Maximizing the Performance of Digital Multi-Carrier Systems with Transmission-Aware Joint Carrier Phase Recovery

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Abstract *Theoretical gains of digital multi-carrier systems are hindered by the use of sub-optimal conventional phase recovery, especially after fiber transmission. We experimentally validate an advanced, dispersion-aware algorithm that addresses this issue, achieving SNR gains up to ∼0.5 dB with 800G 125 Gbaud 16-carrier PCS-64QAM, transmitted over 1800 km.*

Introduction

Carrier phase recovery (CPR) algorithms for single-carrier modulation formats have reached a high level of maturity, thanks to over a decade's worth of R&D in coherent optical systems. They come in many flavors, including the computationally efficient pilot-based CPR[1], which has the advantage of being format-independent, as it operates solely on the known pilot symbols inserted regularly between data symbols. Better performance—at the expense of complexity—can be achieved with blind phase search (BPS)[2], or using decision-directed maximum-likelihood (DD-ML) CPR[3] as a second stage.

Digital multi-carrier (MC) modulation can be advantageous over single-carrier in channels with significant colored noise[4], as well as due to its higher tolerance to equalization-enhanced phase noise (EEPN)[5]. On the other hand, individual processing of the subcarriers can lead to lower DSP performance, which is mainly the case for CPR: performance is degraded compared to a single-carrier system with the same overall baudrate. While this can be countered by applying joint-subcarrier CPR (JCPR)[6],[7], it will only recover the penalty incurred in back-to-back (B2B); after sufficiently long transmission, any gains from JCPR will be lost or even reversed, as a consequence of the chromatic dispersion (CD) inducing different group delays between the subcarriers.

Recently, a novel dual reference subcarrier (DRS) CPR has been proposed. This low-complexity algorithm is transmission-aware and takes into account the accumulated CD, separately estimating the transmitter and receiver phase noise[8],[9]. It was shown, via linear channel simulations, that it is possible to jointly process the subcarriers and recover a large part of the performance lost after transmission. In this work, we present the first ever experimental validation of this transmission-aware CPR algorithm. We transmit 800G, 125 Gbaud, 8- and 16-carrier dual-polarization (DP) PCS-QAM over a range of fiber lengths up to 1800 km. We compare against CPR applied independently on the subcarriers, as well as with joint processing, and show significant SNR gains of up to ∼0.5 dB at the optimum launch power.

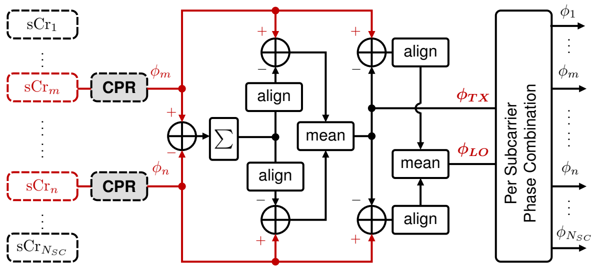

Fig. 1: Simplified block diagram of the DRS algorithm.

Algorithm Description

In Fig. 1 a simplified illustration of the DRS operation principle is shown. The detailed description can be found in[8],[9] and will not be repeated here, for the sake of brevity. The basic idea is to first separately estimate the phase noise associated with the transmitter and local oscillator (LO) lasers (ϕ_{TX} and ϕ_{LO}, respectively), using two reference subcarriers and pilot-based CPR, by taking advantage of the delays imposed by CD. Having achieved the separation of these two phase noise processes, the phase noise estimates of individual subcarriers are re-

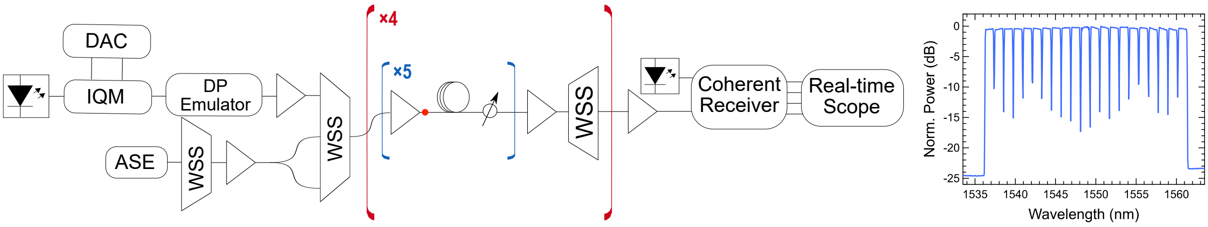

Fig. 2: Experimental setup of the 21×125 GBaud WDM PCS-64QAM multi-carrier transmission system. An example transmitted optical spectrum is also shown.

constructed from the combination of ϕ_{TX} and ϕ_{LO}, which are time-aligned appropriately to account for the CD-induced (frequency-dependent) group delays. Compensation is then performed on a per-subcarrier basis.

Experimental Setup

The experimental setup of Fig. 2 was used to evaluate the transmission performance of the CPR algorithms. A 125 Gbaud MC PCS-64QAM signal was generated with a 2-channel 128 Gsample/s DAC. QPSK pilots were inserted at regular intervals between the data symbols, with the pilot rate per subcarrier depending on the MC configuration (8 or 16 carriers) and the CPR algorithm considered. Taking into account ~3% pilot overhead (constant for all cases), and assuming a 25% FEC overhead, a net bitrate of 800 Gbit/s was achieved with an entropy of 4.5 bit/symbol/polarization. Digital and optical pre-emphasis compensated for transceiver bandwidth limitation. After amplifying the driving signals, the optical carrier generated by a ~150 kHz laser was modulated by an IQ modulator. The DP signal was created via emulation.

The channel under test (CUT) was launched into the fiber along with 20 channels (10 on each side, 150 GHz spacing); these were emulated using an ASE noise source and a wavelength selective switch to achieve spectral shaping similar to that of the CUT. The transmission setup consisted of a straight line with 4 sections of 5 spans each. The spans were 80 km long for sections 1 and 4, and 100 km for sections 2 and 3. The dispersion values were 7000, 17700, 28800, and 33900 ps/nm after 400, 900, 1400 and 1800 km of fiber. After polarization-diversity coherent reception with a local oscillator laser of ~150 kHz linewidth, the digitized signals were processed with DSP that included CD compensation, adaptive equalization, frequency offset compensation, carrier phase recovery, and post-equalization.

The performance of three pilot-based CPR approaches was compared: (i) standard per-subcarrier processing; (ii) JCPR; and (iii) DRS. The JCPR was implemented according to[7], where a common phase noise for all the subcarriers was obtained by the averaging of the individual phase noise estimates. In the case of the DRS algorithm, two reference subcarriers were selected to perform the estimation; their positions were chosen to maximize the overall performance. For a fair comparison, the same overall pilot rate of 1/32 was used in all cases. For the DRS, which has pilots on only two of the subcarriers, the pilot rate on these reference subcarriers was set to 1/8 and 1/4 (for the 8 and 16 carrier cases respectively) in order to keep the overall overhead of the MC scheme the same. For all considered CPR algorithms, the averaging filter length was optimized for each subcarrier.

Results and Discussion

The performance was assessed in terms of effective SNR. Note that, while in our long-haul transmission scenario there was little noise coloring within the CUT bandwidth, the SNR per subcarrier may still vary. Therefore the meaningful metric to use here is the Global SNR, which is given by $[\prod_{n=1}^{N}(1+SNR_n)]^{1/N}-1$, for an N-carrier system. It is directly related to the achievable capacity of the MC system[4].

Figures 3 (a) and 4 (a) present the evolution of the SNR as a function of total launch power for a transmission distance of 1800 km, with 8 and 16 carriers respectively. The optimum launch power is observed at 19 dBm. The DRS clearly outperforms per-subcarrier processing and JCPR, both in the linear and nonlinear operating regions. At optimum launch power for the 1800 km case, we obtained an achievable rate (GMI-based) of ~850 Gbit/s with DRS, and <800 Gbit/s with either JCPR or per-subcarrier CPR, highlighting the importance of using DRS in our long-haul 800G scenario, including some margin for non-ideal FEC. On the other hand, we see that JCPR achieved a slightly higher SNR performance than per-subcarrier CPR, only for the 16-carrier case, due to the lower baudrate per subcarrier.

In order to obtain a clear understanding of

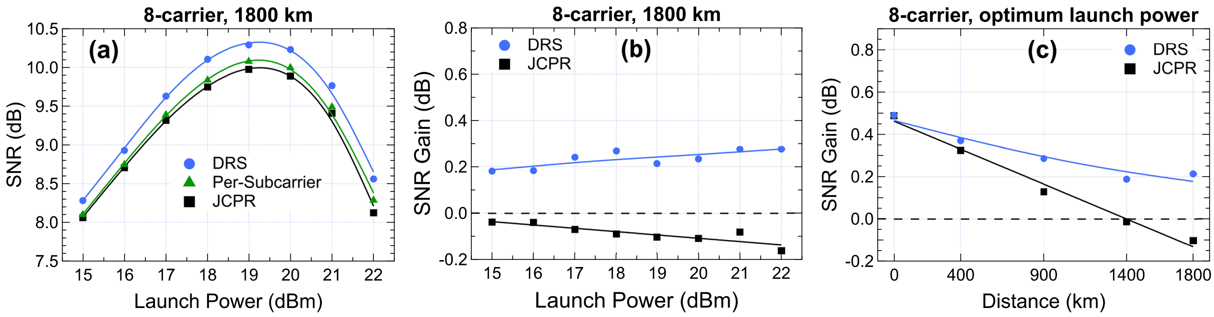

Fig. 3: Performance of DRS, per-subcarrier and JCPR for an 8-carrier system: (a) SNR vs launch power (after 1800 km); (b) SNR gain w.r.t. per-subcarrier as a function of launch power (after 1800 km); (c) SNR gain as a function of transmission distance.

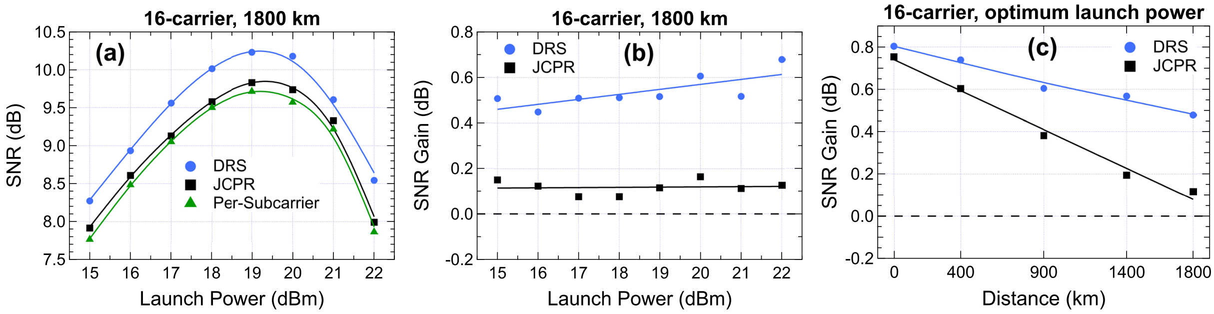

Fig. 4: Performance of DRS, per-subcarrier and JCPR for a 16-carrier system: (a) SNR vs launch power (after 1800 km); (b) SNR gain w.r.t. per-subcarrier as a function of launch power (after 1800 km); (c) SNR gain as a function of transmission distance.

the performance dependency on launch power, Figs. 3 (b) and 4 (b) show the SNR gains of DRS and JCPR, calculated with respect to the per-subcarrier CPR performance. The DRS exhibits a slightly increasing gain with launch power, whereas the gain of JCPR tends to be constant, or slightly decreasing with higher input power. Indeed, at the optimum launch power, DRS provides an SNR improvement of ∼0.22 dB and ∼0.5 dB for 8 and 16 carriers respectively, and these gains increase to ∼0.3 dB and ∼0.6 dB at the highest launch power (22 dBm). Although further investigation is needed to verify and understand these results, they imply that the DRS not only provides superior tolerance to laser linewidth, but is also more tolerant to nonlinear phase noise. This may prove useful in mitigating the modulation format dependence of nonlinear interference noise, which would, in turn, enable better nonlinear performance for digital MC systems through symbol rate optimization[10],[11].

Finally, we assessed the SNR gain of DRS and JCPR over per-subcarrier CPR, as a function of transmission distance at the optimum launch power, as shown in Figs. 3 (c) and 4 (c). It should be noted that the averaging filter length was optimized for each transmission distance, for all subcarriers. For DRS, the position of the two reference subcarriers was also optimized as a function of distance. As expected, we observe that the gain of JCPR degrades with increasing transmission distance, due to the larger CD-induced walk-off between subcarriers. The benefit of JCPR was obtained for distances up to 1400 km, after which per-subcarrier processing is the better of the two options. Indeed, this issue is what the DRS algorithm is designed to combat: As can be seen, while the SNR gain provided by DRS also degrades with distance, the slope is less steep. Note that the gains shown here also depend on the achieved SNR for each distance, which is of course higher for the shorter distances; as such, the gain vs. distance plots are a product of multiple effects, and thus we would not expect the DRS gain plot to be flat.

Finally, it should be noted that the significant gains of the DRS come at a small price in terms of complexity; as discussed in[9], it mostly comprises of a few additional signal delays, additions and subtractions.

Conclusion

We have experimentally demonstrated transmission-aware carrier phase recovery in a 21×125 Gbaud WDM PCS-64QAM multi-carrier transmission system. The DRS algorithm takes the effects of CD into account, enabling improved joint processing of the subcarriers. Significant performance improvement with respect to per-subcarrier processing is obtained, with ∼0.22 dB and ∼0.5 dB SNR gains at the optimum launch power after 1800 km transmission, for 8 and 16 carriers, respectively.

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