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Improving Nonlinearity Tolerance of PCS-QAM Digital Multi-Carrier Systems Through Symbol Rate Optimization

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Abstract
We experimentally demonstrate that symbol-rate optimization (SRO) provides nonlinear gains in multi-carrier systems, even with PCS modulation and realistic DSP. Optimized carrier phase recovery is crucial to achieving 0.2 dB gain for 1400 km 800G transmission, out of the ∼0.7 dB theoretical maximum gain we measured. ©2022 The Author(s)

Introduction

The impact of nonlinear interference noise (NLIN) in long-haul optical fiber systems has a strong dependence on the symbol-rate of the transmitted signals[1]. This phenomenon has been widely reported through nonlinear modeling studies, simulations and experiments[1]–[3]. To efficiently exploit this effect, digital subcarrier multiplexing (SCM) divides each optical wavelength into lower-baudrate digital subcarriers. Nonlinear performance is then improved by optimizing the number of subcarriers, in what is termed symbol-rate optimization (SRO). Large gains in the range of 0.5–1 dB have been reported for SCM with constant-modulus formats such as QPSK, while reduced, but still significant benefits have been observed with 16-QAM[4]. However, with the recent widespread adoption of probabilistic constellation shaping (PCS), the exploitation of SRO gains has become even more challenging[5],[6]. The quasi-Gaussian distribution of PCS signals maximizes non-linear phase noise (NLPN), to the point that the SRO effect is nullified. NLIN-tailored PCS distributions have been proposed recently[7], in an attempt to find the right balance between performance in the linear and nonlinear regimes. Ultimately, to be compatible with standard PCS approaches, the best solution lies in the optimization of the DSP for SCM, including reducing the penalty due to the lower baudrate/linewidth ratio, and compensating as much NLPN as possible. Therefore, and as will be shown in this paper, the carrier phase recovery (CPR) plays a key role.

We carry out experiments with 110 Gbaud SCM signals in a 17-channel wavelength-division multiplexing (WDM) system transmitted over a 1400 km straight line link, to determine whether the SRO effect can be observed when employing PCS-64QAM. Using pilot-only joint CPR (JCPR), up to 0.1 dB signal-to-noise ratio (SNR) benefit is observed. We improve to 0.2 dB by adding a second-stage CPR operating on a per-subcarrier basis. Moreover, we evaluate the performance of single-carrier (SC), 4-, 8- and 16-SCM signals at various transmission distances along the line (400, 900 and 1400 km); a clear tendency for the optimal number of subcarriers to increase with distance is observed, as expected by theory[1]. This work represents the first ever experimental demonstration of the SRO effect (and associated gains) for PCS signals with realistic DSP.

Experimental Setup

The setup shown in Fig. 1 was used for transmission performance evaluation. Our channel un-

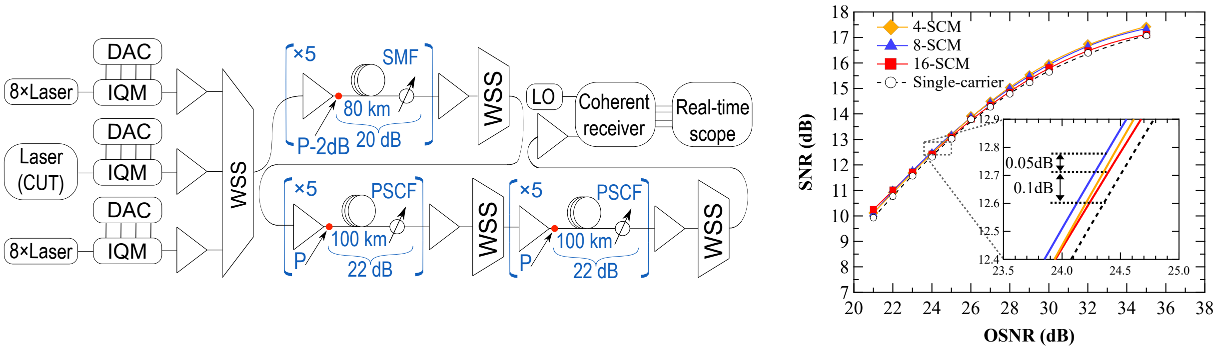

Fig. 1: Experimental setup of the 17×110 Gbaud WDM PCS-64QAM transmission system (left) and measured back-to-back SNR vs. OSNR curves for single carrier and SCM cases (right).

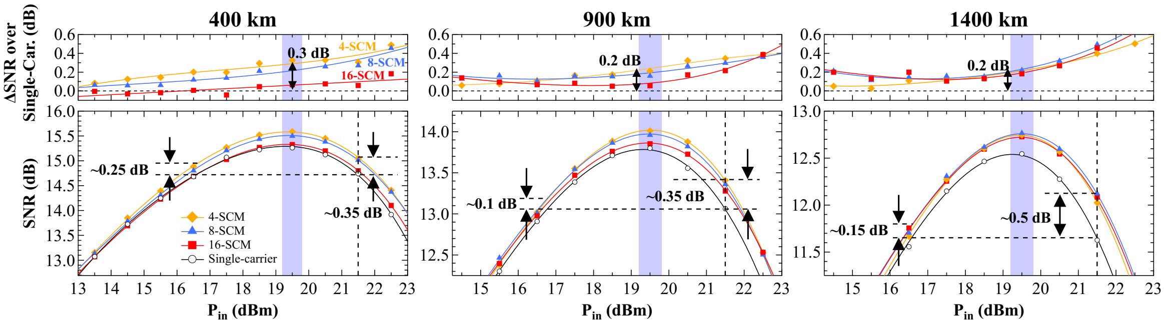

Fig. 2: Measured SNRs vs total launch power (2 dB lower for the SSMF spans) after the receiver-side DSP processing employing pilot-only CPR (SC) or joint pilot-only CPR (4-, 8-, and 16-SCM).

der test (CUT), 110 Gbaud dual-polarization (DP)-PCS-64QAM single- or multi-carrier, was generated with a 4-channel 120 Gsample/s digital to analog converter (DAC). QPSK pilots were inserted at a rate of 1/32 between the data symbols. A net bitrate of 800 Gbit/s was achieved with an entropy of 5 bit/symbol/polarization, taking into account pilot and 25% forward error correction (FEC) overhead. Root-raised cosine shaping with 0.02 roll-off factor was applied. The DAC signals were amplified and used to modulate an optical carrier generated by a low-linewidth external cavity laser (ECL) with a DP-IQ modulator. In addition to digital, optical pre-emphasis was employed to compensate for transceiver bandwidth limitations, implemented using the wavelength selective switch (WSS) which combined the CUT with the remaining channels.

The CUT was launched into the fiber along with 16 interferer (INT) channels (8 on each side), spaced at 125 GHz. Two sets of 8 INTs were generated using another two (separate) transmitters. Though the data on each set was different, the modulation format for all WDM channels was always kept the same as that of the CUT. In order to avoid correlation between neighbors, the outputs of the two INT-generating transmitters were interleaved in frequency.

The transmission setup consisted of a straight-line with 3 sections of 5 spans each. In the first section, 80 km standard single mode fiber (SSMF) spans were used, with the span loss adjusted to 20 dB using a variable optical attenuator. Sections 2 and 3 consisted of 100 km, pure silica core fiber (PSCF) with 125 μm^2 effective area. Here, the span loss was adjusted to 22 dB. The WSSs at the input and between sections were used to equalize the WDM spectrum at the middle of each section. After transmission, a WSS filtered the CUT before being mixed with an ECL in a coherent receiver. The signals were captured by a real-time scope, and offline DSP was applied, including chromatic dispersion compensation, pilot-aided adaptive equalization, frequency and carrier phase recovery.

Results and Discussion

We first characterized the back-to-back (B2B) performance in a noise-loading setup, using pilot-only CPR for the SC case and joint pilot-only CPR for all the SCM cases, with optimized number of averaging taps. This was done in order to be able to isolate the nonlinear gains obtained during transmission, decoupling them from gains due to B2B performance differences. We use the global SNR (also known as geometric SNR[8]), given by $[\prod_{n=1}^{N}(1+\mathrm{SNR}_n)]^{1/N}-1$, where N is the number of subcarriers and SNR_n is the SNR of the n-th subcarrier. This metric is directly related to the achievable capacity of the SCM system, assuming entropy-loading is employed[9], and is therefore equivalent to SNR for SC, when $N=1$. Using global SNR therefore allowed us to assess the performance without actually having to carry out entropy-loading in the experiment, since it is implicit in the metric itself. Moreover, it enables a direct comparison between systems with different number of subcarriers.

As can be seen in Fig. 1 (right), SCM can provide slightly better performance, mainly at the high optical SNR (OSNR) region where transceiver noise limits the performance. Since the transceiver noise is heavily colored in our case, entropy-loaded multi-carrier is advantageous over SC, an effect that is captured by the global SNR, as explained above. At the SNR region corresponding to 1400 km transmission ($\sim$12.5 dB), we can observe a 0.15 dB benefit for 8-SCM and about 0.1 dB benefit for 4- and 16-SCM cases (see inset of Fig. 1, right).

We then investigated the SRO benefits for different transmission distances, using the same (pilot-only) CPR algorithms as in the B2B case. Note that for this part of the study we did not consider blind decision-aided CPR, since this would give an unfair advantage for the shorter distances, where we operate at SNRs that are much higher

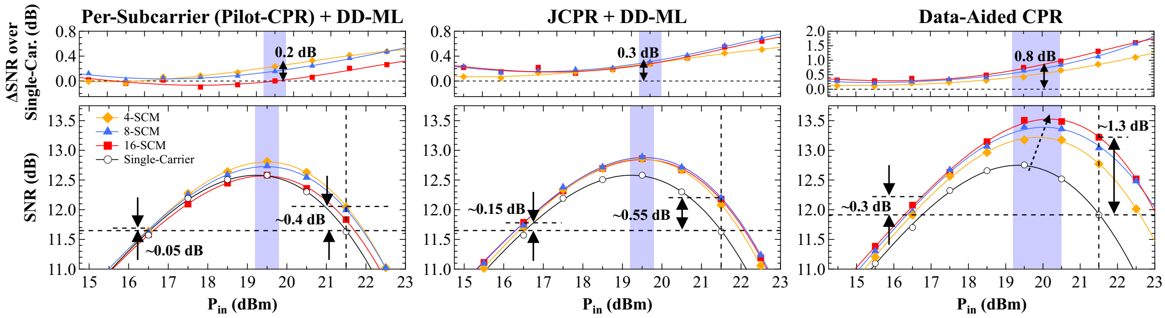

Fig. 3: Measured SNRs after a transmission length of 1400 km for the indicated CPR strategies.

than the FEC limit (operation close to the FEC limit is only achieved after 1400 km). In Fig. 2 we show the measured SNRs after DSP processing for transmission after Section 1 (400 km), Section 2 (900 km) and Section 3 (1400 km). These results allow for the visualization of the SRO effect, as we can observe that with the increase of the transmission length, there is a tendency for the optimum number of subcarriers to increase. The gains of the best-performing SCM signal over SC at 400, 900 and 1400 km are 0.3, 0.2 and 0.2 dB respectively. However, subtracting the B2B gains we end up with 0, 0.05 and 0.1 dB improvement due to nonlinearity tolerance alone. These trends of the nonlinear benefit of SCM are confirmed by comparing the SNR gain at 2 dB over the optimal launch power (i.e. at 21.5 dBm), to that obtained at the same SC SNR in the linear region. We observe larger gains in the nonlinear region for all cases, but with a larger gap in the case of 1400 km, where the difference is ∼0.35 dB (0.5 dB in the nonlinear region minus 0.15 dB in the linear). We should also emphasize that despite not being included here for lack of space, the trend of increasing optimum number of subcarriers, and the magnitude of the gains with the distance, are in good agreement with split-step Fourier method simulations.

To highlight the importance of the CPR algorithm performance on SRO efficiency, we show the measured SNRs after 1400 km for different CPR schemes (Fig. 3): (i) per-subcarrier independent processing with a first-stage pilot-only CPR and a second-stage decision-directed maximum-likelihood (DD-ML); (ii) first-stage pilot-only JCPR and second-stage per-subcarrier DD-ML; and (iii) ideal, fully data-aided (DA)-CPR, where we ensure that the Gaussianity of the noise on the constellation points is preserved. The DA-CPR represents a maximum attainable performance that *cannot* be reached with known realistic DSP—it serves only as a theoretical benchmark.

Comparing Fig. 2 (right) to Fig. 3 (left), we observe that using per-subcarrier processing instead of single-stage JCPR has a detrimental effect on the performance of 8- and 16-SCM (∼0.1 and 0.2 dB loss in gain w.r.t. SC), while the gain of 4-SCM over SC remains virtually unchanged. On the other hand, when adding a second-stage DD-ML CPR after joint pilot-only CPR (Fig. 3, middle), the gain of the SCM cases is ∼0.3 dB; i.e. 0.1 dB larger than in the case of the single-stage joint-CPR shown in Fig. 2 (right). Moreover, with the two-stage joint-CPR & DD-ML we note that 16-SCM provides a 0.2 dB gain over SC due to the SRO benefit (after removing the 0.1 dB B2B gain). It should be highlighted that the performance in the linear case is similar to the B2B, showing that equalization-enhanced phase noise (EEPN) is *not* providing any gain. This has been confirmed by simulations where the EEPN penalty for SC was negligible. The nonlinear benefits are again confirmed by comparing the SNR gains in the linear and nonlinear-dominated regions.

It is important to note that there is still plenty of room for improvement of NLPN compensation, as indicated by the benchmark DA-CPR results (Fig. 3, right). These show an additional 0.5 dB gain over the realistic JCPR & DD-ML. Moreover, the optimum number of subcarriers with DA-CPR is 16 which is in line with theoretical predictions[1], and we can observe a much clearer shift of the optimal launch power by ∼0.5 dB.

Conclusions

We have verified that making use of optimized—but nonetheless realistic—DSP in SCM systems, it is possible to obtain SRO nonlinearity benefits, even with PCS-64QAM modulated subcarriers: we have achieved up to 0.2 dB SNR gain for long-haul 800G transmission. Due to NLPN, this gain is, as expected, lower than previous reported gains with QPSK/16-QAM, and requires careful design of the CPR algorithms for it to be reached. Larger gain would be possible if NLPN compensation could be further improved, to close the gap with the theoretical maximum we observed.

Acknowledgement

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