In-service simultaneous monitoring of transceiver and channel impairments in DSCM systems without impairments compensation

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Abstract: In-service simultaneous transceiver and channel impairments monitoring scheme is proposed and experimentally verified in dual-polarization DSCM system. The monitoring scheme is based on frequency-domain pilot tones and involves no impairments compensation.

1. Introduction

In access and metro network, coherent digital subcarrier modulation (DSCM) enables the enhancement of traffic capacity and inherently fulfills the predominant point-to-multipoint (PTMP) network architecture [1]. In the DSCM, individual subcarriers can be defined as a virtual channel, allowing for the seamless integration of software-defined network (SDN) [2]. However, DSCM systems are extremely sensitive to transceiver impairments [3]. Moreover, in the SDN-based reconfigurable optical networks, the network's elasticity results in variations in the fiber links, and the channel impairments, including chromatic dispersion (CD), polarization dependent loss (PDL) and polarization mode dispersion (PMD), will also change. Therefore, in-service monitoring of transceiver and channel impairments is one of the prerequisites for a stable elastic optical network using DSCM.

In single-carrier systems, extensive research efforts have been devoted to developing in-service monitoring targeting individual transceiver impairments or link impairments [4-7]. For the transceiver impairments monitoring, the prevailing approach follows the principle of "post-introduction, pre-compensation." Here, individual impairments are sequentially compensated, and compensation parameters are used for impairments estimation [4,5]. However, these schemes are marked by high complexity, and exhibit limited tolerance to channel impairments. The channel impairments can be estimated with the impulse responses of the adaptive filter [6,7]. Yet, these approaches suffer from low tolerance to transceiver impairments, failing to achieve separation between transceiver and channel impairments. Consequently, there remains a notable absence of joint monitoring of transceiver and channel impairments. Furthermore, the scarcity of research in this area is even more pronounced when considering multicarrier systems.

In this paper, we propose a joint and in-service monitoring scheme for transceiver and channel impairments, which utilizes frequency-domain pilots (FPTs) and involves no impairments compensation DSP. In the proposed scheme, FPTs are inserted into the I and Q branches of the transmitted signal, respectively. After the transmission, both transceiver and channel impairments are modulated onto the amplitudes and phases of the FPTs. Utilizing the pair of FPTs resulted from frequency offset (FO) between local oscillator (LO) and signal carrier, transceiver impairments and channel impairments can be de-coupled effectively, thus enabling the simultaneous monitoring of transceiver and channel impairments. The proposed scheme has been experimentally validated in a polarization-multiplexing 12 Gbaud/SC×4 DSCM system. Experimental results demonstrate that the scheme achieves wide-ranging and accurate monitoring of multi-dimensional impairments including transceiver IQ imbalance, CD, PDL and PMD.

2. Principle

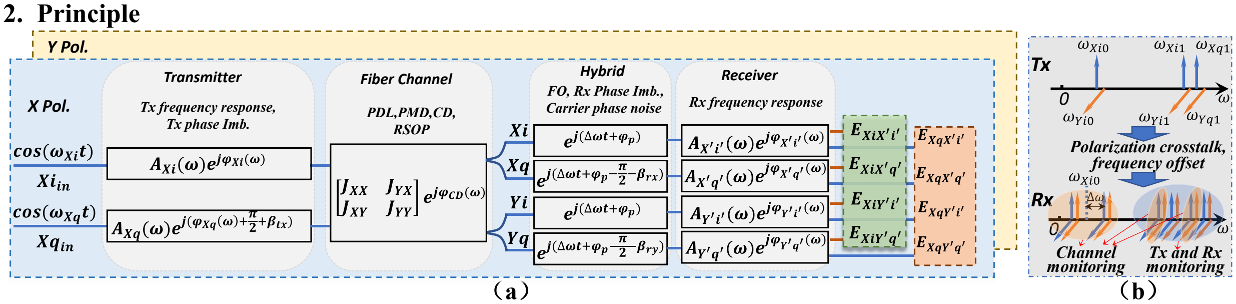


Fig. 1: (a) Mathematical model of the system and (b) distribution of the Tx and Rx FPTs

The model for FPTs passing through a typical coherent optical communication system is firstly established, as shown in Fig. 1. In the figure, corner labels with and without $\{\cdot\}'$ denote the parameters of receiver (Rx) and transmitter (Tx), respectively. The Tx frequency response, CD, PDL, PMD, polarization various, frequency offset (FO), carrier phase noise, and Rx frequency response are considered. Finally, the received FPTs at each branch can be expressed as:

$$E_{PbP'b'} = E^{+}_{PbP'b'} + E^{-}_{PbP'b'} \tag{1}$$

$$E_{PbP'b'}^{\pm} = \frac{1}{2} A_{Pb}(\omega_{Pb}) A_{PP'} A_{P'b'}(\omega_{Pb} \pm \Delta\omega) e^{j\left[(\omega_{Pb}+\Delta\omega)t+\varphi_{Pb}(\omega_{Pb})+\varphi_{P'b'}(\omega_{Pb}\pm\Delta\omega)\pm\varphi_{ch}\pm\varphi_{ph}\right]} \quad (2)$$

where $P \in \{X,Y\}$, $P' \in \{X',Y'\}$, $b \in \{i,q\}$ and $b' \in \{i',q'\}$; $E_{PbP'b'}^{+}$ and $E_{PbP'b'}^{-}$ are the FPTs with frequencies $\omega_{Pb} + \Delta\omega$ and $\omega_{Pb} - \Delta\omega$, respectively, generated from the FPT after FO; $A_{PP'}$ is the magnitude of element $J_{PP'}$ of the matrix related to polarization dependent effects; $\varphi_{ch} = \varphi_{CD} + \varphi_{PP'}$ is the phase introduced by CD and polarization effects in the channel; φ_{ph} is the phase noise, including carrier phase noise and transceiver IQ phase imbalance.

For transceiver impairments monitoring, FPT is inserted into each of I and Q branches of the X and Y polarizations. Due to the frequency dependence of PMD and CD, an additional FPT must be inserted into the X and Y polarizations to serve as a reference. The final distribution of the FPTs is illustrated in Fig. 1(b), and the modulated signal is $E_P = s_P + C_0\cos(\omega_{Pi0}t) + C_0\cos(\omega_{Pi1}t) + C_0\cos(\omega_{Pq1}t)$, where s_P represent the modulated DSCM signals in P polarization; C_0 is the amplitude of the FPT, and is determined by the pilot-to-signal power ratio (PSR) [3]; $\omega_{Xi0} \approx \omega_{Yi0}$ and $\omega_{Pi1} \approx \omega_{Pq1}$. After the signal has been received, the FPTs are individually down-converted to zero, and then be extracted with low-pass filters. According to Eq. (2), the FPTs, denoted as $F_{PiP'b'0}^{\pm}$ and $F_{PbP'b'1}^{\pm}$, can be obtained:

$$F_{PbP'b'k}^{\pm} = \frac{1}{2} A_{Pb}(\omega_{Pbk}) A_{PP'} A_{P'b'}(\omega_{Pbk} \pm \Delta\omega) e^{j\left[\varphi_{Pb}(\omega_{Pbk})+\varphi_{P'b'}(\omega_{Pbk}\pm\Delta\omega)\pm\varphi_{ch}\pm\varphi_{ph}\right]} \quad (3)$$

where $k \in \{0,1\}$; $F_{PbP'b'k}^{\pm}$ originate from Tx FPTs with frequencies ω_{Pbk}. For transceiver impairments estimation, the obtained FPTs $F_{PbP'b'1}^{\pm}$ are utilized. The key challenge lies in eliminating the influence of channel impairments and phase noise. Notably, channel impairments exert a uniform impact on the amplitudes of both I and Q branches, thus not altering the estimation of IQ amplitude imbalance. The transceiver r IQ amplitude imbalance can be estimated as:

$$\hat{\gamma}_{P'} = 20\lg\left\{\left|F_{PbP'q'k}^{\pm}\right| / \left|F_{PbP'i'k}^{\pm}\right|\right\}, \quad \hat{\gamma}_{P} = 20\lg\left\{\left|F_{PbP'q'k}^{\pm}\right| / \left|F_{PbP'i'k}^{\pm}\right|\right\} \quad (4)$$

where $\hat{\gamma}_{P'}$ and $\hat{\gamma}_{P}$ are the estimated Rx and Tx IQ amplitude imbalance in P' and P polarization, respectively, measured in decibels (dB). To mitigate the phase interference, the following equation is applied:

$$F_{PbP'b'1} = \sqrt{F_{PbP'b'1}^{+} \cdot F_{PbP'b'1}^{-}} \approx \frac{1}{2} A_{Pb}(\omega_{Pb1}) A_{PP'} A_{P'b'}(\omega_{P}) e^{j\left[\varphi_{Pb}(\omega_{Pb1})+\varphi_{P'b'}(\omega_{Pb1})\right]} \quad (5)$$

After eliminating the phase interference, the transceiver impairment can be estimated as:

$$\hat{\tau}_{P'} = \frac{arg\{F_{PbP'q'1} \cdot F_{PbP'i'1}{}^{*}\}}{\omega_{Pb1}}, \quad \hat{\tau}_{P} = \frac{arg\{F_{PqP'b'1} \cdot F_{PiP'b'1}{}^{*}\}}{\omega_{Pq1} + \omega_{Pi1}/2} \quad (6)$$

$$\hat{\beta}_{P'} = ang\left\{F_{PbP'i'1}^{\pm} \cdot F_{PbP'q'1}^{\pm}{}^{*} \cdot e^{i[(\omega_{Pb1}\pm\Delta\omega)\hat{\tau}_{P'}+\pi/2]}\right\}, \quad \hat{\beta}_{P} = ang\left\{F_{PqP'b'1}^{\pm} \cdot F_{PiP'b'1}^{\pm}{}^{*} \cdot e^{-i[(\omega_{Pb1}\pm\Delta\omega)\hat{\tau}_{P'}+\pi/2]}\right\} \quad (7)$$

where $\hat{\tau}_{P'/P}$ and $\hat{\beta}_{P'/P}$ are the estimated Rx/Tx IQ skew and phase imbalance in P' and P polarization, respectively.

For the channel impairments estimation, it is imperative to prevent interference from transceiver impairments. Here, the FPTs $F_{PiP'i'k}^{\pm}$, which involving only the I path of the transceiver, are employed for estimation. This avoids the interference of IQ mismatch. In addition, interference from transceiver phase response can be eliminated by employing:

$$T_{PiP'i'k} = \sqrt{F_{PiP'i'k}^{+} \cdot F_{PiP'i'k}^{-}{}^{*}} \approx \frac{1}{2} A_{Pi}(\omega_{Pik}) A_{PP'} A_{P'i'}(\omega_{Pi}) e^{j(\varphi_{ch}+\varphi_{ph})} \quad (8)$$

The channel estimation can be obtained as: $\widehat{\mathbf{H}}_k = \begin{bmatrix} T_{XiX'i'k} & T_{YiX'i'k} \\ T_{XiY'i'k} & T_{YiY'i'k} \end{bmatrix}$

Then, PDL, CD and PMD can be obtained with a few matrix calculations by $\widehat{\mathbf{H}}_k$ [7]. Let $\mathbf{W}_k = \widehat{\mathbf{H}}_k{}^{\dagger}\widehat{\mathbf{H}}_k$, and λ_{1k} and λ_{1k} are the eigenvalues of the matrix $\mathbf{W}_k$. PDL can be evaluated as: $PDL_k(dB) = |10log_{10}(\lambda_{1k}/\lambda_{2k})|$.

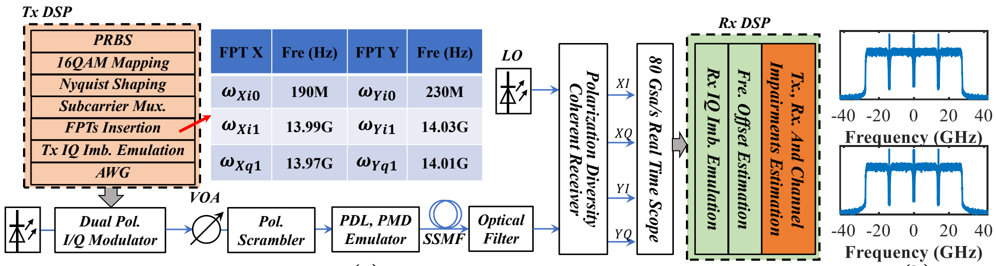
CD can be estimated as: $CD(ps/nm) = \arg\left\{\sqrt{\det\{\widehat{\mathbf{H}}_1\} \cdot \det\{\widehat{\mathbf{H}}_0\}^{*}}\right\} \cdot \frac{4\pi c}{[\lambda^2(\omega_{Pi1}{}^2 - \omega_{Pi0}{}^2)]}$

Let $\mathbf{U} = \widehat{\mathbf{H}}_1/\widehat{\mathbf{H}}_0$, and ρ_1 and ρ_2 are the eigenvalues of the matrix $\mathbf{U}$. The first-order PMD, differential group delay is

$$DGD(ps) = |\arg\{\rho_1/\rho_2\}/\omega_{Pi1} - \omega_{Pi0}| \quad (9)$$

3. Experient and discussions

The proposed scheme is validated experimentally via dual-polarization 16-QAM DSCM system with baud rate of 12Gbaud/SC×4. The experimental setup and DSP flow is shown in Fig. 2. In the transmitter, the DSCM signal with four subcarriers are generated. A guard band of 1 GHz is left between subcarriers. Then, FPTs with frequency shown in Fig. 2(a) are inserted into the signal. The power spectrum of the generated signals is shown in Fig. 2(b). The Tx impairments are emulated in the Tx DSP. A continuous-wave laser with the linewidth of 100 kHz is fed into the modulator. A polarization scrambler (EPS1000) introduces random RSOP with rate of 300 krad/s in the fiber link. PDL and PMD are also introduced with emulator. In the receiver, after coherent detection, a real-time oscilloscope with 80 GSa/s is used to capture the detected signals. The Rx IQ impairments are first emulated. Then, the FO is estimated. After that, the proposed scheme is employed for joint monitoring of transceiver and channel impairments.



Impairment	Value
Tx & Rx IQ skew	10 ps
Tx & Rx IQ Pha. Imb.	10 deg
Tx & Rx IQ Amp. Imb.	2 dB
PMD	22 ps
PDL	3 dB
Fiber Length	40 km

(c)

Fig.2: (a) experimental setup and DSP flow; (b) Power spectrum of the transmitted signal

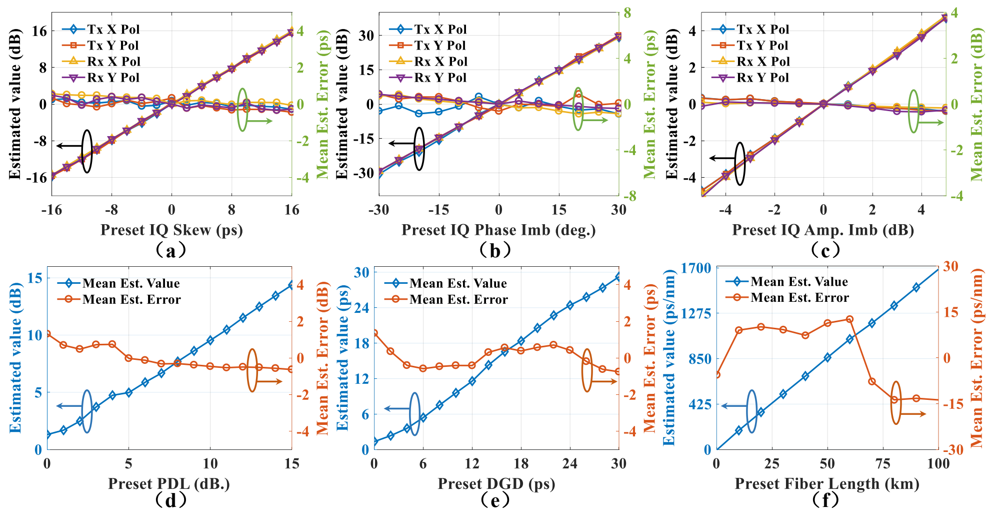


Fig.3: Monitoring of (a) IQ skew, (b) IQ phase imbalance, (c) IQ amplitude imbalance, (d) PDL, (e) DGD and (f) CD

The experimental results are illustrated in Fig. 3. Except for the monitored parameters, the settings for other system impairments are depicted as shown in Fig. 2(c). The transceiver IQ skew, IQ phase and amplitude imbalance in X and Y polarizations are monitored simultaneously. Specifically, the error for IQ skew within the range of ± 16 ps, is less than 0.5 ps. The estimation error for IQ phase imbalance, within ± 30 degrees, is below 1.5 degrees. The estimation error for amplitude imbalance, within 5 dB, is less than 0.3 dB. For the monitoring of PDL, the applied PDL is tuned from 0 to 15 dB. Notably, at lower PDL values, the error in estimation is considerably larger. This discrepancy primarily stems from the inherent error in estimating PDL with eigenvalue, which increases as PDL decreases. For PDL exceeding 1 dB, the error remains below 0.6 dB. Concerning DGD within 30 ps, the estimation error is within 0.5 ps. In the estimation of CD, we implemented a predetermined fiber length at the Rx DSP to ensure the accuracy of introducing CD. The emulated dispersion coefficient is 17 ps/nm/km. Remarkably, for the fiber length within 100 km, the estimation error remained within 15 ps/nm, corresponding to a length error of less than 1 meter.

4. Conclusion

In this paper, an in-service and joint monitoring scheme for transceiver and channel impairments has been demonstrated for the first time. The scheme involves no impairment compensation and has the advantage of robust monitoring performance and simple implementation. With the assistance of inserted FPTs, multi-dimensional impairments of transceiver IQ imbalance, CD, PDL, and PMD are monitored successfully in dual-polarization 16-QAM DSCM system with baud rate of 12Gbaud/SC×4. The experiments have verified the capability of our scheme to achieve accurate monitoring for various impairments over a wide range.

Acknowledgements

Shenzhen Municipal Science and Technology Innovation Council under Grants (JCYJ20210324131408023) and the National Natural Science Foundation of China (62201308)

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