

Optical performance monitoring in coherent optical OFDM systems

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Abstract: Optical performance monitoring is an indispensable feature for optical systems and networks. In this paper, we propose the concept of optical performance monitoring through channel estimation by receiver signal processing. We show that in coherent-optical-orthogonal-frequency-division-multiplexed (CO-OFDM) systems, critical optical system parameters including fiber chromatic dispersion, Q value, and optical signal-to-noise ratio (OSNR) can be accurately monitored without resorting to separate monitoring devices.

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1. Introduction

Optical performance monitoring is an indispensable feature for future optical networks that are envisioned to be all-optical in the core [1]. The fundamental challenge for all-optical networks hinges upon how to monitor, maintain and control the optical signals along intermediate paths. The pertinent parameters that affect the system performance include the signal power, wavelength, optical signal-to-noise ratio (OSNR), polarization-mode-dispersion (PMD) and polarization-dependent-loss (PDL). Various devices and subsystems have been proposed to monitor one or multiple parameters [2, 3, 4, 5, 6, 7, 8, 9]. In the mean time, there has been rapid advancement in receiver electrical equalization which takes advantages of powerful and cost-effective silicon signal processing capability [10]. Additionally, we have recently proposed a novel modulation format of coherent optical orthogonal frequency division multiplexing (CO-OFDM) [11]. This is essentially an optical equivalent of RF OFDM that has been widely adopted into numerous communication standards such as WiFi (IEEE 802.11a). We showed that with CO-OFDM, the signal can tolerate a chromatic dispersion equivalent to 3,000 km standard-single-mode-fibre [11]. We also showed that the CO-OFDM signal is robust against PMD and may provide a practical solution for complete PMD mitigation [12]. In the context of RF OFDM, channel estimation has been an actively pursued research topic [13]. In this paper, we propose a similar concept of optical channel estimation (OCE) as one approach to optical performance monitoring. Specifically, we show that with CO-OFDM, various important parameters such as Q margin, OSNR, and chromatic dispersion can be monitored through receiver signal processing. Most importantly, performance monitoring by OCE is basically free because it is embedded as a part of the intrinsic receiver signal processing. Such a monitoring device could be also placed anywhere in the network without concern about the large residual chromatic dispersion of the monitored signal.

2. The principle of OCE in a CO-OFDM system

OFDM is a special form of multi-carrier modulation where a single data stream is transmitted over a number of lower rate orthogonal subcarriers [14]. It is worth mentioning that OFDM has been extensively investigated as a means of combating RF microwave multi-path fading, and has been widely implemented in various digital communication standards such as wireless local area network standards (WiFi IEEE 802.11 a) [14]. Figure 1 shows a time and frequency domain representation of an OFDM signal. The OFDM signal in the time domain consists of a continuous stream of OFDM symbols with a regular period T_s , each containing an observation period t_s and a guard interval Δ_G . A complete CO-OFDM system consists of an electrical OFDM transmitter, an OFDM RF-to-optical up converter, an optical link, an OFDM optical-to-RF down converter, and an electrical OFDM receiver [11]. The principle of OCE is to treat the large number of subcarriers as probes by processing the received subcarrier information symbols, and subsequently the overall channel characteristics are accurately estimated. In this paper, for the sake of simplicity, we limit the study of OCE to the monitoring of CD, OSNR and system Q. Other parameters such as PMD/PDL can be monitored in a similar fashion.

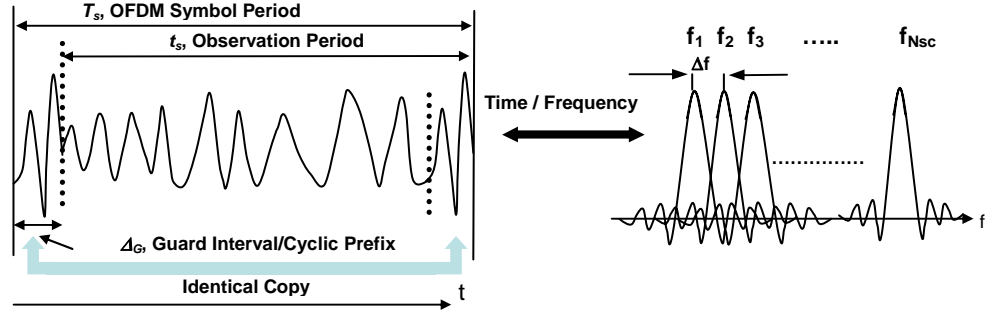


Fig. 1. Time and Frequency representations of an OFDM signal

The optical channel model for a CO-OFDM signal is given by [11]

$$c'_{ki} = e^{j(\phi_i)} \cdot c_{ki} \cdot e^{j\Phi_D(k)} + n_{ki} \quad (1)$$

$$\Phi_D(k) = \phi_0 + 2\pi\tau_0 \cdot f_k + \frac{\pi \cdot c}{f_{LD1}^2} D_t \cdot f_k^2 \quad (2)$$

where c_{ki}/c'_{ki} is the transmitted/received symbol for the k th subcarrier in the i th OFDM symbol, ϕ_i is the phase noise from transmit/receive lasers, and transmit/receiver RF local oscillators (LO), $\Phi_D(k)$ is the subcarrier phase from CD, presumably a quadratic function of the subcarrier frequency f_k , and n_{ki} is the noise from the accumulated amplified-spontaneous-emission (ASE) noise. Equation (2) shows the quadratic expression of $\Phi_D(k)$ as a function of f_k consisting of a zero-order dc term ϕ_0 , a linear term proportional to the time delay of the first subcarrier τ_0 , and a quadrature term proportional to the fiber chromatic dispersion D_t in the unit of ps/pm. Although the subcarrier phase $\Phi_D(k)$ can be an arbitrary function of the subcarrier frequency f_k , for the sake of simplicity, we have assumed that in Eq. (2) a quadratic dependence of $\Phi_D(k)$ on f_k , i.e., the chromatic dispersion D_t is constant within OFDM spectrum. The estimation of fiber chromatic dispersion D_t is of the interests of this paper.

In order to perform the channel estimation, the phase noise ϕ_i for each OFDM symbol has to be obtained [11]. For the sake of simplicity, BPSK encoding for each subcarrier is assumed. The phase noise can be estimated by averaging over all the subcarriers given by [11]

$$\phi_i = \left\langle 0.5 \cdot \text{mod} \left(2 * \arg \left(c'_{ki} \right), 2\pi \right) \right\rangle_k \quad (3)$$

where $\langle \rangle_k$ in Eq. (3) stands for the averaging over the index k or the subcarriers. Removing the phase noise ϕ_i from Eq. (1), we obtain

$$c_{ki}^p = e^{j\Phi_D(f_k)} \cdot c_{ki} + n_{ki}^p \quad (4)$$

where $c_{ki}^p = c'_{ki} \cdot e^{-j\phi_i}$, and $n_{ki}^p = n_{ki} \cdot e^{-j\phi_i}$, which are the received symbol and noise after

the symbol phase correction, respectively.

Equation (4) is the fundamental equation for extracting various critical parameters. The thrust of this work is the signal processing of the received subcarrier symbol c_{ki}^p . In this paper, we perform the signal processing in a block of OFDM symbols consisting of a large number of OFDM symbols, for instance, 100 OFDM symbols. This implies that the channel estimation is averaged and updated every 100 OFDM symbols, which is in the order of μs for 10 Gb/s OFDM systems. This monitoring speed could be sufficient to accommodate the chromatic dispersion and OSNR change from the environment disturbance.

For chromatic dispersion monitoring, we first assume that the transmitted symbol c_{ki} is known. This is the case when (i) the pilot-assisted channel estimation is used, where a known training sequence is used [14], and (ii) the data-assisted channel estimation is used and the decision of the transmitted signal based on the receiver one has already made. In either case, from Eq. (4) the subcarrier phase is given by

$$\Phi_D(f_k) = \langle \arg(c_{ki}^p) - \arg(c_{ki}) \rangle_i \quad (5)$$

where $\arg(\cdot)$ stands for the phase for a complex signal, $\langle \cdot \rangle_i$ stands for the mathematic mean over multiple OFDM symbols or over index i . The chromatic dispersion D_i is estimated by a simple second-order curve fitting of $\Phi_D(f_k)$ as a function of the subcarrier frequency f_k .

Another important parameter to monitor is the system Q margin. A live system could run error-free even without FEC for an extended period, making it hard to detect the system margin by measuring BER directly. From Eq. (4), we can see that each subcarrier channel is essentially a linear channel with an additive white Gaussian noise. Subsequently the bit-error-ratio (BER) of the system is given by [15]

$$BER = 0.5 \cdot \text{erfc}(2\sqrt{ESNR}) \quad (6)$$

$$ESNR = \langle \langle c_{ki}' \rangle_i^2 / \delta_k^2 \rangle_k \quad (7)$$

where ESNR is the (electrical) signal-to-noise ratio per bit, $\langle \cdot \rangle_k$ stands for the averaging over the subcarriers or the index k , $\langle c_{ki}' \rangle_i$ is the expectation value of the received symbol for subcarrier k , and $\delta_k \equiv \sqrt{\langle |c_{ki}'|^2 \rangle_i - \langle c_{ki}' \rangle_i^2}$ is the standard deviation of the received symbol for subcarrier k . Equation (7) shows that ESNR can be obtained by first constructing the constellation of the received symbol and then performing the computation of ESNR for symbol '0' and ' π ' separately. We further convert the BER in Eq. (6) into the Q value [16] which is commonly used in optical community. From Eq. (6), the system Q is thus given by

$$Q = 10 \log_{10}(2 \cdot ESNR) \quad (8)$$

From Eqs. (7)-(8), the system Q can be effectively monitored by computing the subcarrier symbol spread in the constellation diagram.

We have shown that in a CO-OFDM system, by choosing the guard interval to be larger than the CD-induced delay spread, the inter-symbol-interference (ISI) can be completely removed [11]. Subsequently the electrical noise characterized by δ is predominately from the accumulation of the ASE noise from optical amplifiers, and it can be shown that

$$\frac{1}{ESNR} = A \frac{1}{OSNR} + B \quad (9)$$

where A is a proportional constant between $ESNR$ and $OSNR$, and B is attributed to the background noise not counted for by ASE noise, which is mainly from the phase noise of the transmit/receive lasers. From Eqs. (6)-(9), we can see that by acquiring $\langle c'_{ki} \rangle_i$ and δ_k through receiver signal processing, the $ESNR$ for the OFDM signal can be computed, and subsequently both the system Q and the $OSNR$ can be monitored. The coefficients A and B in Eq. 9 can be obtained practically with a calibration procedure by measuring $ESNRs$ against a series of known $OSNRs$ and performing a linear fit between $1/ESNR$ and $1/OSNR$.

It is quite instructive to explicitly write out the ideal coherent detection performance for CO-OFDM systems where the linewidths of the transmit/receive lasers are assumed to be zero. From Eq. (4), the corresponding BER, Q and $ESNR$ in this ideal condition can be shown given by

$$BER = 0.5 \cdot \operatorname{erfc} \left(2 \sqrt{2 \cdot OSNR \cdot \frac{B_0}{R}} \right) \quad (10)$$

$$Q = 10 \log_{10} \left(4 \cdot OSNR \cdot \frac{B_0}{R} \right) \quad (11)$$

$$ESNR = 2 \cdot OSNR \cdot \frac{B_0}{R} \quad (12)$$

where B_0 is the optical ASE noise bandwidth used for $OSNR$ measurement (~ 12.5 GHz for 0.1 nm bandwidth), $R \equiv N_{sc} \cdot \Delta f$ is the total system symbol transmission rate, N_{sc} and Δf are the number of the subcarriers and channel spacing of the subcarriers, respectively.

3. Simulation model and results

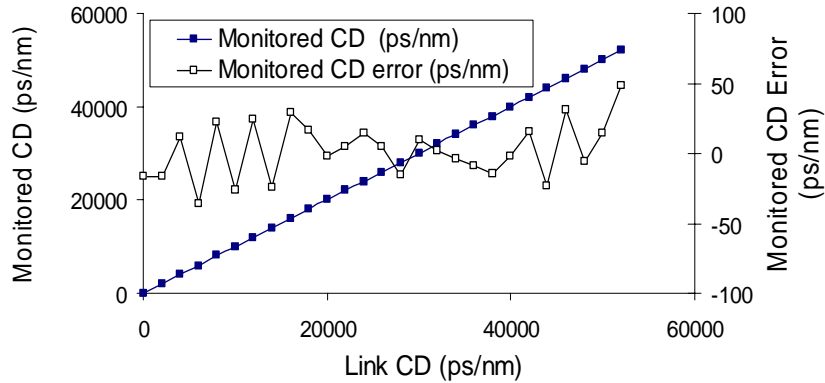


Fig. 2. Performance of CD monitoring through channel estimation.

To demonstrate the proposal, we carry out a Monte Carlo simulation with an OFDM symbol period of 25.6 ns, a guard time of 3.2 ns, and 256 subcarriers. BPSK encoding is used for each subcarrier resulting in a total bit rate of 10 Gb/s. The linewidth of the transmitter and receiver lasers are assumed to be 100 kHz each, which is close to the value achieved with commercially available semiconductor lasers [17-18]. The link ASE noise from the optical amplifiers is assumed to be white Gaussian noise and the phase noise of the lasers is modelled as white frequency noise characterized by its linewidth. The chromatic dispersion is assumed to be constant within OFDM spectrum. A total 8 blocks of OFDM symbols each consisting of

100 OFDM symbols are used for extracting various parameters including CD, system Q and OSNR. In the following text, we use ‘calculate’ to mean the BER results obtained by Monte Carlo simulation, and ‘monitor’ to mean the interpolation results obtained by Eqs. (5)-(9).

Figure 2 shows the monitored CD from the receiver signal processing. The input OSNR is set at 3.8 dB, which gives a BER of 10^{-3} for a CD below 34,000 ps/nm. We can see that the chromatic dispersion up to 50,000 ps/nm can be monitored with an accuracy of 50 ps/nm. The simultaneous large dynamic range and good accuracy of CD monitoring is the unique feature of the OFDM modulation format, namely, a large number of subcarriers spread cross wide spectrum of 10 GHz resulting in good accuracy, and narrow subcarrier channel spacing of 44.6 MHz resulting in wide dynamic range. This wide dynamic range is over one-order of magnitude improvement over a prior report using single or a few auxiliary subcarriers [19].

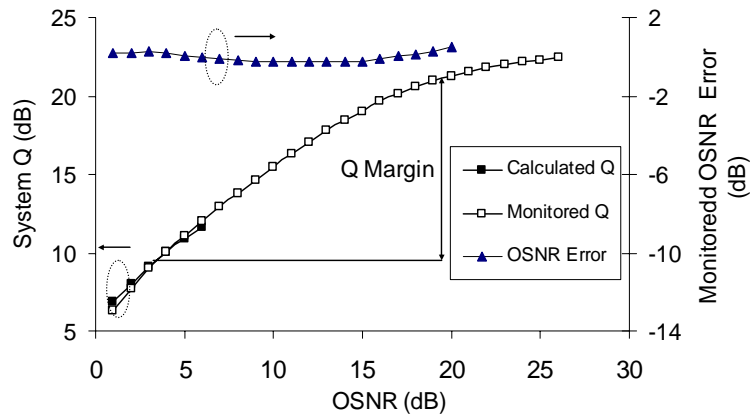


Fig. 3. The monitored system Q and OSNR as a function of input OSNR

Figure 3 shows the monitored system Q and OSNR through OCE. The Q is calculated from 7 dB to 12 dB by Monte Carlo simulation, i.e., direct BER simulation with a signal duration of 20.5 μ s, shown in solid square in Fig. 3. This demonstrates a good agreement with the monitored Q by Eq. (8). Beyond that, we rely on Eq. (8) for system Q estimation. To appreciate the advantage of this approach, for instance, at an input OSNR of 20 dB, the system Q for this OSNR is monitored to be 21.3 dB, which gives a Q margin of 11.5 dB over a BER of 10^{-3} . Such a method of Q margin prediction at high OSNRs is similar to that in the direct-detected systems [16]. Thus the margin monitoring is achieved non-intrusively. Note that this level of system margin can not be measured directly. Additionally, the OSNR is monitored by computing ESNR and estimating OSNR using Eq. (9). The curve with solid triangle in Fig. 3 shows that the OSNR can be monitored with errors within 0.5 dB for an input OSNR dynamic range of 1 dB to 20 dB. The maximum OSNR that can be monitored is limited by the laser phase noise.

Although there is a great advantage of performing the OCE in the receiver, it might be beneficial to move the monitoring function out of the receiver and distribute the monitoring devices somewhere within the transmission link. The benefit of distributed monitoring is that the fault can be accurately located once it takes place. The cost of the monitoring device, essentially a high speed coherent receiver for CO-OFDM, might be a disadvantage for this approach, although this could be partially mitigated by sharing one such monitoring device for multiple wavelength channels or even multiple fibers. Another important advantage of performance monitoring based upon OCE is that the monitoring device can be placed anywhere in the system without concern about the dispersion compensation due to its enormous dynamic range over chromatic dispersion, whereas with alternative monitoring

techniques, for instance, asynchronous histogram approach [9], the signal needs to be dispersion pre-compensated before being monitored, which is due to the limited dynamic range for that approach. The nonlinearity impact on the channel estimation and performance monitoring is of the great importance and will be discussed in a subsequent submission.

4. Conclusion

We have proposed the concept of optical performance monitoring through channel estimation by receiver signal processing. We show that with CO-OFDM, the various critical optical system parameters can be accurately monitored without resorting to separate monitoring devices.

Acknowledgment

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