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WSS Filtering Penalties with Bandwidth-Variable Transceivers: On the Debate Between Single- and Multi-Carrier

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Abstract *We experimentally compare the WSS filtering tolerance of single-carrier (SC) and digital subcarrier multiplexing (DSCM) at 95–105 Gbaud. Whereas DSCM tends to be advantageous when using excessive baudrates, the two modulation options yield similar performance if the baudrate is optimized.*

Introduction

The transmission performance in metro optical networks is largely determined by the impact of optical filtering imposed by inline wavelength selective switches (WSS). Many recent studies have been devoted to the modeling and mitigation of these filtering effects, which generate strong inter-symbol interference (ISI)[1]. In traditional systems employing uniform QAM, it has been shown that multi-carrier modulation, namely implemented through digital subcarrier multiplexing (DSCM), provides significant gains over single-carrier (SC) transmission, owing to its frequency diversity that allows to perform bit and/or power-loading among subcarriers to adjust the signal to spectral shape imposed by the WSS cascade[2]. However, with the commercial dissemination of probabilistic constellation shaping (PCS), a quasi-continuous bit-rate granularity can be achieved even in SC signals[3]. When the PCS granularity is associated with the paradigm of bandwidth-variable transceivers[4], where the transmitted symbol-rate can be digitally reconfigured within a given range, it has been shown that the resilience towards WSS filtering can be significantly enhanced[5],[6]. Following these recent reports, it remains an open question whether the transmission performance can still be further improved through the use of DSCM together with PCS modulation and bandwidth-variable transmission.

In this work, we provide a detailed experimental comparison between the WSS filtering resilience of baudrate-optimized and entropy-loaded SC and DSCM signals. Experiments are performed for baudrates in the range of 95–105 Gbaud, with the signal passing through a 2040 km straight line of fiber and up to 18 inline WSSs. In general, it is demonstrated that, if the transceiver is able to coarsely adjust the baudrate, the two modulation strategies tend to yield similar results. However, if an excessive baudrate is imposed by the system, DSCM can provide some enhanced performance.

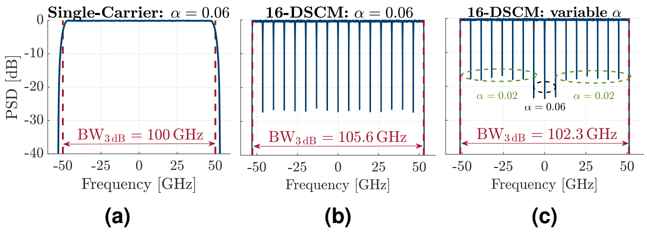

Fig. 1: Spectral shaping and 3-dB bandwidth comparison between SC and 16-DSCM (with fixed and variable roll-off) for 100 Gbaud transmission.

Simulation Performance Comparison

For the following simulation analysis, we consider transmission baudrates in the range of 92.5–110 Gbaud in steps of 2.5 Gbaud. SC is compared against DSCM with two different number of subcarriers (8 and 16). A roll-off factor, α, of 0.06 is applied to the SC signal, whether two possible approaches are considered for the DSCM signal: i) fixed roll-off ($\alpha = 0.06$) assigned to all subcarriers, and ii) variable roll-off assignment, with $\alpha = 0.06$ for the two central subcarriers (reserved for clock recovery implementation[7]) and $\alpha = 0.02$ for the remaining ones. An example of the respective spectral shaping is shown in Fig. 1 for 100 Gbaud transmission, where the 3-dB bandwidth of each signal is also indicated. At 0.06 roll-off factor, it becomes clear that the considered DSCM configuration is roughly 5% less bandwidth efficient than SC, which might lead to higher filtering-induced power loss. Nevertheless, this excess bandwidth can be reduced to about 2% when employing a practical variable roll-off assignment strategy[7].

For the numerical evaluation of WSS filtering impact, let us consider periodic amplification using an erbium-doped fiber amplifier (EDFA) with amplified spontaneous emission (ASE) noise insertion occurring after every WSS. The system is simulated with a launch power of 0 dBm. Fur-

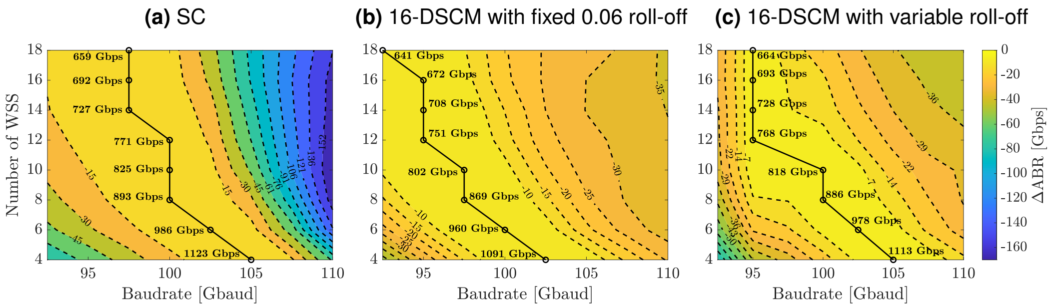

Fig. 2: Simulated achievable bit rate of a (a) SC, (b) 16-DSCM with fixed roll-off and (c) 16-DSCM with variable roll-off signals for a set of baudrates and number of WSSs.

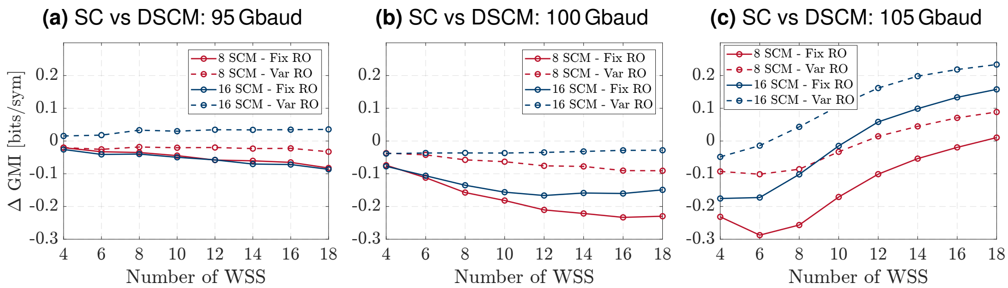

Fig. 3: ΔGMI versus number of WSSs for signals with (a) 95 Gbaud, (b) 100 Gbaud and (c) 105 Gbaud.

thermore, two fiber spans with 20 dB loss are inserted in between the inline WSSs. The bandwidth of each WSS is 112.5 GHz. In the contour maps of Figs. 2 (a), 2 (b) and 2 (c), we can observe the variations of bit rate as a function of the number of WSS filters and transmission baudrates for SC and 16-DSCM, using as a reference the maximum achievable bit rate (ABR) obtained at the optimum baudrate (highlighted by the black solid line with circle markers). The ABR is calculated as, $\mathrm{ABR} = 2R_{\mathrm{s}}\mathrm{GMI}$, where GMI is the generalized mutual information (GMI) and R_{s} the symbol-rate. From the analysis of the contour maps, two main observations shall be highlighted to help settling the debate between SC and DSCM in WSS-impaired optical systems:

i) at the optimal baudrate, SC and DSCM with variable roll-off are almost equivalent in terms of achievable bit rate. However, if the same 0.06 roll-off is applied to all DSCM subcarriers, a slight (2–3%) but consistent ABR loss is observed, which is caused by higher WSS-induced power loss on the edges of the DSCM signal, as shown in Fig. 1. It therefore becomes clear that baudrate optimization plays the central role in WSS filtering mitigation, whereas only slight performance fluctuations can be attributed to these different modulation options.

ii) if baudrate optimization is not permitted (or hardware-limited) by the coherent transceiver, then it is relevant to observe that SC might show significant performance penalties when operating at excessive baudrates, as clearly seen in the right-upper part of Fig. 2 a). This is due to the impossibility of performing frequency-resolved entropy allocation in SC signals. In contrast, DSCM can inherently adapt to these extreme filtering scenarios, by simply reducing the entropy on the edge subcarriers down to the limit of even discarding them.

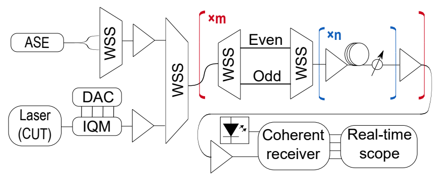

Fig. 4: Diagram of the experimental setup for the WSS system.

To complement this analysis, in Fig. 3 we show a direct comparison between the GMI of SC and DSCM signals, $\Delta\mathrm{GMI} = \mathrm{GMI}_{\mathrm{DSCM}} - \mathrm{GMI}_{\mathrm{SC}}$, at 95, 100 and 105 Gbaud. Once again, these results clearly show that SC and variable roll-off DSCM tend to be almost matched in terms of performance if the operating baudrate is close to the optimum (with a trend for a slight SC advantage of less than 0.1 bpcu, see Figs. 3 a) and b)), whereas DSCM starts to become more advantageous when the baudrate is overly increased in strong filtering scenarios (see Fig. 3 c)).

Experimental Setup

Figure 4 shows a block diagram of the experimental setup. A DAC operating at 120 Gbaud was used to generate either SC or DSCM signal with PCS-64QAM whose entropy was adapted to

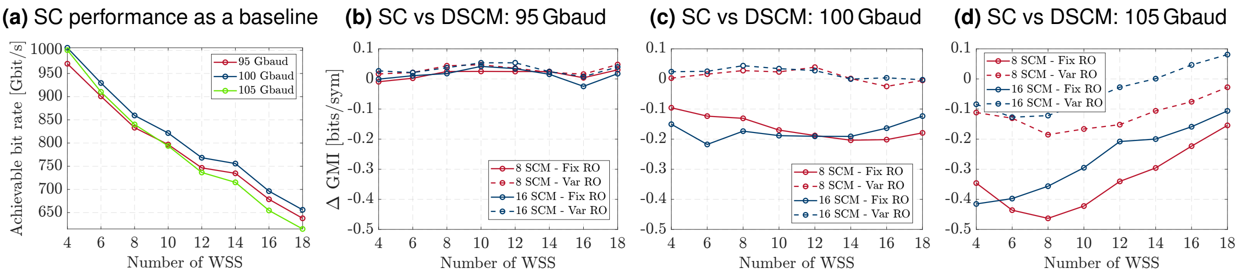

Fig. 5: Experimental results, including (a) the achievable bit-rate with SC transmission and $\Delta\mathrm{GMI}$ versus number of WSSs for signals with (b) 95 Gbaud, (c) 100 Gbaud and (d) 105 Gbaud.

for the different SNRs. Three different baudrates were selected based on the previous simulation data: 95, 100, and 105 Gbaud. The signal was combined with ASE noise shaped as $\sim$100GHz bandwidth in order to emulate a total of 21 WDM channels spaced by 112.5 GHz.

Each section is composed of an initial EDFA followed by two WSSs, in which filtering could be configured by diving the spectrum into even and odd channels in the first WSS and combining them in the second WSS. The remaining of each section containing several spans, making a total of 25 spans. Using a variable optical attenuator (VOA), the span loss was configured between 20 and 23 dB based on the EDFA capabilities. After transmission, another WSS was used to demultiplex our channel of interest, making a total of 18 WSS for the 8 sections (2 WSS per section, 1 WSS to combine signal with ASE, and the demultiplexing WSS).

At the receiver side, the signal was mixed with the local oscillator and detected in a real-time scope after coherent detection. Offline DSP included chromatic-dispersion compensation, frequency-domain equalization, frequency and carrier recovery and post-equalization.

Experimental Validation

The obtained experimental results are presented in Fig. 5, where we start by characterizing the achievable bit rate of the SC signal versus number of WSSs for the 3 tested baudrates (see Fig. 5 a)). For the full range of WSS filtering, we verify that the ideal baudrate is achieved at 100 Gbaud, producing the highest achievable bit rate. The interplay between baudrate and WSS filtering can be observed by the crossing of the 95 Gbaud and 105 Gbaud curves after about 10 WSS filters. We should however note that, in the experiment, 105 Gbaud is also affected by the transceiver bandwidth limitation, which mainly dominates at low number of WSSs.

The $\Delta\mathrm{GMI}$ between SC and DSCM is depicted in Figs. 5 (a), 5 (b) and 5 (c), as a function of the number of WSSs for 95, 100 and 105 Gbaud, respectively. In general, we can observe a good agreement with the simulation results presented in Fig. 3, where the same trends can be identified:

i) at low baudrate, i.e. 95 Gbaud, the impact of WSS filtering is almost negligible, and therefore $\Delta\mathrm{GMI}$ stays within less than ± 0.05 bpcu;

ii) at the optimum baudrate, i.e. 100 Gbaud, SC and DSCM are roughly compatible if DSCM is designed with the variable roll-off of Fig. 1 c). Instead, if fixed 0.06 roll-off is utilized, the extra bandwidth consumption of DSCM leads to about 0.1–0.2 bpcu loss.

iii) at excessive baudrate, i.e. 105 Gbaud, there is a general trend for DSCM to recover from its initial loss at low-to-moderate optical filtering, starting to pay-off after about 14 WSSs, with 16-DSCM assisted by variable roll-off leading to $\sim$0.1 bpcu gain after 18 WSSs.

Conclusions

With many coherent transceiver manufacturers making their bets on either single- or multi-carrier transmission, a heated discussion on the merits of these different modulation options is being recurrently brought to light, namely regarding their eventual robustness to tight optical filtering. In this work, we have tried to enlighten this debate by carrying out a detailed comparison on the WSS filtering resilience of SC and DSCM modulation options. The main takeaway message is that baudrate optimization plays the key role in minimizing WSS filtering penalties, whereas only slight performance gaps between SC and DSCM are expected if the baudrate is not too far (roughly within $\pm$5%) from the optimum. However, in the case of excessive baudrate ($>$10% above the optimum), DSCM can effectively lead to enhanced performance, owing to its frequency diversity feature that inherently provides some degree of baudrate adaptation.

Acknowledgements

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