Low-Complexity Frequency Packing to Enable Filtering-Tolerant DSCM Transmission

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Abstract: Employing optimized frequency packing over digital subcarrier multiplexing (DSCM), we exploit the mitigation of WSS filtering penalties. After transmitting a 60 Gbaud 8-DSCM with 0.2 roll-off over 5-10 WSSs, we experimentally demonstrate OSNR gains of >3 dB, without additional DSP complexity.

1. Introduction

Owing to their reduced baud rate per subcarrier, digital subcarrier multiplexing (DSCM) systems are known to provide superior network flexibility and physical layer resilience towards linear and nonlinear fiber impairments [1]. However, to avoid inter-subcarrier channel interference (ICI), DSCM requires a wider bandwidth occupation, mainly when the minimum pulse shaping roll-off is limited by practical DSP constraints. This might become a major limitation when the signal has to pass over multiple reconfigurable optical add-drop multiplexers (ROADM) that utilize wavelength selective switches (WSS) to drop channels optically [2, 3, 4].

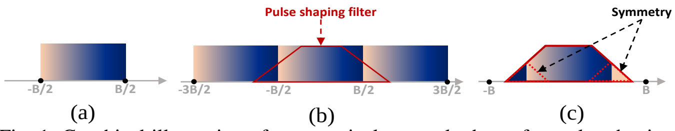
To address this issue, in wavelength division multiplexing (WDM) superchannel transmission, various approaches exploiting faster-than-Nyquist (FTN) signaling have been proposed [5, 6, 7]. These methods involve densely packed symbols and channels in both time and frequency domains, a technique known as time-frequency packing (TFP). However, dealing with the adverse effects of inter-symbol interference (ISI) and ICI due to this tight packing demands complex DSP at the receiver end [5, 8, 9]. Furthermore, there is presently a lack of research specifically focused on utilizing these TFP techniques in the context of DSCM systems. It is important to highlight that ISI effects arising from time packing necessitate more intricate DSP processes, involving feedback after forward error correction (FEC) [5, 8, 9]. Therefore, in this study, we focus solely on digital frequency packing within the DSCM system, eliminating the necessity for post-FEC feedback. This approach allows for simpler solutions that can seamlessly integrate with an existing DSP framework.

In this work, we exploit the digital frequency packing to mitigate the impact of WSS filtering penalties in DSCM systems. Importantly, it's worth mentioning that employing digital frequency packing doesn't entail any additional complexity in the DSP setup. We conducted an experimental analysis, evaluating the transmission of a 60 Gbaud signal at 400 Gbps (with 20% FEC overhead) through a sequence of cascaded 75 GHz WSS filters. We experimentally demonstrate that significant optical signal-to-noise ratio (OSNR) gains of more than 3 dB can be achieved when using DSCM with 0.2 roll-off, without any modification to the DSP stack. Further gains of up to 1 dB can be achieved by using a joint subcarrier equalizer (JSE), with incremental DSP complexity.

2. Frequency Packing & Joint Subcarrier Equalizer

To mitigate the impact of WSS filtering, we adopt a strategy of digital frequency packing, which allows a reduction in bandwidth requirements in DSCM systems. In DSCM signals, the central frequency of the n-th subcarrier can be written as $f_{\mathrm{SC},n} = \Delta f \left(n - \frac{N_{\mathrm{SC}}-1}{2} - 1\right)$, where N_{SC} represents the total number of subcarriers, and Δf represents inter-subcarrier spacing as, $\Delta f = \frac{R_{\mathrm{S}}}{F_{\mathrm{P}} N_{\mathrm{SC}}}(1+\alpha)$, where R_{S} is the symbol-rate, α is the roll-off factor of the pulse shaper, and F_{P} is the frequency packing factor. Note that, $F_{\mathrm{P}} = 1$ corresponds to the ideal ICI-free condition. Instead, $F_{\mathrm{P}} > 1$ can reduce the DSCM bandwidth, at the expense of ICI caused by partial spectral overlap between subcarrier edges. Subsequently, we briefly discuss the JSE strategy for addressing ICI when $F_{\mathrm{P}} > 1$.

Figure 1 depicts the effects of pulse shaping in communication systems. Fig. 1a illustrates the spectra of the n-th subcarrier at 1 sample per symbol (SPS). Fig. 1b demonstrates the impact of upsampling and pulse shaping operations on the subcarrier. These operations result in symmetrical spectral content at the subcarrier edges, as shown in Fig. 1c. This spectral symmetry serves as redundancy that can be utilized to partially remove the ICI using a JSE approach.



(a) (b) (c)

Fig. 1: Graphical illustration of symmetrical spectral edges after pulse shaping. (a) Signal spectrum at 1 SPS, (b) Upsampling and application of the pulse shaping filter, (c) Spectral symmetry on the edges of the pulse-shaped signal.

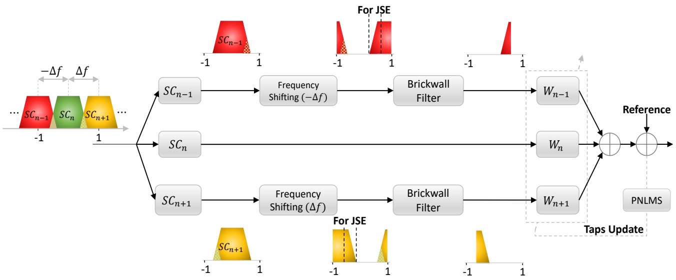


Fig. 2: JSE architecture. PNLMS: Power Normalized LMS

Figure 2 shows the architecture of the proposed adaptive JSE technique operating at 2 SPS. First, subcarrier demultiplexing is performed, wherein each subcarrier is downconverted to the baseband using a sampling rate of 2 SPS. Under the equalization process, SC_n represents the specific subcarrier being processed, while SC_{n-1} and SC_{n+1} refer to the subcarriers on the left and right sides of SC_n, respectively. The success of the equalization relies on the precise alignment of the baseband spectra of the central subcarrier with the adjacent subcarriers. To achieve the spectral components alignment, the baseband spectra of the adjacent subcarriers SC_{n-1} and SC_{n+1} are shifted by $-\Delta f$ and Δf, respectively. To mitigate equalizer-noise enhancement, both adjacent channels are subjected to a brickwall filter to provide only overlapped information to the JSE, significantly reducing its implementation complexity when implemented in the frequency domain. Notice that, the JSE utilizes the symmetrical edges located on the opposing side of the overlapping edges. Finally, the equalizer coefficients within each branch (W_{n-1}, W_n, and W_{n+1}) are adjusted to function as an adaptive equalizer. Also, notice that if we remove the W_{n-1} and W_{n+1} filter branches depicted in Fig. 2, we obtain the conventional per-subcarrier equalizer (PSE) utilized in present-day DSCM systems.

3. Experimental Setup

Figure 3 shows the experimental setup, where the electrical signal is generated by a Keysight M8194A arbitrary waveform generator (AWG) with 45 GHz bandwidth and 120 Gsa/s sampling rate. Subsequently, the information signal is modulated using a polarization-multiplexing IQ modulator (PM-IQM) with a bandwidth of ∼35 GHz and a tunable laser (13 dBm output power and 100 kHz linewidth), then amplified using an Erbium-doped fiber amplifier (EDFA). To emulate the optical filtering effects caused by the cascaded WSS filters operating in a 75 GHz slot, a Finisar WS4000S waveshaper is used. The experimental analysis adjusts the OSNR condition through amplified spontaneous emission (ASE) noise loading after WSS optical filtering, representing a worst-case scenario. The OSNR value is adjusted using a variable optical attenuator (VOA) and an optical spectrum analyzer (OSA) in a feedback loop. After detection in a 40 GHz coherent receiver, a Tektronix DPO70002SX real-time oscilloscope (RTO) with 70 GHz bandwidth and 200 Gsa/s sampling rate captures the received signal.

The experimental testbed utilizes MATLAB to implement the DSP and control mechanisms. The transmitter generates 60 Gbaud PCS-64QAM signals with a net bitrate of 400 Gbps (including 20% overhead) and uses root-raised cosine (RRC) pulse shaping with roll-off factors of 0.12 and 0.2. The 400 Gbps transmission scenarios are evaluated during the experiment using 8 subcarriers with varying frequency packing factors. The receiver DSP implements analog front-end correction to compensate for skew, perform orthonormalization, remove DC offset, and apply first-stage frequency offset correction before demultiplexing subcarriers. After subcarriers demultiplexing, a constant modulus equalizer with 30 taps is applied, followed by frequency and phase recovery. Next, an equalizer with 51 taps is used either in per-subcarrier (PSE) or joint-subcarrier (JSE) mode for adaptive equalization.

4. Experimental Results

Figure 4 displays the obtained experimental results categorized into two groups: (i) upper row for 0.12 roll-off factor, and (ii) lower row for 0.2 roll-off factor. Figure 4a presents the collected raw results, in terms of NGMI performance versus OSNR, considering different numbers of cascaded WSS filters, first without frequency packing ($F_P = 1$) and then with optimized frequency packing. Note that, for clarity of presentation, only a few selected curves are shown. From these results, we determine the required OSNR that provides an NGMI above

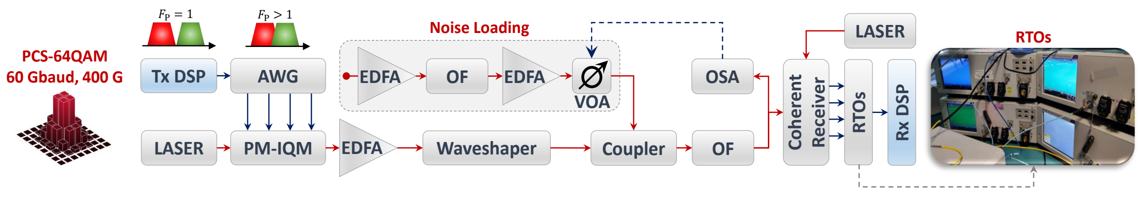


Fig. 3: Experimental setup with worst-case noise loading to evaluate the filtering penalties caused by cascaded WSS. OF: Optical Filter

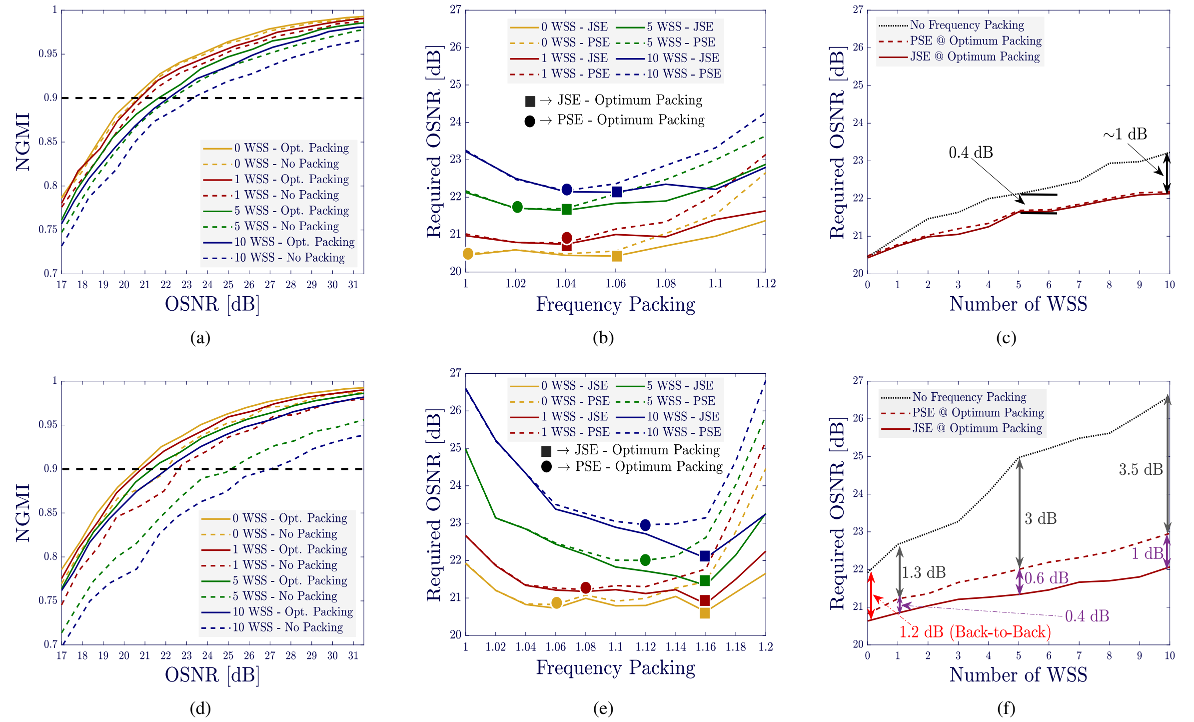


Fig. 4: Experimental results of effects of cascaded 75 GHz WSS filtering with frequency packing. (a)–(c) 0.12 roll-off, (d)–(f) 0.2 roll-off.

the established threshold of 0.9. Then, in the central (b) and (e) and rightmost columns (c) and (f) of Fig. 4, we show how the required OSNR varies with the frequency packing factor and the number of cascaded WSS filters, respectively, for both PSE and JSE methods. Notice that we used the terms 'frequency packing' and 'packing' interchangeably in the paper. From the analysis of these figures, the following main conclusions can be drawn:

i) Figure 4b and 4e depict that the optimum frequency packing factor mainly depends on the utilized roll-off factor, while it seems to be rather insensitive to the number of cascaded WSSs. Furthermore, JSE enables the use of larger frequency packing factors, as the introduced ICI is partially compensated by the equalizer.

ii) Notably, without any dedicated ICI equalization, i.e. using the standard PSE equalizer, we find important OSNR gains (see Fig. 4c and 4f), which are more pronounced both with a higher number of cascaded WSS filters and also with a larger roll-off: up to 1 dB gain is achieved after 10 WSS filters with 0.12 roll-off (Fig. 4c), and more than 3 dB gain is achieved after 5 WSS filters with 0.2 roll-off (Fig. 4f).

iii) The use of JSE instead of PSE is only adequate for large roll-off values. Indeed, we observe that at 0.12 roll-off, no meaningful gap is found between the required OSNR curves of PSE and JSE in Fig. 4c, provided that the F_P factor is properly optimized for both cases. Instead, at 0.2 roll-off (see Fig. 4f), we observe that JSE delivers some additional OSNR gain, starting at around 0.4 dB with 1 WSS filter and opening towards 1 dB after 10 WSS passes. This shows that most of the gain enabled by frequency packing in WSS-impaired DSCM systems can be directly achieved without modifying the legacy DSP stack.

5. Conclusion

The role of digital frequency packing in WSS-impaired DSCM systems has been somewhat overlooked so far, much owing to the additional DSP complexity that is typically associated with this strategy. Nevertheless, we have experimentally shown that in DSCM systems operating at moderate to large roll-offs (0.12 to 0.2 in this work), significant gains in the range of 1–3 dB can be achieved from digital frequency packing without increasing the baseline DSP complexity. Optionally, the use of a low-complexity joint-subcarrier equalizer (JSE) is also shown to be beneficial when the utilized roll-off is in the range of 0.2, providing additional OSNR gains of up to 1 dB.

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