Enhanced Carrier Phase Recovery for Spectral-efficient Digital Subcarrier Multiplexing Transmissions

Meng Xiang[1,2], Sailan Yan[1], Can Wei[1], Hong Lv[1], Jianping Li[1,2], Songnian Fu[1,2*], and Yuwen Qin[1,2]

1 Advanced Institute of Photonics Technology, School of Information Engineering, and Guangdong Provincial Key Laboratory of Photonics Information Technology, Guangdong University of Technology, Guangzhou 510006, China
2 Key Laboratory of Photonic Technology for Integrated Sensing and Communication, Ministry of Education of China, Guangdong University of Technology, Guangzhou, 51006, China
** Author e-mail address: songnian@gdut.edu.cn*

Abstract: We demonstrate a performance enhanced carrier-phase-recovery (CPR) method for spectral-efficient digital-subcarrier-multiplexing transmissions with two-interleaved-pilot-tones. By reconstructing and compensating transmitter-side and receiver-side laser phase noises separately, equalization-enhance-phase-noise (EEPN) can be circumvented.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.1660) Coherent communications

1. Introduction

Optical coherent detection along with digital signal processing (DSP) has become a compelling solution for the implementation of long-haul high-capacity fiber optical transmission systems, by encoding the information on all dimensions of the optical field. Recently, digital-subcarrier-multiplexing (DSM) was extensively studied, because dividing the available bandwidth of a high baud-rate single-carrier transmission into several low baud-rate subcarriers without the spectrum overlapping can significantly improve the tolerance of fiber nonlinearity [1,2]. Additionally, recent studies also reveal that the DSM transmission outperforms the traditional single-carrier transmission, in term of flexible bit-rate [3], tolerance towards optical filtering, chromatic dispersion (CD) as well as equalization-enhance-phase-noise (EEPN) [2,4, 5], and network scalability for point-to-multipoint scenarios [6].

Despite those advantages, DSM transmission systems impose some challenges on the receiver-side (Rx) DSP. In particular, the carrier-phase-recovery (CPR) becomes the primary issue to be solved, because DSM transmission relies on longer symbol periods per subcarrier, leading to lower sensitivity to laser phase noise (LPN) in comparison with the equivalent data-rate single-carrier transmission [7]. Consequently, there occurs a significant performance penalty if a conventional CPR method on a per-subcarrier basis is employed. Although this can be partially solved by applying the joint-subcarrier CPR (JCPR) method [8], it will only mitigate the penalty under the condition of back-to-back (B2B) transmission. After the long-haul fiber transmission, any gains from JCPR will disappear or even be reversed, as a result of the chromatic dispersion (CD) induced different group delays between subcarriers. To maintain the JCPR performance after the fiber optical transmission, a pilot-symbols aided JCPR was recently proposed, by considering the walk-off effect between subcarriers [9,10]. Resorting to pre-selected dual reference subcarriers (DRS) where all pilot-symbols are concentrated, this DRS JCPR method can achieve unprecedented performance even when the symbol-rate of each subcarrier is as low as 1 GBaud. However, the performance of the DRS JCPR method is dependent on the overall overhead of pilot-symbols. Thus, it is expected to sacrifice the information of DRS to fully load the pilot-symbols, resulting in a significant reduction of the spectral efficiency [9]. Alternatively, the use of pilot-tone offers another solution for CPR for DSM transmissions with enhanced spectral-efficiency, in comparison with the DRS JCPR method [11,12]. However, the generated EEPN during the CD compensation (CDC) is still a problem for the DSM transmission, when the aggregate baud-rate of DSM signal is high for 800G/1.6T applications [2]. Unfortunately, existing CPR schemes cannot tackle with the EEPN issue, to the best of our knowledge.

In this submission, we propose a CPR method for spectral-efficient DSM transmissions, by utilizing two-interleaved-pilot-tones (TIPT). Relying on separately reconstructing the Transmitter-side (Tx) and Rx LPNs according to TIPT and compensating the Rx and Tx LPNs before and after CDC, respectively, the generation of EEPN can be avoided, leading to an enhanced CPR performance. The effective function of the proposed CPR method is numerically verified by recovering 95.6 GBaud DSM signals with only 0.2% bandwidth overhead, and we identify that the achieved CPR gain gradually increases along with larger accumulated CD, larger laser linewidth and higher modulation format.

2. Principle of proposed TIPT CPR for DSM transmissions

The principle of the proposed TIPT CPR scheme is to transmit TIPT at Tx, and extract the phase of TIPT at Rx in order to separately reconstruct the LPNs from the Tx and Rx lasers, as shown in Fig. 1. Specifically, as for the generation of the DSM signal at Tx, two protection intervals (PIs) are reserved among subcarriers and TIPT with a constant amplitude are inserted symmetrically on two orthogonal linear polarizations, respectively. As for the reconstruction of Tx and Rx LPNs, TIPT are firstly extracted using two digital 4-th Gaussian filters after frequency synchronization by locating the TIPT positions [11], and then the phase of TIPT, namely the combination of Tx and Rx LPNs, are acquired by implementing the $angle(\cdot)$ operation. We should note that the Tx LPN associated with TIPT is staggered after the fiber optical transmission due to the frequency-dependent differential group delay, while the Rx LPN associated with TIPT is exactly the same. Therefore, the phases of TIPT at time t can be expressed as:

$$\hat{\phi}_{PN_{left}}(t)=\phi_{TX}(t-|P|L\beta_2\Delta\omega_{subcarrier}-L\beta_2\Delta\omega_{interval}/2)+\phi_{LO}(t);\ \hat{\phi}_{PN_{right}}(t)=\phi_{TX}(t+|P|L\beta_2\Delta\omega_{subcarrier}+L\beta_2\Delta\omega_{interval}/2)+\phi_{LO}(t) \quad (1)$$

where, ϕ_{TX} and ϕ_{LO} are the Tx and Rx LPNs, respectively. $P\in[-N_{SC}/2, N_{SC}/2]$ is the subcarrier number where PIs are reserved for the insertion of TIPT, and N_{SC} is the total number of subcarriers. L and β_2 is the fiber length and fiber dispersion coefficient, respectively. $\Delta\omega_{subcarrier}$ and $\Delta\omega_{interval}$ are subcarrier spacing and bandwidth of the PI, respectively. Thereafter, we can obtain the phase difference of TIPT at the kth sampling point as follows:

$$\Delta\hat{\phi}_{TX}(k)=\hat{\phi}_{PN_{left}}(k)-\hat{\phi}_{PN_{right}}(k)=\phi_{TX}(kT_S-|P|L\beta_2\Delta\omega_{subcarrier}-L\beta_2\Delta\omega_{interval}/2)-\phi_{TX}(kT_S+|P|L\beta_2\Delta\omega_{subcarrier}+L\beta_2\Delta\omega_{interval}/2) \quad (2)$$

where T_S is the Rx sampling time interval. Since $\Delta\hat{\phi}_{TX}$ represents the phase change in ϕ_{TX}, the evolution of ϕ_{TX} at each symbol period can be approximated by:

$$\phi_{TX}(k)-\phi_{TX}(k-1)=\Delta\hat{\phi}_{TX}(k)/\alpha,\quad \alpha=L\beta_2(2\cdot|P|\cdot\Delta\omega_{subcarrier}+\Delta\omega_{interval})/T_S \quad (3)$$

Therefore, we can reconstruct the Tx LPN by means of integral accumulation, considering LPN is a Wiener process:

$$\hat{\phi}_{TX}(k)=(\frac{1}{\alpha}\sum_{m=1}^{k}\Delta\hat{\phi}_{TX}(m))+\hat{\phi}_{TX}(0) \quad (4)$$

where $\hat{\phi}_{TX}(0)$ is an initial phase with a constant value, which has no impact on the CPR performance. Afterwards, we can reconstruct the Rx LPN by substituting Eq. (4) into Eq. (1):

$$\hat{\phi}_{RX}(k)=[(\hat{\phi}_{PN_{left}}-\hat{\phi}_{TX}(kT_S-|P|L\beta_2\Delta\omega_{subcarrier}-L\beta_2\Delta\omega_{interval}/2))+(\hat{\phi}_{PN_{right}}-\hat{\phi}_{TX}(kT_S+|P|L\beta_2\Delta\omega_{subcarrier}+L\beta_2\Delta\omega_{interval}/2))]/2 \quad (5)$$

Finally, we can compensate the Rx and Tx LPNs before and after CDC, respectively, as shown in Fig. 1(b). In this way, EEPN can be avoided, assuming of high estimation accuracy of Tx and Rx LPNs estimation.

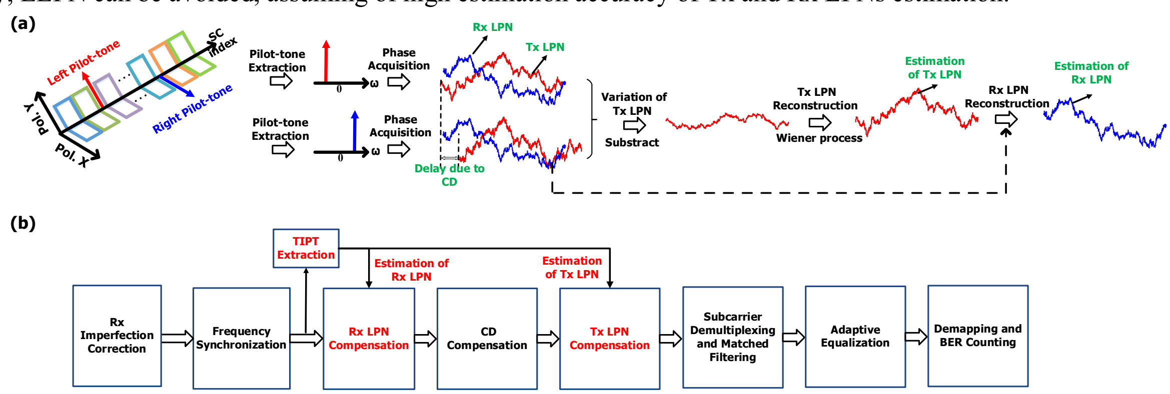

Fig. 1. (a) Estimation of Tx and Rx LPNs using TIPT; (b) Rx DSP flow for DSM transmissions.

3. Setup, results and discussions

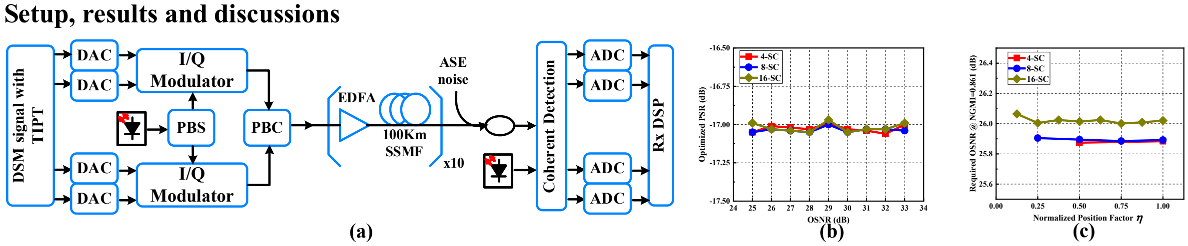

Fig. 2. (a) Simulation Setup; (b) Optimized PSR Vs. OSNR; (3) TIPI position optimization.

We consider a single-channel DSM system with an aggregate baud-rate of 95.6 GBaud for the performance evaluation, as shown in Fig. 2(a). At Tx DSP, DP-64QAM sequency is first generated and allocated to each subcarrier. Then, root-raised cosine (RRC) pulse shaping with a roll-off factor of 0.01 is implemented. The PI between two subcarriers is set to 0.1 GHz, leading to a 0.2% bandwidth overhead for the ITPT insertion. The power of the inserted TIPT determines the pilot-to-signal power ratio (PSR) and optimized as -17 dB irrespective of optical signal-to-noise-ratio (OSNR) and number of subcarriers, as shown in Fig. 2(b). After subcarrier multiplexing and ITPT insertion, the processed samples are introduced to digital-to-analog converters (DACs) followed by the optical IQ modulation and polarization division multiplexing (PDM). The transmission link consists of 10×100 km standard single-mode fiber (SSMF) and Erbium-doped fiber amplifiers (EDFA). Note that fiber nonlinearity is ignored during our investigation for simplicity. At Rx, amplified spontaneous emission (ASE) noise is loaded to adjust the OSNR. The linewidths of the Tx and Rx lasers are set to be 100 kHz. The Rx DSP flow is started with the Rx imperfection correction followed by frequency synchronization by locating TIPT positions. Then the proposed TIPT CPR scheme is implemented combined with the CD compensation. After subcarrier demultiplexing and matched filtering, the adaptive equalization (AEQ) is performed by four butterfly 21-tap T/2-spaced finite impulse-response (FIR) filters for each subcarrier. Finally, the normalized generalized mutual information (NGMI) is obtained as an average value among all subcarriers.

First, we investigate the impact of the TIPI position on the proposed CPR performance. We define a normalized factor $\eta = 2|P| / N_{sc}$ to quantify the position with respect to the total number of subcarriers. As shown in Fig. 2(c), the proposed CPR performance is almost irrelevant to the TIPT position under conditions of different number of subcarriers. We choose $\eta = 0.5$, indicating the TIPT are inserted in the middle of the left and right sideband spectrum, respectively. Next, the impact of the accumulated CD on the CPR performance is explored in Fig. 3(a). The conventional pilot-tone based CPR method is also under investigation for the ease of comparison [11,12]. As we can see, the required NGMI gradually increases along with the growing SSMF reach for the conventional scheme. However, the required NGMI keeps almost unchanged under various transmission reach by the use of our proposed scheme, due to the avoidance of EEPN. Consequently, an enhanced CPR performance of about 0.38 dB is observed for the DSM signal with 16-subcarriers (16-SC), when the transmission reach is 1500 km. Afterwards, we examine the CPR performance under conditions of various laser linewidth, as shown in Fig. 3(b). The CPR performance generally degrades along with the growing laser linewidth. Whereas, the proposed CPR scheme always outperforms the conventional scheme, and the obtained gain increases along with the increment of laser linewidth. When the laser linewidth increases from 100 kHz to 1 MHz, we observe a 0.23 dB and 3.7 dB performance gain utilizing our proposed CPR scheme for the DSM signal with 16-SC, respectively. Finally, The NGMI curve with respect to the OSNR for DSM signals with different number of subcarriers and modulation formats is presented in Fig. 3(c). Obviously, the proposed CPR scheme is insensitive to the used modulation formats. Due to the fact that higher-order modulation format is more prone to EEPN, the proposed CPR scheme guarantees a higher performance gain by circumventing the EEPN issue, in comparison with conventional pilot-tone based CPR method.

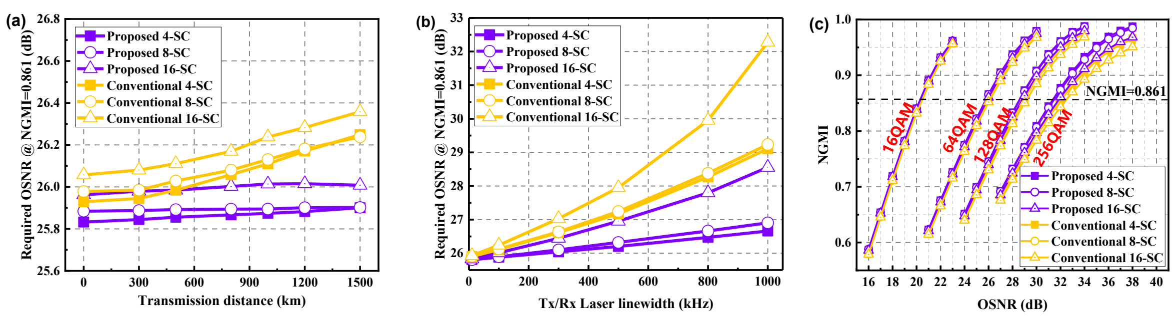

Fig. 1. (a) Required NGMI Vs. Transmission distance (Tx/Rx laser linewidth=100kHz); (b) Required NGMI Vs. Tx/Rx laser linewidth (1000 km transmission); (c) NGMI Vs. OSNR (Tx/Rx laser linewidth=100kHz, 1000 km transmission).

4. Conclusions

Utilizing two-interleaved-pilot-tones for the extraction of transmitter-side and receiver-side phase noises is proposed for the CPR of spectral-efficient DSM transmissions, when the EEPN generation is successfully suppressed. The enhanced CPR performance from 0.23 dB and 3.7 dB is verified for a 95.6 GBaud DSM system, depending on the accumulated CD, laser linewidth, and modulation format.

5. Acknowledgement

This work was supported in part by the National Key R&D Program of China (2021YFB2900702), the National Natural Science Foundation of China (62025502, 62075046, U21A20506), and Guangdong Introducing Innovative and Entrepreneurial Teams of "The Pearl River Talent Recruitment Program" (2021ZT09X044).

6. References

[1] M. Qiu et al., Opt. Express., 22(15), 2014.
[2] H. Sun, et al., J. Lightw. Technol., 38(17), 2020.
[3] F. P. Guiomar et al., J. Lightw. Technol., 36(20), 2018.
[4] M. Xiang, et al., Opt. Express., 25(21), 2017.
[5] A. Rashidinejad, et al., OFC2020, Paper W2A.30.
[6] D Welch, et al., J. Lightw. Technol., 39(16), 2021.
[7] S. M. Bilal, et al., IEEE Photonics Tech. L., 28(19), 2016.
[8] Manuel S. Neves, et al., J. Lightw. Technol., 39(20), 2021.
[9] Manuel S. Neves et al., J. Lightw. Technol., 39(9), 2021.
[10] Manuel S. Neves et al., J. Lightw. Technol., 40(16), 2022.

[11] M. Xiang, et al., Opt. Express., 25(1), 2017.
[12] T.Kobayashi et al., J. Lightw. Technol., 30(24), 2012.