Mitigation of Equalization-Enhanced Phase Noise Using Reduced-Guard-Interval CO-OFDM

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Abstract: We demonstrate that reduced-guard-interval (RGI) CO-OFDM systems are more tolerant to equalization-enhance phase noise (EEPN), which is a non-negligible impairment of single-carrier systems in long-haul transmissions, especially for next generation transport systems.

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1. Introduction

As the commercialization of the 100G optical transmission technology is in progress, research activities are focused on the transmission beyond 100 Gb/s per-channel data rate, including 400G systems which are one of the potential candidates for next generation transport. A 448 Gb/s transmission with 56 Gbaud 16-QAM polarization-division multiplexed (PDM) single carrier (SC) signals has been demonstrated with a propagation length of 1200 km [1]. More recently, by employing state-of-the-art forward error correction (FEC), a 16-QAM reduced-guard-interval (RGI) CO-OFDM system with a date rate of 485 Gb/s achieved a transmission length of 4800 km [2]. Furthermore, in order to increase the spectral efficiency along with scaling the per-channel data rate, Nyquist 32-QAM SC signals were used to realize a 450 Gb/s transmission [3]. On the other hand, the speed of digital-to-analog converters (DACs) is continuously increasing. Sampling rates of up to 56 GSample/s [4] have been demonstrated, allowing the realizations of both Nyquist SC and RGI OFDM with 50 Gbaud 16-QAM signals for 400G. However, with the increase of baud rate and the use of higher order QAM, the equalization-enhanced phase noise (EEPN) for SC systems becomes non-negligible even when using external cavity lasers (ECLs) [5-7], and limits the achievable transmission distance.

In this work, we propose the use of RGI CO-OFDM to mitigate the EEPN encountered by SC systems. We show that RGI CO-OFDM has the capability to achieve higher linearity tolerance than SC systems when taking into account the large accumulated chromatic dispersion (CD) in dispersion-unmanaged long-haul transmission. We numerically demonstrate that the signal-to-noise ratio (SNR) penalty induced by laser phase noise (PN) is higher for SC systems than it is for RGI CO-OFDM systems after approximately 1600 km and 800 km transmission for 112 Gb/s (28 Gbaud and QPSK) and 448 Gb/s (56 Gbaud and 16-QAM) transport, respectively. We also show that the linewidth tolerance at 1 dB SNR penalty for SC systems (including the penalty induced by differential coding) is reduced to 300 kHz and 70 kHz for 112 Gb/s at 4800 km distance and 448 Gb/s at 2400 km distance, respectively. But with RGI CO-OFDM, it reaches 2 MHz and 350 kHz at the cost of 2.5% and 1.25% pilot subcarriers (PS) overhead, respectively.

2. Mitigation of equalization-enhanced phase noise

The EEPN induced penalty results from the fact that the multiplication and the convolution are not commutable, which makes the digital CD equalizer unable to completely equalize CD when PN from local oscillator (LO) is applied before the equalizer [5, 7]. Intuitively, because the pulse is dramatically broadened after a long distance transmission, it would collect laser PN with a much larger variance from the LO at the receiver, and afterwards the collected PN is converted into amplitude noise by the CD equalizer [6].

Fig. 1. The model for RGI CO-OFDM systems. CPR: carrier phase recovery.

Fig. 1 depicts the model for RGI CO-OFDM systems, where only CD $h(t)$ and ASE noise $z(t)$ are included in the fiber channel. The laser phase noise (PN) is added at both transmitter and receiver sides, which is denoted as $\phi(t)$ and $\phi(t)$, respectively. Each symbol after CD compensation can be expressed as
\[ r_{ck}[n] = \sum_{k=1}^{N_c} c_k \cdot e^{j2\pi k \Delta f n + j\phi_k[n] + j\phi_k[n+D_k]} + z'[n] \]  

(1)

where \( N_c \) is the number of the subcarriers, \( c_k \) denotes the \( k \)th subcarrier, \( \Delta f \) is the subcarrier frequency spacing, \( D_k \) is the CD-induced walk-off, and \( z'[n] \) results from the ASE noise \([8]\). As shown in Fig. 2, rather than increase the symbol duration as for SC systems, the impact of CD on RGI CO-OFDM symbols is to impose different phase shifts on different subcarriers, which can be easily compensated by adopting grouped maximum-likelihood (GML) algorithms or carrier phase recovery (CPR) algorithms designed for SC systems \([8-11]\). Consequently, although OFDM symbols suffer from the inter-carrier interference induced by both transmit and receive lasers, it is anticipated that RGI CO-OFDM would become more linewidth tolerant than SC systems after a certain transmission distance, where the latter suffers from a larger amount of EEPN. Fig. 3 shows the laser PN induced noise variance including both phase noise and amplitude noise versus the transmission distance \( L \) with 56 Gbaud 16-QAM signals and 100 kHz linewidth. We observe that OFDM systems have lower noise variance than SC systems when \( L \) is larger than approximately 900 km.

Fig. 2. Illustration of the interplay between laser PN and accumulated CD in dispersion-unmanaged transmissions for (a) SC systems and (b) RGI CO-OFDM systems.

3. Simulation results and discussions

Extensive simulations have been conducted to compare the performance of SC and OFDM systems. For SC systems, the root raised cosine (RRC) pulse with roll-factor \( \alpha = 0.1 \) is used in order to make the spectral efficiency comparable to OFDM. For RGI CO-OFDM, the number of subcarriers is 80 and 160 for 112 Gb/s and 448 Gb/s, respectively. For both SC and OFDM systems, 28 Gbaud QPSK and 56 Gbaud 16-QAM single-polarization transmissions are simulated, corresponding to PDM systems with 112 Gb/s and 448 Gb/s data rates, respectively. For the fiber channel, only CD with dispersion parameter \( D = 17 \) ps/(nm·km) and ASE noise are taken into consideration. The transmit and LO lasers have the same linewidth. CD is assumed to be completely compensated by the frequency domain equalizer at the receiver for both systems. Viterbi and Viterbi CPR and QPSK-partition CPR is used for QPSK and 16-QAM, respectively \([11, 12]\). It should be noted that for RGI CO-OFDM, the phase shift can’t be fully removed by CPR as shown by the constellation in Fig. 3. This is because that the CPR is implemented within one OFDM symbol, and thus the averaging length for the edge subcarriers will be shortened, resulting in a residual phase shift for them.

Fig. 3. Normalized variance induced by laser PN for both SC and OFDM systems. 56 Gbaud, 16-QAM, and 100 kHz linewidth.

Fig. 4. Required SNR at BER = 10^{-3} versus transmission distance \( L \) with a data rate of (a) 112 Gb/s and (b) 448 Gb/s.
Fig. 4 shows the required SNR versus the transmission distance. Note that for SC systems, differential coding was not adopted and the results from the set of data without the occurrence of cycle slip were chosen, so the penalties only result from EEPN. For 112 Gb/s transmissions as shown in Fig. 4 (a), SC systems perform slightly better (0.27 dB for $\beta = 1$ MHz and 0.11 dB for $\beta = 500$ kHz) in the back-to-back scenario. However, as $L$ increases, the penalties for SC systems are considerably increased, and become larger than OFDM systems with $L > 1600$ km for both $\beta = 1$ MHz and 500 kHz. This result is expected because the pulse width for SC signals (= 6.13 ns) is a little larger than twice of the symbol duration of OFDM signals (= 2.86 ns) at $L = 1600$ km, but since the former only collects PN at the receiver while the latter collects PN from both ends, the total amount of PN they experience should be similar. As $L$ continues to increase, the penalties for SC systems are still linearly increasing, where the results are consistent with previous works [5-7]. At $L = 7200$ km, the penalties for SC systems are 1.5 dB and 0.5 dB larger than OFDM systems with $\beta = 1$ MHz and 500 kHz, respectively. But with $\beta = 100$ kHz, the impact of laser PN is negligible for both systems. However, when upgraded to 448 Gb/s transmissions, even with a linewidth as low as 100 kHz, the penalties caused by EEPN become non-negligible as shown in Fig. 4 (b). At $L = 4800$ km, SC systems require 2.1 dB and 0.7 dB higher SNR than OFDM systems for $\beta = 200$ kHz and 100 kHz, respectively.

![Graph](image)

Fig. 5. SNR Penalty at BER = $10^{-3}$ versus the laser linewidth with a data rate of (a) 112 Gb/s and (b) 448 Gb/s.

The comparisons of linewidth tolerance are explored in Fig. 5. We applied differential coding to SC systems here, which is usually required in real systems to remove the angle ambiguity and cycle slip. In fact, the probability of cycle slip will be increased in the presence of EEPN [7]. For OFDM systems, 2 PS’s in each symbol were used to remove the angle ambiguity. Therefore, OFDM exhibits less penalty than SC systems at low linewidth, at the cost of 2.5% (= 2/80) and 1.25% (= 2/160) PS overhead for 112 Gb/s and 448 Gb/s systems, respectively. In back-to-back cases, SC systems exhibit very high tolerance as expected. But the tolerance at 1 dB penalty is limited to 300 kHz and 70 kHz by EEPN for 112 Gb/s transmission at $L = 4800$ km and 448 Gb/s transmission at $L = 2400$ km, respectively, whereas OFDM reaches up to 2 MHz and 350 kHz, respectively.

We would like to emphasize that the complexities of CPR for SC and OFDM systems in this work are identical, since they are using the same algorithms. The other complexities (e.g. dispersion compensation) of RGI OFDM are expected to be similar as SC systems [12]. On the other hand, since the cyclic prefix (CP) can be completely removed as demonstrated in our previous work [13], the total overhead for OFDM can be very small. Therefore, with DACs available at transmitters, OFDM will be a cost-effective way to combat EEPN. In addition, when using fibers with a larger dispersion parameter (e.g. ultra-large-area fiber), the tolerance to EEPN of OFDM systems becomes even more important.

4. Conclusions

Single carrier (SC) systems are very tolerant to laser phase noise in the back-to-back case or with a small residual dispersion in dispersion-managed transmissions. However, for dispersion-unmanaged scenarios, equalization-enhanced phase noise (EEPN) becomes the main limiting factor and considerably reduces the linewidth tolerance of SC systems. Reduced-guard-interval (RGI) CO-OFDM can be used to mitigate EEPN and increase the linewidth tolerance, which is essential for next generation 400G systems.

Reference

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