diameter and thickness represent the power of signal and noise respectively. However, this OSNR monitoring accuracy may degrade in the presence of residual CD and DGD, resulting in the thickness of annulus getting larger. The OSNR is set as 14 dB to investigate the effect of residual CD and DGD, as the OSNR requirement of present commercial optical coherent receiver is about 13～15 dB[13]. Fig. 3 depicts constellation diagrams of the signal for different residual CD and DGD in 14 dB OSNR. As shown in the figures, the larger CD and DGD are, the more scattered points become, which brings larger monitoring errors.

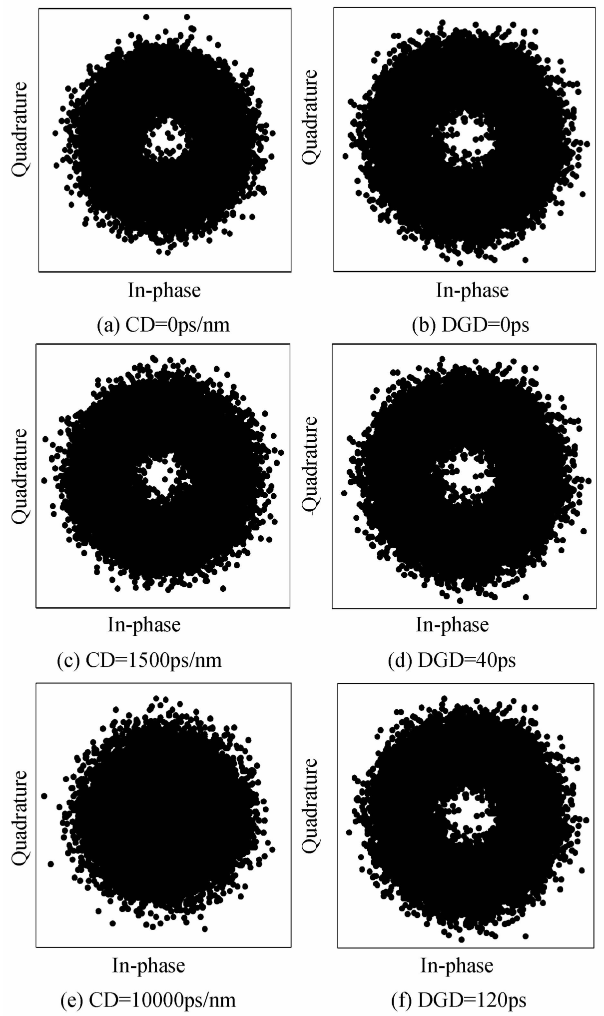
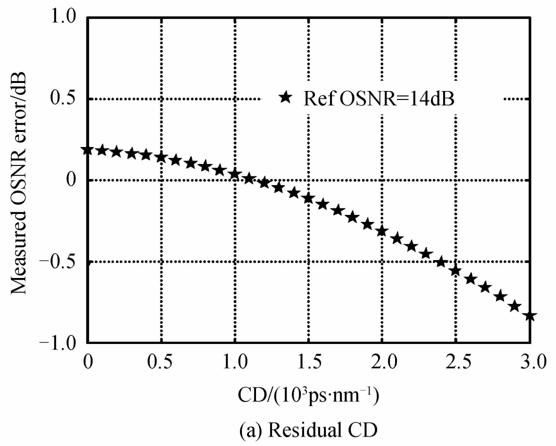


Fig. 3　The constellation diagrams with different residual DGD

As shown in Fig. 4, the measured OSNR error deteriorates with the residual CD and DGD increasingly. RZ50 modulation format is taken for example for the convenience of simulation. The simulation results indicate that this proposed method has higher tolerance of 2 400 ps/nm residual CD and 62 ps DGD under 14 dB reference OSNR with 0. 5 dB OSNR monitoring error.



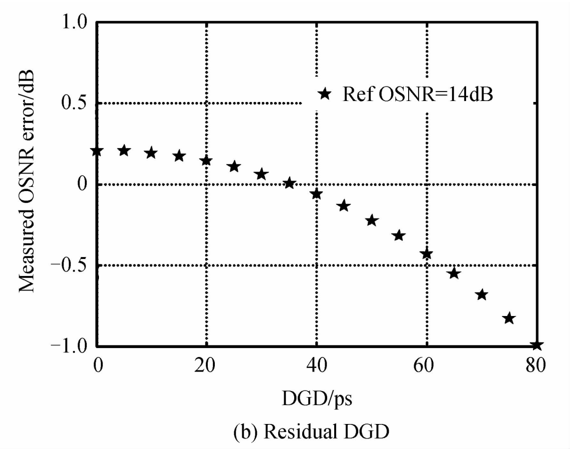


Fig. 4 Measured OSNR error vs. residual CD and residual DGD

The proposed method can also be applied in the future B-100G higher-order mQAM modulation system, since the constellation of equalized received signals is several annuluses, and each annulus is equivalent to an independent PSK modulation.

4 Conclusion

An improved in-band OSNR monitoring method was proposed, which takes the effect of the electrical noise and incomplete linear impairment compensation into account and is transparent to modulation formats. According to the theoretical analysis, a 100 Gb/s PM-QPSK optical coherent communication simulation system based on different duty cycles RZ signal is set up. The results show that the system has 2 400 ps/nm of CD tolerance and 62 ps of DGD tolerance for 14 dB OSNR with measurement error in 0.5 dB, which prove that the proposed OSNR monitoring method is effective.

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