Experimental investigation of the equalization-enhanced phase noise in long haul 56 Gbaud DP-QPSK systems

Qunbi Zhuge,[*] Xian Xu, Ziad A. El-Sahn, Mohammad E. Mousa-Pasandi, Mohamed Morsy-Osman, Mathieu Chagnon, Meng Qiu, and David V. Plant

Department of Electrical and Computer Engineering, McGill University, Montreal, QC, H3A 2A7, Canada
[*]*qunbi.zhuge@mail.mcgill.ca*

Abstract: We experimentally demonstrate the impact of equalization-enhanced phase noise (EEPN) on the performance of 56 Gbaud dual-polarization (DP) QPSK long haul transmission systems. Although EEPN adds additional noise to the received symbols, we show that this reduces the phase variance introduced by the LO laser, and therefore should be considered when designing the carrier phase recovery (CPR) algorithms and estimating system performance. Further, we experimentally demonstrate the performance degradation caused by EEPN when a LO laser with a large linewidth is used at the receiver. When using a 2.6 MHz linewidth distributed feedback (DFB) laser instead of a ~100 kHz linewidth external-cavity laser (ECL) as a LO, the transmission distance is reduced from 4160 km to 2640 km due to EEPN. We also confirm the reduction of the phase variance of the received symbols for longer transmission distances showing its impact on the CPR algorithm optimization when a DFB laser is used at the receiver. Finally, the relationship between the EEPN-induced penalty versus the signal baud rate and the LO laser linewidth is experimentally evaluated, and numerically validated by simulations.

OCIS codes: (060.1660) Coherent communications; (060.2330) Fiber optics communications.

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1. Introduction

Equalization-enhanced phase noise (EEPN) is a non-negligible impairment in dispersion-unmanaged single carrier transmission systems when inexpensive local oscillator (LO) lasers (with large linewidths) are used at the receiver [1–4]. The impact of EEPN has been analytically investigated in [1,3], where its origin and statistical properties were fully studied. Moreover, EEPN-induced performance degradation has been experimentally demonstrated for 28 Gbaud dual-polarization (DP) quadrature phase shift keying (QPSK) systems over a 3000 km transmission distance [4]. Furthermore, this penalty scales with the signal baud rate and transmission distance [1,2]. Therefore, it is more important to identify the impact of EEPN on higher rate long haul systems. For example, the 56 Gbaud DP-QPSK (224 Gb/s) systems have been demonstrated in [5,6] but the impact of EEPN was not evaluated.

In this paper, we conduct experimental investigations of the effects of EEPN for 56 Gbaud DP-QPSK (224 Gb/s) transmission over a 4160 km transmission distance. First, we show that although EEPN increases the noise variance of the received symbols it actually reduces the variance of the symbol phase drift because of the chromatic dispersion (CD)-induced correlation between symbols. This should be considered in designing and optimizing carrier phase recovery (CPR) algorithms, and/or estimating system performance. Next we experimentally demonstrate that the transmission distance of the system with a 2.6 MHz linewidth distributed feedback (DFB) laser employed as the LO is reduced from 4160 km to 2640 km when compared to the case where a ~100 kHz linewidth external-cavity laser (ECL) is employed. With the DFB laser as the LO, we experimentally show that the symbol phase variance decreases as the transmission distance increases, which affects the optimization of the CPR algorithm. Finally, we calculate the EEPN-induced Q-factor penalty versus the signal baud rate and the LO laser linewidth, through both experiments and simulations.

2. Equalization-enhanced phase noise

Analytically, the received signal $r(t)$ assuming only CD in the optical channel and laser phase noise can be expressed as

$$r(t)=\left\{\left[s(t)\cdot e^{j\phi_t(t)}\right]*h_{CD}(t)\cdot e^{j\phi_r(t)}\right\}*h_E(t), \tag{1}$$

where $s(t)$ is the transmitted signal. $\phi_t(t)$ and $\phi_r(t)$ is the phase noise from the transmitter laser and LO, respectively. $h_{CD}(t)$ and $h_E(t)$ represent the impulse response of the CD effect and CD equalizer, respectively. After down-sampling to the symbol rate, the received k^{th} symbol r_k before phase recovery can be given by

$$r_k = c_k\cdot e^{j\phi[k]}+n_{EEPN}, \tag{2}$$

where c_k is the k^{th} transmitted symbol. The phase shift $\phi[k]$ is given by $\phi[k]=\phi_t[k]+\phi_r'[k]$ where $\phi_t[k]$ is the sampled phase of $\phi_t(t)$ and $\phi_r'[k]$ is the phase shift caused by the LO phase noise $\phi_r(t)$ impacted by $h_E(t)$ in Eq. (1). n_{EEPN} is the additional noise caused by the EEPN. A detailed mathematical model for the n_{EEPN} can be found in [1,3].

Figure 1 illustrates the origin of EEPN. Intuitively, EEPN occurs due to the fact that the transmitted pulses broadened by CD will collect a wide range of LO phase noise which is then converted into amplitude noise by the following CD equalizer $h_E(t)$ in Eq. (1). In this work, we report another impact of EEPN on the system performance. As per Fig. 1, two adjacent pulses significantly overlap at the receiver due to the accumulated CD. Therefore, the LO phase noise they experience will be highly correlated, which will reduce the variance

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of the phase shift $\phi[k]$ in Eq. (2). To date, most CPR algorithms were evaluated and optimized in back-to-back cases [7,8]. However, such a reduction of phase shift variance caused by the EEPN should be taken into account, since it will increase the linewidth tolerance of the CPR algorithms and will also affect the optimization of those algorithms, e.g. the optimal filter length might be increased.

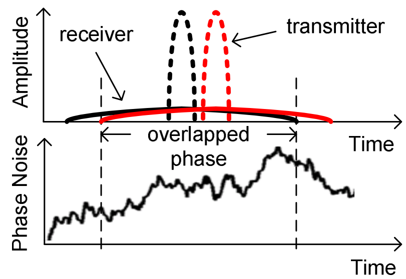

Fig. 1. The origin of EEPN.

One example of the symbol phase shift before and after transmission is shown in Fig. 2(a) via simulations. It can be seen that the symbol phase varies more rapidly in the back-to-back case compared to the transmission case where fluctuations in the phase are reduced due to the high correlation of the LO phase noise between the overlapped symbols. We also illustrate n_{EEPN} in Eq. (2) by comparing the constellation before transmission in Fig. 2(b) and after transmission in Fig. 2(c). The latter exhibits a large amount of the Gaussian-like distributed noise, manifesting the non-negligible penalty caused by n_{EEPN} that contaminates the signal. In general, it is difficult to compensate for n_{EEPN}. However, multi-carrier modulation formats such as the reduced-guard-interval (RGI) coherent optical frequency-division multiplexing (CO-OFDM) were proposed to mitigate EEPN [9]. In addition, a digital coherence enhancement technique was proposed in [10] to compensate for EEPN by utilizing an interferometric device to detect the LO laser phase noise exclusively and compensate it before CD compensation.

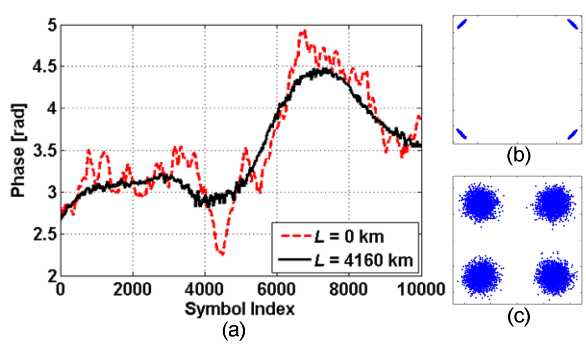

Fig. 2. The effects of the EEPN on 56 Gbaud QPSK signals in simulation. (a) The phase of the received symbols before CPR. The constellations after CPR for (b) back-to-back case and (c) 4160 km transmission distance.

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3. Experimental setup

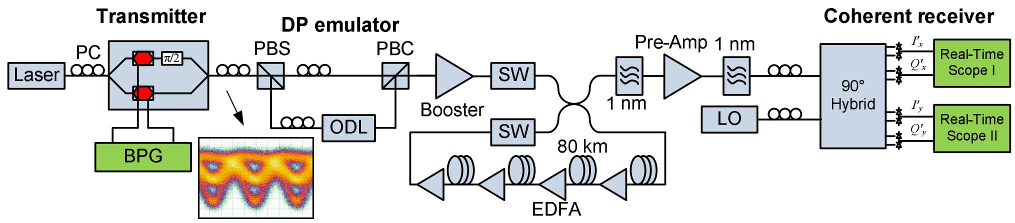

Fig. 3. Experimental setup. Inset: optical eye diagram of the 56 Gbaud QPSK signal. PBC/PBS: polarization beam combiner/splitter. PC: polarization controller. SW: switch.

Figure 3 shows the experimental setup for our 56 Gbaud DP-QPSK system. The electrical 56 Gbaud inphase and quadrature signals were generated by a bit pattern generator (BPG) and skewed using a RF delay line, before being fed into an IQ modulator for electrical-to-optical up-conversion. The inset in Fig. 3 shows the optical power eye diagram of the generated 56 Gbaud single-polarization QPSK signal. The optical signal was then split into two orthogonal polarizations and re-combined with one polarization signal delayed by 650 symbols (11.6 ns) to form the de-correlated DP-QPSK signal. After being amplified by a booster erbium-doped fiber amplifier (EDFA) to −2 dBm, the optical signal was launched into a re-circulating loop, which consisted of 4 spans of 80 km standard single mode fiber (SMF-28e +) and 4 inline EDFAs each having 5 dB noise figure. At the receiver, the out-of-band amplified spontaneous emission (ASE) noise was filtered out using a 1 nm filter. The signal was then pre-amplified and re-filtered before being fed into an optical hybrid and 4 balanced photodiodes for coherent detection. Two 80 Gs/s real-time scopes with 33 GHz analog bandwidth were used to digitize the analog signal. The offline processing included IQ imbalance compensation, resampling to two samples per symbol, CD compensation, channel equalization using the constant modulus algorithm (CMA) with 15 taps, pilot-aided superscalar parallelization-based phase recovery [11], and symbol decision. We evaluated the performance of three systems with: 1) ECLs at both the transmitter and receiver, denoted by ECL/ECL; 2) an ECL at the transmitter and a DFB laser at the receiver, denoted by ECL/DFB; 3) a DFB laser at the transmitter and an ECL at the receiver, denoted by DFB/ECL. The linewidths of the ECLs were less than 100 kHz. For the DFB lasers used in these experiments, we measured the laser phase noise variance σ_ϕ^2 using the coherent detection method described in [12,13] with an averaging window of 50 symbols and a relative delay of 50 symbols. The measured data was converted to linewidth Δf using $\Delta f = \sigma_\phi^2 / 2\pi T$ with T denoting the symbol duration based on the assumption of a Wiener process [12,13].

4. Experimental and simulation results

Figure 4 shows the back-to-back bit error rate (BER) versus the optical signal-to-noise ratio (OSNR) for the ECL/ECL and ECL/DFB systems. The linewidth of the DFB laser was estimated to be approximately 2.6 MHz. Both systems perform almost the same, with approximately a 3 dB OSNR penalty compared to the theoretical limit at a BER = 3.8×10^{-3} (corresponding to the BER threshold of a forward error correction (FEC) with 7% overhead). This is because in a back-to-back configuration the DFB laser only induces larger phase shift variance compared to the ECL, and that variance can still be tolerated with the employed CPR algorithm [11] without introducing penalties.

The comparison of the Q-factor (derived from the measured BER assuming Gaussian statistics) versus the transmission distance for the different systems is shown in Fig. 5. The DFB/ECL system is also included for comparison. Note that the performances of the ECL/ECL and DFB/ECL systems are almost identical. In particular, both systems achieve a transmission distance close to 4160 km with a Q-factor of 8.5 dB (corresponding to the 3.8 ×

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10^{-3} BER threshold). In contrast, the transmission distance of the ECL/DFB system is reduced to 2640 km, due to the large amount of EEPN in such high baud rate and long distance transmission. By comparing the DFB/ECL and the ECL/DFB systems, it is clear that in our 56 Gbaud DP-QPSK system rather than the phase recovery ability of the CPR algorithms, the EEPN-induced noise n_{EEPN} in Eq. (2) limits the laser linewidth tolerance of the ECL/DFB system.

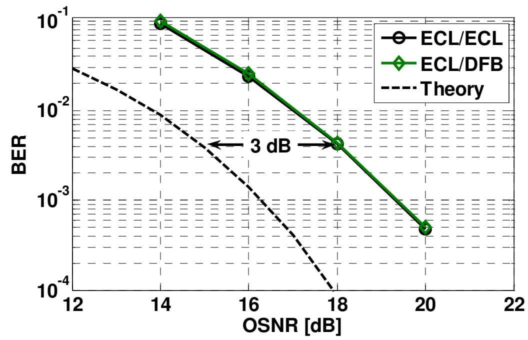

Fig. 4. Measured back-to-back BER vs. the OSNR (measured over a 0.1 nm resolution).

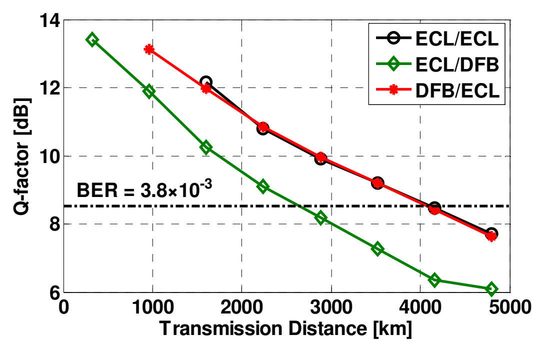

Fig. 5. Measured Q-factor versus transmission distance.

Figure 6 studies the impact of EEPN on the phase shift variance and the implementation of the CPR algorithms. The phase variance was estimated using the method described in the previous section [12,13]. It was also converted to linewidth for a more straightforward evaluation as shown in Fig. 6(a). The calculated linewidth of the ECL/ECL and DFB/ECL systems remains around 100 kHz and 2.6 MHz, respectively, regardless of the transmission distance. However, due to the CD-induced correlation of the LO phase noise between symbols as explained in Section 2, the calculated linewidth of the ECL/DFB system significantly decreases as the distance increases and approaches 400 kHz after a 1000 km distance. The Q-factor versus the filter length employed in the CPR algorithm is illustrated in Fig. 6(b). It is known that for a smaller phase shift variance the optimal filter length becomes larger. For the ECL/ECL and ECL/DFB systems, the Q-factor starts to decrease for a filter length larger than 1040 symbols, which demonstrates that the ECL/DFB system has a very small phase variance similar to the ECL/ECL system. The optimal filter length for the DFB/ECL system is only around 60 symbols, because the phase variance caused by the DFB laser at the transmitter is not reduced by the EEPN.

Finally, we investigate the EEPN-induced Q-factor penalty versus baud rate and LO laser linewidth at 4160 km for the ECL/DFB system in Fig. 7(a) and Fig. 7(b), respectively. The performance of the ECL/ECL system is used as a reference. For all systems in Fig. 7(a), ASE noise was first loaded at the receiver if necessary to get a Q-factor of 8.5 dB for the ECL/ECL system. Then the ECL LO laser was replaced with the 2.6 MHz linewidth DFB laser, and the

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Q-factor penalty was obtained. Simulations were also conducted, where 3rd order Butterworth low pass filters with 25 GHz cutoff frequency were used to mimic the bandwidth limitation of the transmitter and the laser phase noise was modeled as a Wiener process. As expected, in Fig. 7(a) the Q-factor penalty scales with the baud rate, which is proportional to the accumulated CD during the transmission. For the experimental results, the Q-factor penalty was 0.9, 1.2, 1.9 and 2.2 dB for 22, 28, 44 and 56 Gbaud DP-QPSK systems, respectively, which matches the simulation results with a deviation less than 0.17 dB. In Fig. 7(b), four DFB lasers with different estimated linewidths were used as the LO in the 56 Gbaud experiment. The penalty was only 0.2 dB for a 300 kHz linewidth DFB laser. With linewidth larger than 1 MHz, the performance degradation starts to be non-negligible (> 0.5 dB). Again, our simulations almost match the experimental results.

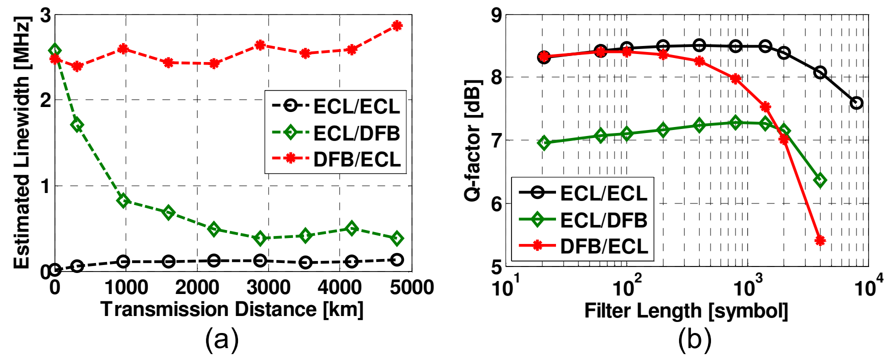

Fig. 6. (a) Estimated linewidth versus transmission distance and (b) Q-factor versus CPR filter length at 4160 km distance with different lasers at the two ends.

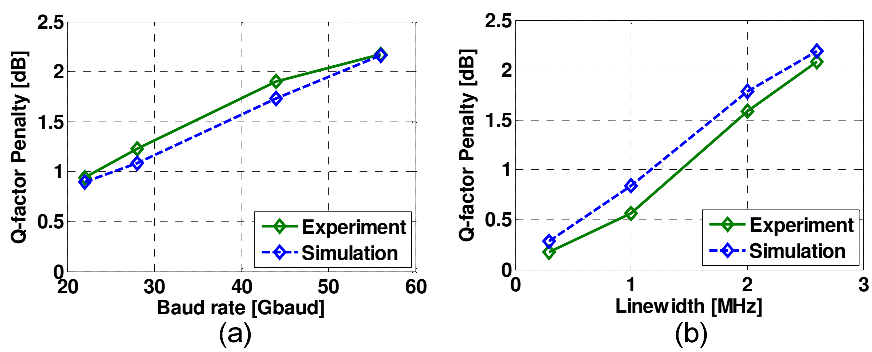

Fig. 7. Q-factor penalty of an ECL/DFB system (with respect to ECL/ECL) at 4160 km distance versus: (a) the baud rate and (b) the LO laser linewidth.

5. Summary

In this paper, we investigated the equalization-enhanced phase noise (EEPN) for 56 Gbaud dual-polarization (DP) QPSK long haul systems. We first illustrated the two effects of EEPN: 1) additional noise added to the symbols; 2) reduction of the symbol phase variance due to the chromatic dispersion (CD)-induced correlation of symbols. We then experimentally demonstrated that using a distributed feedback (DFB) laser with a 2.6 MHz linewidth as the local oscillator (LO) reduces the transmission distance from 4160 km to 2640 km compared to the system using a ~100 kHz external cavity laser (ECL) as the LO. When the DFB laser was employed as the LO, we showed the reduction of the symbol phase variance for larger transmission distances, and we illustrated its impact on the carrier phase recovery algorithm. Finally, we experimentally demonstrated that the EEPN-induced penalty scales with the signal baud rate and LO laser linewidth, and confirmed our results by simulations.

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