

Simultaneous chromatic dispersion, polarization-mode-dispersion and OSNR monitoring at 40Gbit/s

Lamia Baker-Meflah, Benn Thomsen, John Mitchell, Polina Bayvel

Dept. of Electronic & Electrical Engineering, UCL (University College London), Torrington Place, London WC1E 7JE, United Kingdom
l.baker@ee.ucl.ac.uk

Abstract: A novel method for independent and simultaneous monitoring of chromatic dispersion (CD), first-order PMD and OSNR in 40Gbit/s systems is proposed and demonstrated. This is performed using in-band tone monitoring of 5GHz, optically down-converted to a low intermediate-frequency (IF) of 10kHz. The measurement provides a large monitoring range with good accuracies for CD (4742 ± 100 ps/nm), differential group delay (DGD) (200 ± 4 ps) and OSNR (23 ± 1 dB), independently of the bit-rate. In addition, the use of electro-absorption modulators (EAM) for the simultaneous down-conversion of all channels and the use of low-speed detectors makes it cost effective for multi-channel operation.

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1. Introduction

High-bandwidth transparent optical networks have provided the main drive to develop new techniques for optical performance monitoring without the use of optical-to-electrical-to

optical (OEO) conversion [1,2]. Ideally, a single monitor should: (i) allow for the simultaneous and independent measurement of chromatic dispersion (CD); polarization mode dispersion (PMD) and optical signal-to-noise ratio (OSNR) and (ii) provide a cost effective solution for multi-channel operation. Several methods for CD, PMD and OSNR monitoring have been proposed in the literature, but these fail in all or part of the criteria mentioned above. Some of the reported methods for CD and PMD monitoring include clock tone power detection [3]; RF power detection [4,5]; coherent detection [6] and sampling techniques [7]. However, these methods suffer from requiring the measurement of one impairment in the absence of the other; being bit-rate dependent or requiring high-speed electronics per-channel, making them unsuitable for wavelength division multiplexing (WDM) applications. It is also noted that, to the authors' knowledge, none of the methods reported to date reach the monitoring range and accuracy for a 40Gbit/s transmission line achieved in this paper.

In this paper, a novel method for independent and simultaneous CD, first-order PMD and OSNR monitoring in 40Gbit/s systems is proposed and demonstrated, using an in-band tone monitoring of 5GHz optically down-converted to a low intermediate-frequency (IF) of 10kHz. The use of a 5GHz monitored tone provides large monitoring range with good accuracies for CD (4742 ± 100 ps/nm), differential group delay (DGD) (200 ± 4 ps) and OSNR (23 ± 1 dB), independently of the bit-rate. In addition, the use of electro-absorption modulators (EAM) for the simultaneous down-conversion of all wavelength channels and the use of low-speed detectors makes it cost effective for multi-channel operation.

2. Principle of operation

The CD, 1st order PMD and OSNR measurement principle is shown schematically in Fig. 1.

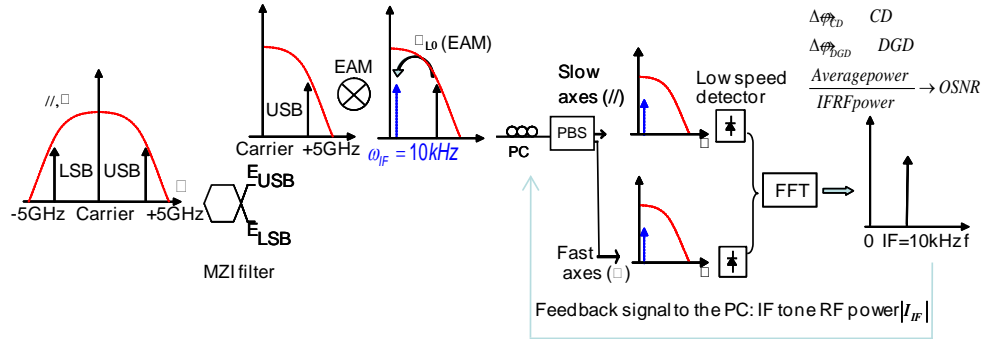


Fig. 1. Principle of the spectral analysis method after optical frequency down-conversion.

The measurement is based on the principle of determining the relative phases of a selected radio-frequency (RF) tone that is present in the signal due to the data modulation, for CD and PMD measurements, and the tones' amplitude relative to the signal average-power for OSNR measurement. The signal is, first, optically filtered using a partial bit-delay Mach-Zehnder interferometer (MZI) to select the optical carrier and a single sideband. It is necessary for the free spectral range (FSR) of the filter to be twice the frequency spacing between the upper and lower sideband tones, so that we simultaneously obtain both sidebands from the two outputs of the MZI. Also, for the multi-wavelength operation, it is necessary to ensure that the WDM channel spacing is a multiple of the FSR. Each single sideband (SSB) signal is then electro-optically heterodyned down to an intermediate-frequency (IF) in the order of few kHz (compared to the monitored tone of few GHz). A polarizing beam splitter (PBS) is used to separate each SSB signal into two orthogonal polarization states, which are then detected using four low bandwidth (<500MHz) square-law photodetectors (only one sideband is depicted in Fig. 1). The electrical signals are then digitized and the IF tones are extracted in software with a fast Fourier transform (FFT). The phases of the four IF tones are a measure of CD (see Eq. 1 [8]) and DGD (see Eq. 2 [9]) and the IF tones' amplitude in conjunction with the total average power is a measure of OSNR.

$$CD = \frac{11}{(2\pi)^{322}} \frac{c}{\lambda_{SSB} f} (\varphi_U \varphi_L) \quad (1)$$

and
$$\Delta\tau = \frac{11}{2\pi} \frac{1}{f_{SSB}} (\varphi_F \varphi_S) \quad (2)$$

where φ_U , φ_L are, respectively, the phases of the upper and lower sidebands of a single polarization state; φ_F , φ_S are, respectively, the phases of the fast and slow axis within one sideband; c is the light velocity; λ_{SSB} and f_{SSB} are, respectively, the optical wavelength (of 1550nm) and frequency (of 5GHz) of the single-sideband monitored tone. In this, we don't consider higher order PMD which is wavelength dependent. This would however have an impact on the accuracy of the CD measurement thus the CD monitoring is not independent of higher order PMD. The CD and DGD maximum measurement range, respectively CD_{max} and $\Delta\tau_{max}$, are defined such that the measured phase difference, in Eq. 1 and Eq. 2, is equal to 2π ,

and given by:
$$CD_{max} = \frac{11}{(2\pi)^{222}} \frac{c}{\lambda_{SSB} f} \quad \text{and} \quad \Delta\tau_{max} = \frac{1}{f_{SSB}}.$$

3. Experimental configuration

The experimental setup for the simultaneous CD, 1st order PMD and OSNR measurements is shown in Fig. 2. The data signal is a 40Gbit/s, 2^{15} -1 pseudorandom binary sequence (PRBS) non-return-to-zero (NRZ). Four spools of SMF are used to vary the CD and a 1st order PMD emulator is used to introduce a variable DGD. The main signal is tapped and sent through an optical filter to select the SSB signals. In this experiment, the MZI filter has a FSR of 20GHz, thus the monitored tone to satisfy the conditions stated in section 2 was 5GHz. The LSB and USB signals are down-converted using two EAMs with a 25GHz bandwidth, and 8dB insertion-loss (IL), where the 5GHz tone of both sidebands is monitored. This tone is simply one of the tones present in the PRBS data pattern. Alternatively, a tone could be introduced by modifying the data sequence or for a continuum data spectrum (such as that for a truly random data). Rather than tracking a particular tone, the phase and amplitude could be obtained by integrating over a small spectral slice of the down-converted data spectrum about the IF frequency.

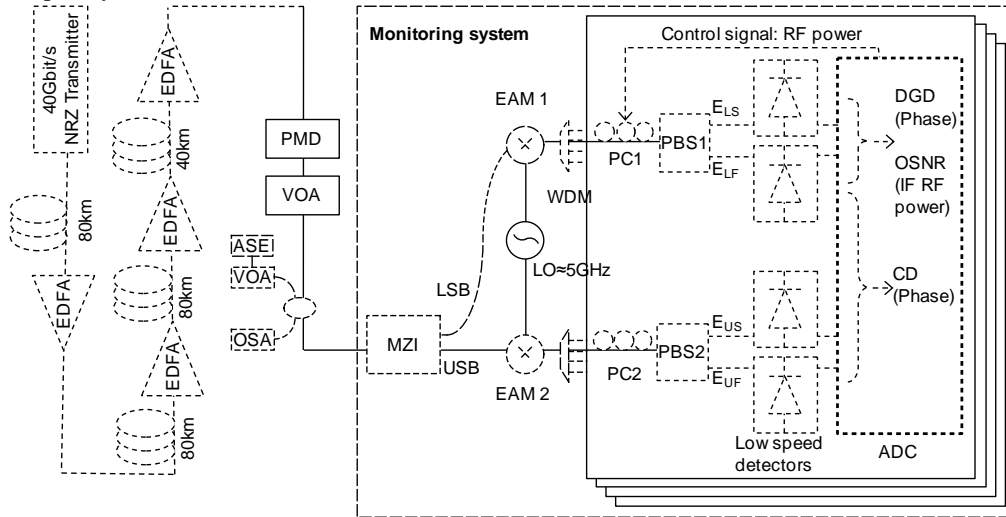


Fig. 2. Experimental setup of the 40Gbit/s multi-channel CD, DGD and OSNR monitoring system.

The EAMs were driven with a free running local oscillator (LO) using a sinusoidal signal at a frequency ω_{LO} shifted from the sideband offset frequency by $\sim 10\text{kHz}$ (ω_{IF}). The signals were digitized for further processing using an analog-to-digital card (ADC) with a sampling rate of 380kS/s and 16bit resolution. An FFT is applied to the four signals, and the amplitude and phase of the tone at the IF of 10kHz is extracted for each signal. To allow for DGD measurements, the RF power of the IF tones, corresponding to the two polarization states of the LSB and USB signals, is used as a control feedback to tune the polarization controllers (PC) placed before the PBS (see Fig. 2) [10]. The PC is adjusted to maximize the power of the IF tone in one of the polarizations states (corresponding to the minimum RF power of the IF tone in the other polarization state) such that the alignment of the PBS and signal principal states of polarization (PSPs) coincide. In this experiment, PC1 and PC2 were adjusted manually, however, in the field; the control system could be automated. Once the PCs are adjusted, the phase measurement of these four IF tones is extracted to provide a measurement of CD and DGD. It is noted that drifts of the local oscillator relative to the signal carrier will vary the IF, but will not have an impact on the monitoring technique since the IF tone is tracked. However, drifts in the IF will limit the integration time. In this experiment the IF was observed to drift by only 0.1Hz/s observed over a period of 4 hours. In these experiments, the maximum integration time used was 200ms and so will not be significantly affected by the IF drift.

4. Experimental results

4.1 CD, DGD and OSNR monitoring range and accuracy

Chromatic dispersion was added to the signal using four spools of SMF of 80, 160, 240 and 280km corresponding, respectively, to 1350, 2685, 4035 and 4742ps/nm. A 1st-order PMD emulator was used to vary the DGD value from 0 to 200ps with steps of 25ps and the OSNR was varied with a variable noise loading stage using an ASE source. The OSNR was maintained at a 30dB level for all CD and DGD measurements. The CD measurement was first tested without introducing any DGD. Figure 3(a) shows the comparison between the CD measured using this technique and the actual CD. When measuring the CD the values obtained for each polarization state were averaged to improve the accuracy. The root-mean-square (RMS) error in the measured CD is calculated to be 100ps/nm over the range of 4742ps/nm. The theoretical maximum range of 4992ps/nm in this system is determined by the choice of the 5GHz tone that is monitored (see Eq. 1). The CD tolerance in a 40Gbit/s system is typically 60ps/nm, thus a field implementation would require the monitoring of a higher tone frequency to ensure that the accuracy is better than this. The phase measurement uncertainty in this experiment is 2% and is independent of the monitored tone frequency. Thus the accuracy can be improved by reducing the monitoring range. For example, a 7GHz tone would half the monitoring range and improve the accuracy to $\pm 50\text{ps/nm}$.

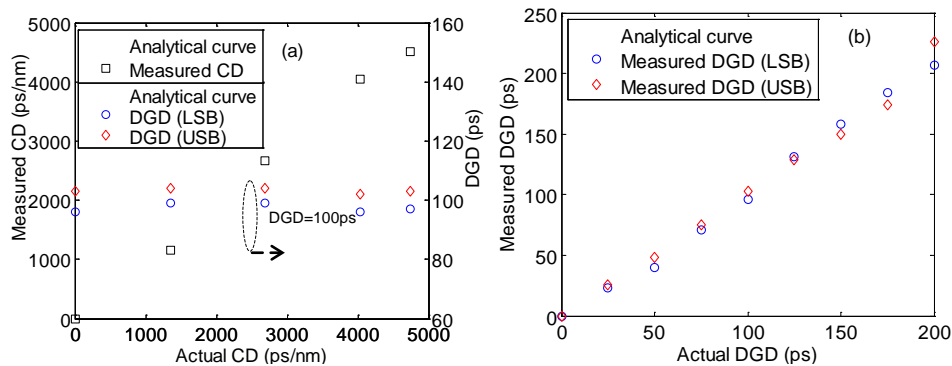


Fig. 3. (a) CD monitoring range (DGD=0ps) and CD impact on DGD measurements. (DGD=100ps), (b) DGD monitoring range (CD=0ps/nm.).

In a second experiment, the level of DGD was maintained at an arbitrary constant level of 100ps while varying the CD from 0 to 4742ps/nm. Figure 3(a) also shows the comparison between the DGD measured using this technique and the actual CD. It is shown that the DGD measurement is insensitive to CD. The DGD measurement was then tested without introducing any chromatic dispersion. Figure 3(b) shows the comparison between the measured DGD obtained using this technique for both the upper and lower sidebands and the actual DGD. The DGD measurement RMS error is calculated to be 4ps over the measurement range of 200ps. The theoretical maximum range of the DGD monitoring technique is 200ps (see equation 2). Figure 4(a) shows the comparison between the OSNR measured using this technique and the OSNR measured using an OSA. The standard error arising from the calibration and experimental uncertainty is also shown in Fig. 4(a). For OSNR values less than 23dB the standard error is less than 1dB, however, the standard error increases considerably for OSNR values higher than 23dB. The measurement range could be further improved by reducing the noise in the detection and processing electronics. The levels of CD and DGD were maintained at an arbitrary constant level of 2685ps/nm and 100ps respectively, while varying the OSNR from 10 to 30dB. Figure 4(b) shows the comparison between the CD and DGD measured using this technique and the actual OSNR. It is shown that the CD and DGD measurements are insensitive to OSNR.

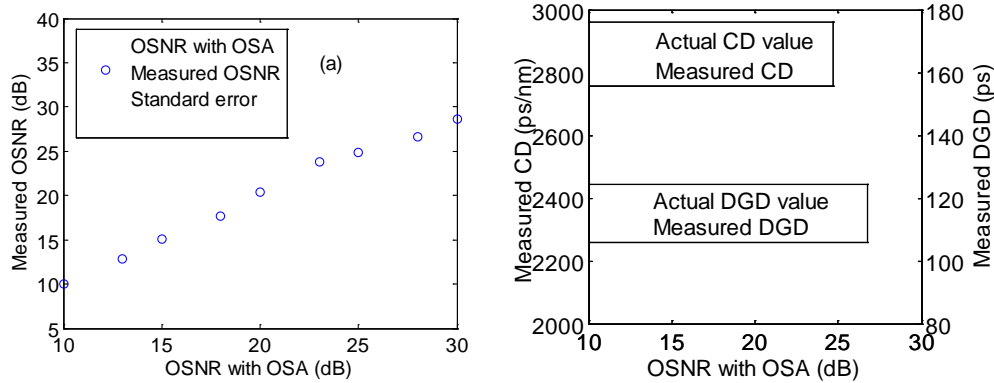


Fig. 4. (a) OSNR monitoring range (CD=0ps/nm, DGD=0ps), (b) OSNR impact on CD and DGD measurements.

4.2 Multi-Wavelength Operation

In this experiment, the input optical signal was a WDM signal of 9 channels spaced at 100GHz. The simultaneous down-conversion of multi-wavelength tones using a single EAM was assessed by turning-off two channels at a time, symmetrically around a central channel, leaving the system with 9, 7, 5, 3 and 1 channel(s), in turn. The central channel was monitored keeping the CD, DGD and OSNR at a constant arbitrary level, respectively equal to 2685ps/nm, 100ps and 20dB. The monitored channel was attenuated by the appropriate amount at each measurement, in order to retain a constant OSNR level of 20dB. Figure 5(a) shows the RMS error in the CD and DGD measurements as a function of the number of channels present in the system and Fig. 5(b) shows the RMS error in the OSNR measurement. All impairments remain constant within their measurement errors. The use of a single EAM is, thus, resilient to the number of channels to be down-converted. This is due to the fact that both CD and DGD monitoring are based on a phase determination principle which is inherently a narrow-band measurement. The OSNR is also shown to be insensitive to crosstalk from adjacent WDM channels. The reason for this is because the interfering signal is not coherent with the measured channel and, thus, the interfering term time-averages to zero and so does not affect the measurement of the IF tone amplitude.

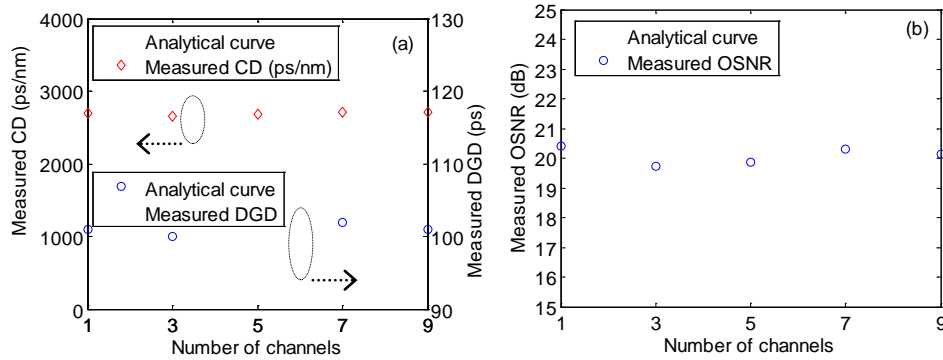


Fig. 5. WDM crosstalk effect on (a) CD and DGD measurement, (b) OSNR measurement.

4.3 Measurement Acquisition time

The impact of the measurement acquisition time was investigated by acquiring a single scan over a duration of 100ms, with a sampling rate of 380kS/s. Shorter acquisition-times are then obtained by processing a smaller number of data-points from the original scans. The measurement accuracy, as the acquisition time was increased, was observed to saturate for acquisition times greater than 10ms, with a measured accuracy for CD, DGD and OSNR, of 100ps/nm, 2.5ps and 1.5dB respectively at an acquisition time of 10ms. This saturation point in the accuracy is caused by the system noise which is due to various effects such as the PC adjustment accuracy and the noise floor of the electronic stage. In a real implementation, the choice of the parameters will be a compromise between the acquisition-time, to adapt to new network conditions, and the required measurement accuracy. The detuning of the MZI filter, used to filter each sideband from the dual-sideband incoming signal, will impact on the measurement accuracy. To assess the impact of this, the filter tuning is optimized at the point corresponding to zero detuning, at which point the setup calibration is performed for all impairment monitoring. The filter is then detuned by 5GHz, in 2.5GHz steps, from either side of the zero detuning position in order to assess the impact this has on the CD, DGD and OSNR measurements. These experiments show that phase-based measurements (thus CD and PMD) are insensitive to filter detuning over a range of 5GHz; however, amplitude-based measurements (thus OSNR) are very sensitive to the filter detuning. In a field deployment, such a monitoring technique would have to maintain the optical filter detuning stability at +/- 2GHz to achieve an OSNR accuracy of +/- 1dB.

5. Summary

An optical performance monitoring technique for the simultaneous and independent monitoring of chromatic dispersion, 1st order PMD and OSNR of WDM signals has been developed. The performance of this technique was experimentally assessed for a 40Gbit/s NRZ system. The monitoring range and error achieved with the proposed method, based on monitoring a 5GHz in-band tone, was 4742 ± 100 ps/nm for CD, 200 ± 4 ps for DGD and 23 ± 1 dB for OSNR. The technique was shown to operate in a multi-wavelength system without degradation to the measurement accuracy due to crosstalk from adjacent WDM channels. The minimum acquisition-time is found to be a trade-off between the required measurement accuracy and the monitoring speed. The 10ms acquisition time, required to obtain the accuracy stated above, is suitable for monitoring applications in dynamic optical networks with reconfiguration times greater than this, such as ASON or OBS networks. Detuning of the MZI optical filter from the optimum position by up to 5GHz does not have any effect on the phase measurements, thus the CD and DGD monitoring; but it does have an impact on the amplitude measurement, thus on the OSNR monitoring. In addition, the use of EAMs for the simultaneous down-conversion of all channels and the use of low-speed detectors makes it potentially cost effective for multi-channel operation.