On the Performance of Super-Symbol PCS-QAM Digital Subcarrier Multiplexing in Coherent Optical Fiber Systems

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Abstract *We experimentally assess the use of super-symbol (SUP) transmission with different distribution matching methods in a 100 GBd PCS-256QAM digital subcarrier multiplexing system. We achieve 0.1 dB SNR improvement after 900 km, a gain which comes almost for free due to the low complexity of SUP. ©2022 The Author(s)*

Introduction

Employing short blocklength probabilistic constellation shaping (PCS) has been shown to provide better nonlinear tolerance in optical transmission systems, while also being more hardware implementation-friendly[1]. However, shortening the blocklength incurs a rate loss, therefore decreasing the achievable information rate (AIR). Various shaping architectures have been proposed to reduce the rate loss, e.g.[2]–[4]. Among them, enumerative sphere shaping (ESS) provides a relatively low rate loss compared to constant composition distribution matching (CCDM) in the short blocklength regime (Fig. 1(a)).

An innovative method termed super-symbol (SUP) transmission has recently been proposed to improve the nonlinear performance of single-carrier PCS-QAM[5]: a block of consecutive symbols from the distribution matcher (DM) is mapped across all four quadrature and polarization components of the QAM signal; therefore, a lower effective DM blocklength is achieved without sacrificing AIR, thus improving its temporal characteristics, and increasing nonlinearity tolerance.[1]. The technique was experimentally investigated in single-carrier PCS-64QAM transmission, yielding a required optical signal-to-noise ratio (ROSNR) gain of 0.5 dB after 1000 km transmission at 22.5 GBd. The same study showed that the gain is reduced (and eventually may vanish) with increasing symbol rate. An obvious way to overcome this limitation is to apply SUP to digital subcarrier multiplexing (SCM), where each optical wavelength carries several subcarriers, with symbol rates closer to that which maximizes nonlinear performance. It also provides an extra dimension in frequency over which DM symbols can be distributed, further lowering the effective blocklength for potentially even better performance. Indeed, this has been studied in numerical simulations, but never experimentally: in[6],[7] SNR gains of ∼0.2-0.3 dB were shown for 8-carrier 70 GBd CCDM-based PCS-64QAM and 4-carrier 40 GBd ESS-based PCS-64QAM. However, simulations neglect some practical implementation aspects of impairments present in real-world systems, and thus present a more optimistic view of what can be achieved in practice.

In this paper, we conduct the first ever experimental performance comparison of different DM mapping strategies for SCM signals. High baudrate, 100 GBd, PCS-256QAM in a 9-channel wavelength-division-multiplexing (WDM) configuration over 900 km is considered. Compared to long-blocklength CCDM, an improvement of ∼0.1 dB in effective signal-to-noise ratio (SNR) is achieved for 8-carrier 256-blocklength SUP, regardless of DM method.

Super-Symbol (SUP) Principle

We follow the convention in[5] to describe the symbol arrangements over the quadratures (I, Q) and polarizations (X, Y), and M subcarriers (in the case of M-SCM). Namely, we refer to traditional mapping of CCDM or ESS symbols as RND, where *independent* shaped sequences are

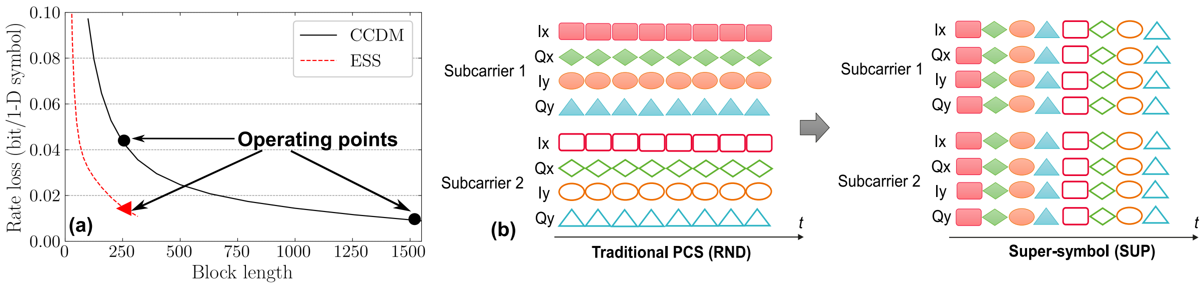

Fig. 1: (a) Rate loss versus block length; (b) Super-symbol illustration with 2 subcarriers.

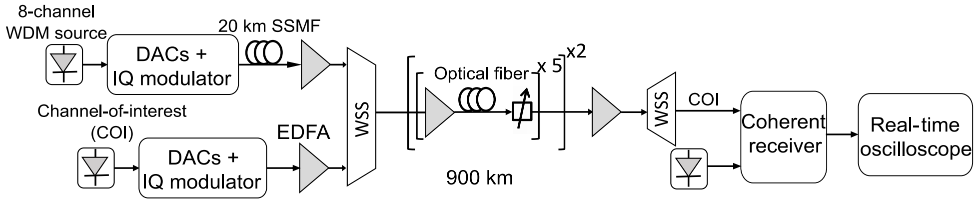

Fig. 2: Experimental setup.

mapped onto each quadrature, polarization and subcarrier (see the RND signal in Fig. 1(b)). SUP CCDM (or ESS) signals are those where a *single* shaped sequence of length n is distributed across all quadrature, polarization and subcarrier tributaries (SUP signal in Fig. 1(b) as an example with 2-SCM). The blocklength per quadrature is hence reduced by $n/(4 \cdot M)$. As a consequence, the temporal length of the output SUP-shaped sequences and the number of sequences simultaneously interacting during propagation are reduced, potentially bringing benefits in terms of nonlinear performance. As the above procedures are a simple redistribution of the symbols, the same power efficiency and linear performance are achieved for both RND and SUP signals. Note that with SCM, we can choose to exploit less dimensionality to organize the shaped sequences by distributing over subsets, as in[6]. For sake of simplicity, we focus on the performance comparison between RND and SUP where we make use of all dimensions for the mapping of symbols.

Experimental setup

Figure 2 presents the experimental setup used for performance evaluation of the 9-channel WDM system transmitted over 900 km. We generate a channel of interest (COI) of 100 GBd dual-polarization (DP) PCS-256QAM single-carrier or 8-carrier, using a 120 GS/s arbitrary waveform generator (AWG). An entropy of 6.125 bit/2D symbol is set to achieve 861 Gbit/s net capacity (taking into account 5% pilot, protocol and 25% forward-error-correction (FEC) overheads). A 0.02 roll-off factor root raised cosine filter is used to spectrally shape the signal. The electrical signals are amplified and modulated onto a low-linewidth continuous-wave (CW) laser by a DP-IQ modulator. The COI is merged with 8 interfering (INT) channels, (4 on each side, spaced at 125 GHz) and launched into the fiber. To emulate the INT channels, a second transmitter is used to modulate multiple CW lasers. The COI and interfering channels carry the same data; thus, a 20 km standard single-mode fiber (SSMF) is placed at the output of the INTs-generating modulator for decorrelation, before multiplexing to form the 9-channel WDM signal. We then launch the signal into the transmission link[8], composed of 2 sections with 5 spans each: 80 km SSMF and 100 km pure-silica core fiber (PSCF) spans are used for the first and second sections, respectively. At the receiver, we extract the COI by a wavelength selective switch (WSS) before mixing with a CW laser in a polarization-diversity coherent receiver. The signals are digitized by a real-time scope and the performance is assessed after digital signal processing (DSP) that includes chromatic dispersion (CD) compensation, pilot-aided adaptive equalization, frequency and carrier phase recovery (CPR). For assessment of the 8-carrier signal, we use the global-SNR[9] metric, which is valid for any number of carriers (including single). For simplicity, we use the term ‘effective SNR’ for both 8-carrier and single-carrier cases: SNR$_{eff} = \left(\prod_{n=1}^{N}(1+SNR_n)\right)^{1/N} - 1$, where N is the number of subcarriers and SNR_n is the n-th subcarrier SNR. Note that in the case of $N = 1$, it is simply equal to the single-carrier SNR. Finally, AIR[2] is also used to quantify the performance.

Results and Discussion

We assess the performance gain of SUP over RND sequences, both numerically and experimentally. CCDM sequences are generated with blocklengths of 256 (CCDM256) and 1536 (long CCDM), whereas the blocklength of ESS is set to 256 (ESS256). ESS256 ensures a rate loss approximately equal to that of long CCDM (Fig. 1(a)), while retaining the good nonlinear performance associated with short blocklengths (similar to that of CCDM256 signals). The simulations have been carried out using the split-step Fourier method (SSFM).

Figures 3(a) and (b) present the simulation results for 1- and 8-carrier respectively. In contrast to previous studies[5],[7], we use up to 9-channel WDM and higher span loss ($>$20 dB), which is more realistic for deployed systems. We also operate at a higher baudrate close to that of modern commercial systems. Thus the symbol period is shorter, and the memory induced by CD is much larger than the DM blocklength. It follows that the temporal reduction of SUP brings almost no gain versus RND signals in single-carrier systems for such a symbol rate ($<$0.05 dB in Fig. 3(a)). Taking the performance of RND long CCDM as a benchmark, a 0.1 dB gain comes from the use of a short DM blocklength. SCM has a lower baudrate per subcarrier and, as expected, SUP exhibits a larger SNR gain against RND long CCDM

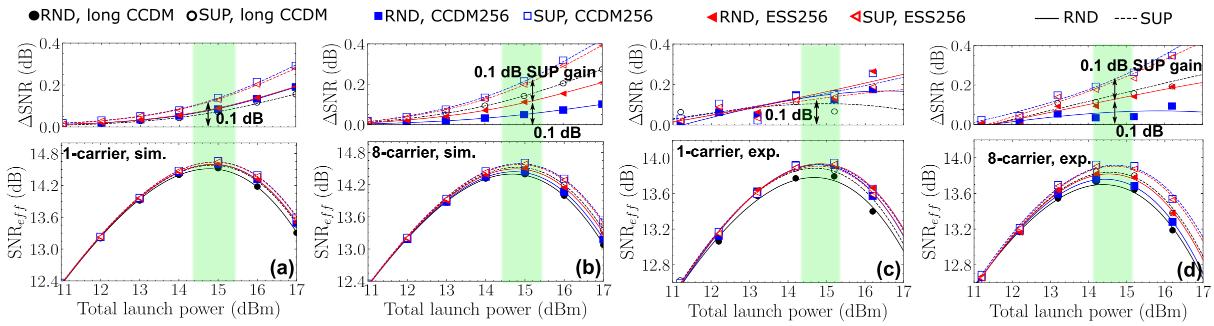

Fig. 3: Effective-SNR versus launch power after 900 km: Simulation (a, b) and experimental (c, d) results of 1- and 8-carrier. Top figures are the SNR difference of various mapping/DM strategies, w.r.t. SNR of RND, long CCDM method.

(Fig. 3(b)). For instance, SUP ESS256 brings 0.2 dB gain versus RND long CCDM, and this can be broken down into ∼0.1 dB gain from the use of short blocklength and ∼0.1 dB gain from the use of SUP. Figs. 3(c) and (d) show the experimental results for the corresponding 1- and 8-carrier signals. The achieved gains versus RND long CCDM match the ones predicted in simulations, confirming that, unlike the single-carrier counterpart, the extension of SUP for 8-carrier results in a non-negligible advantage.

To exclude the possibility that the observed gains are within the range of measurement error, we first evaluate the uncertainty by averaging over 5 data sets for each measured point close to the optimal launch power. It is shown that <0.02 dB variation is observed from the standard deviation error regardless of DM/mapping methods. As the measurements can be severely impacted by the variation of launch powers, we then evaluate the root-mean-square error (RMSE) of the measured values vs. fitting values. It reveals that less than 0.05 dB RMSE is observed, confirming that the conclusions drawn are valid.

However, the SNR increase does not generally mean the increase of AIR, as it also depends on the rate loss of each DM. We present in Figs. 4 and 5 the measured AIR of single- and 8-carrier, respectively. For single-carrier, as the SNR gain of SUP shown in Figs. 3(a) and (c) is very small, almost no AIR gain is observed. It is worth mentioning that the AIRs of ESS and long CCDM are similar, while CCDM256 exhibits a smaller AIR due to the high rate loss (Fig. 1(a)). For 8-carrier at the optimum launch power, the 0.2 dB SNR gain of SUP translates to ∼0.1 bit/4-D symbol AIR gain. The SUP gain is retained for ESS256 due to its low rate loss. Hence, ESS is a good candidate to maintain the advantage of short blocklengths, while still achieving linear performance similar to that of long CCDM (and therefore an overall increase in AIR after transmission). Note that SUP can be employed to provide an extra gain when applied to SCM signals, with little additional cost.

Conclusions

We have conducted the first experimental assessment of the gain when using SUP for digital multi-carrier signals. At high baudrate per optical channel, SUP is more beneficial for SCM than single carrier. Numerical and experimental results with 100 GBd single- and 8-carrier PCS-256QAM transmitted over 900 km confirm that SUP provides ∼0.1 dB SNR gain regardless of the DM method in the SCM case. Even if the gain is relatively low, SUP comes almost for free in terms of hardware complexity, making it an obvious technique to use for long-haul SCM systems.

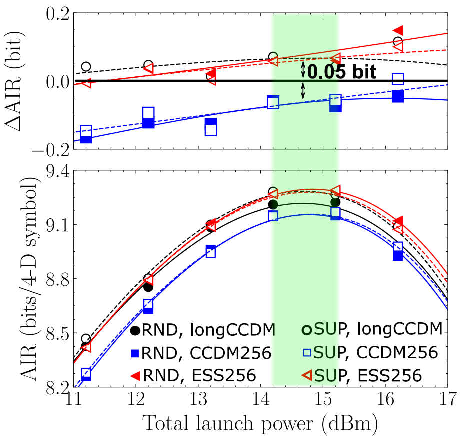

Fig. 4: AIR versus launch power of 1-carrier. Top figure is the AIR difference w.r.t. to that of RND, long CCDM method.

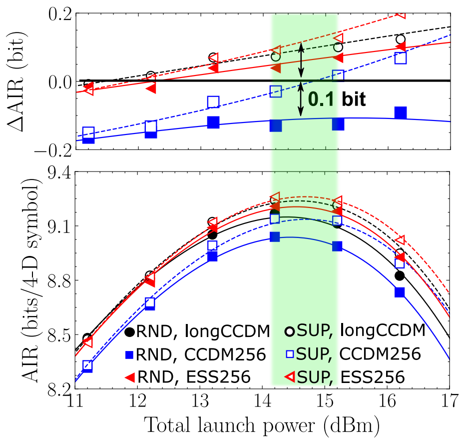

Fig. 5: AIR versus launch power of 8-carrier. Top figure is the AIR difference w.r.t. that of RND, long CCDM method.

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