Doubling the ROADM Sites using Pairwise Coding for 4%-Guard-Band Superchannels

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Abstract: We propose pairwise coding to enhance a superchannel's tolerance to non-idea ROADM filtering effect. Experimental results show that the number of ROADMs can be double in links with 4% guard-band superchannels.
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1. Introduction

Optical superchannels provide a promising technique to upgrade high-speed serial interfaces towards 1-Tb/s and beyond [1]. By synthesizing a number of spectrally shaped optical sub-carriers at near Nyquist bandwidth, superchannels realize spectrally-efficient, high-capacity transmission without being limited by electronic bottlenecks. All the sub-carriers within each superchannel are not only transmitted and received together, but also routed as a single entity. To route the very closely spaced optical superchannels with a reconfigurable optical add-drop multiplexer (ROADM), the wavelength selective switch (WSS) filters would ideally have very sharp cut-off response to prevent inter-(super)channel-interference (ICI). However, the typical liquid crystal on silicon (LCoS) based WSS has a spectral roll-off of approximately ten GHz [2]. A recently reported enhanced WSS (EWSS) still leads to about 8% roll-off [3], which causes ICI and eventually limits the achievable system performance.

As non-ideal ROADM filtering mainly affects the spectral edges of the superchannel, the signal-to-interference-and-noise-ratio (SINR) on the edge sub-carriers is often much worse than the sub-carriers that within the flat pass-band of the ROADM filters. This is an analogous situation to frequency selective fading in wireless communication, and so allows fading mitigation techniques to be applied. Pairwise coding has been employed to improve the overall system performance effectively with: sub-carrier fading in direct-detection orthogonal frequency division multiplexing system [4], polarization fading of dual-polarization signals due to polarization dependent loss [5], sub-band fading in superchannel transmission due to the random laser drift [6]. Pairwise coding features zero overhead pre-coding, computationally-efficient decoding and high performance gain over large range of fading values.

In this work, we employ pairwise coding for improved optical superchannel tolerance against effects from non-ideal ROADM filtering. We emulate accumulated ROADM filtering induced ICI by integrating the EWSS function within a recirculation loop, and experimental results show that pairwise coded superchannel is able to tolerate twice the amount of ROADM filtering-induced inter-channel crosstalk, compared with an uncoded superchannel.

2. Superchannel with pairwise coding

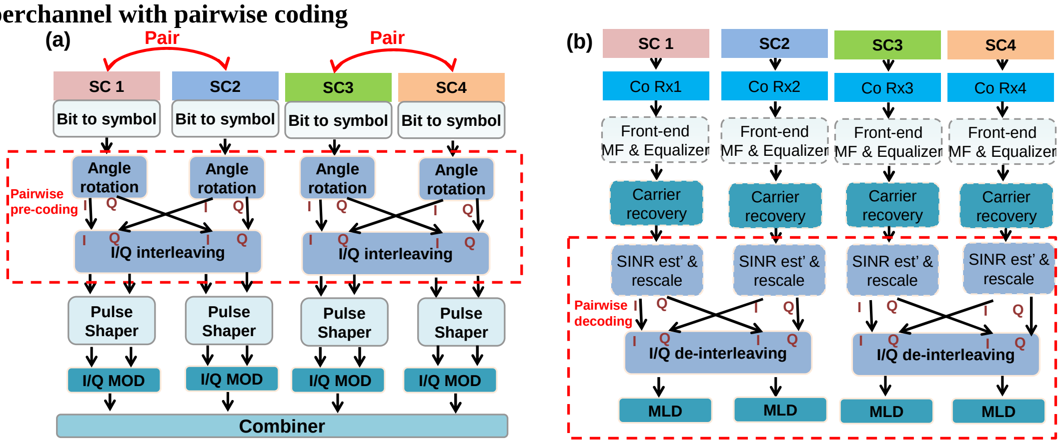

Fig. 1. Structure of the superchannel with pairwise coding at: (a) transmitter and (b) receiver. MF: matched filter.

Figure 1(a) shows the signal generation process of the proposed sub-carrier pairwise coding scheme. Each superchannel has four sub-carriers, which may be modulated onto separate lasers. After bit-to-symbol mapping, the sub-carriers are divided into pairwise groups, each with one edge and one middle sub-carrier, where pairwise pre-coding is applied. For each group, a constant phase shift is first applied to the data symbols, and then the in-phase part of the middle sub-carrier is exchanged with the quadrature component of the edge sub-carrier. The coded symbols of each sub-carrier are then pulse shaped before optical I/Q modulation, and finally all the modulated sub-carriers are combined to form the optical superchannel. Note that the number of sub-carriers within the superchannel can be defined flexibly, the rule for pairwise group design is: group the two sub-carriers with largest SINR difference (ΔSINR) first, and then group the two sub-carriers with second largest ΔSINR, and so on. This will provide the largest coding gain. If sub-carriers with the same SINR are grouped together, there will be – zero coding gain. Pairwise coding is independent of the pulse shaping scheme, e.g. one can choose Nyquist-WDM or OFDM for superchannel generation. For dual-polarization signals, same process is applied separately for two polarizations.

The superchannel reception structure is depicted in Fig. 1(b). Each sub-carrier is received by a coherent receiver, and then front-end correction, matched filtering, equalization and carrier recovery are conducted to recover the signals. Joint pairwise decoding is then performed for each pairwise group: SINR is first estimated for each sub-carrier, which is used to rescale the equalized signals, i.e. multiplying the signals by the square root of SINR. After I/Q de-interleaving, symbol decisions are made based on symbol-by-symbol maximum likelihood detection, which only requires M likelihood calculations for each M-QAM symbol. It is not necessary to have synchronized timing between sub-carriers during modulation and equalization, except that the equalized symbols of the paired sub-carriers have to be synchronized for joint decoding, which can be achieved by pilot based frame synchronization.

3. Experimental demonstration

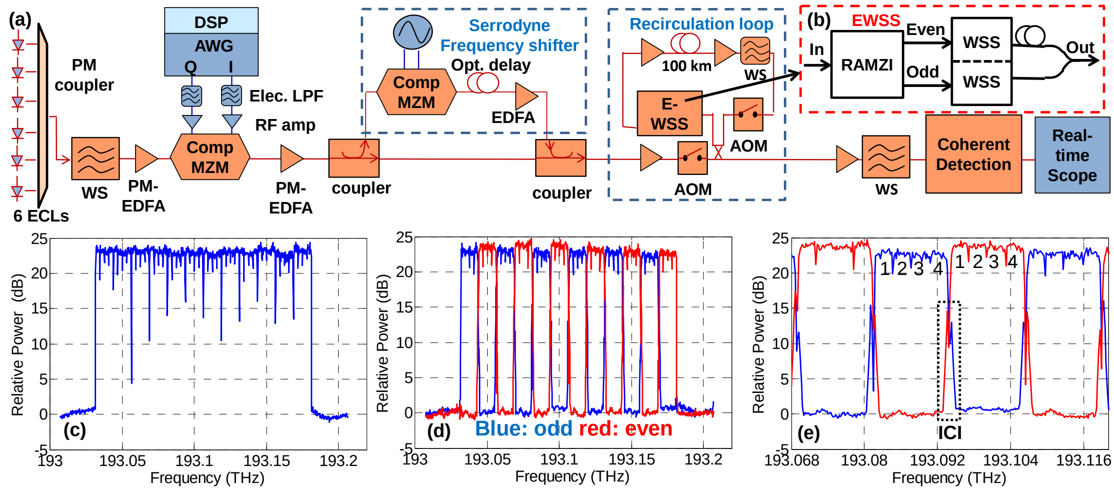

Fig. 2.: (a) Experimental setup, (b) EWSS setup, (c) all superchannels spectrum, (c) odd and even channel spectra after EWSS, (d) zoom in of (c).

The experimental setup is shown in Fig. 2(a). The transmitter comprised of 6 external cavity lasers (ECLs), spaced at 25 GHz, power equalized by a Finisar Waveshaper (WS), and then modulated by electrical signals generated from an Agilent 64 GSa/s DAC. To allow superchannel generation with the equipment on hand, we emulate a 4 sub-carrier superchannel (ideally 4 modulators and lasers) by digitally defining four sub-carriers, modulating a single laser. A 12-Gbaud QPSK (with or without pairwise coding) signal was generated per superchannel (3-Gbaud per sub-carrier), DFT-S-OFDM was used to create near rectangular shape for each sub-carrier [6]. An odd-and-even superchannel structure was achieved by power splitting the 6 modulated superchannels into two arms, delaying one arm and frequency shifting by 12.5 GHz before recombining with the through arm (4% guard band). The spectrum of the combined superchannel is shown as Fig. 2(c). The signals were then launched into a recirculating loop, consisting of two acousto-optic modulators (AOM), one 100-km span of standard single mode fiber, an EWSS for ROADM emulation, a WS for gain flattening and several erbium doped fiber amplifiers (EDFAs). As shown in Fig. 2(b), the EWSS consists of a ring-resonator-assisted MZI (RAMZI) interleaver with a 12.5-GHz free-spectral-range and 8% roll-off to separate the odd and even superchannels, and two 1×12 LCoS-WSSs to perform reconfigurable switching [3]. In this demonstration, the WSS was set to pass all the even/odd channels that are processed. The odd and even channels after the EWSS are then recombined with a 3-dB optical coupler, with the odd channels delayed by ≈10 ns to de-correlate the signals and inter-channel cross-talk. As such, each superchannel experiences the maximum degradation from ICI, which is accumulated loop-by-loop. The odd and even superchannel spectra after EWSS measured with a 15-MHz resolution spectrometer (Agilent 83453B), are shown in Fig. 2(d), with a zoomed-in version in Fig. 2(e), clearly showing that the 8% roll-off of the EWSS exceeds the guard band, leading to ICI on edge sub-carriers of each superchannel. Practically, with a 4×28 Gbaud superchannel targeting 400-Gb/s application, 8% roll-off (10 GHz) is approximately what we would expect from a typical LCoS-WSS [2]. At the receiver, another WS was used to select the channel of interest for coherent detection and sampling. The offline digital signal processing was similar to [6], with extra decoding for the pairwise coded signals.

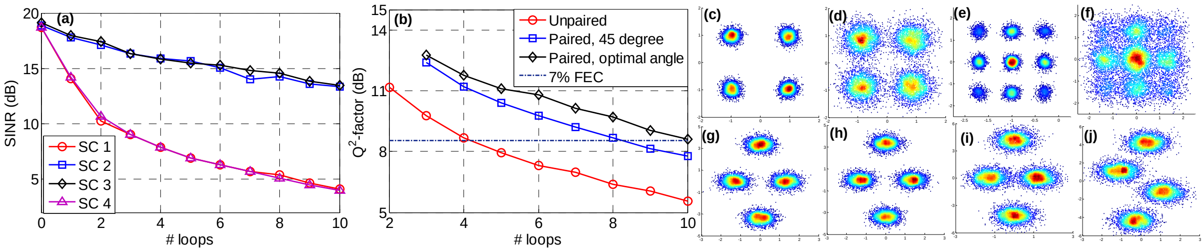

Fig. 3.: (a) Measured SINR, (b) Q^2-factor for different systems, equalized signals after 4 loops for (c),(d) uncoded system and (e),(f) coded system with 45° only, decoded signals with 45° only after (g),(h) 4 loops and (i) 8 loops, (j) decoded signal with optimal angle after 8 loops.

Figure 3 shows the experimental results. The measured SINR for each sub-carrier is shown in Fig. 3(a), based on calculating the variance of recovered signals with respect to transmitted signals. The two edge or middle sub-carriers behave quite similarly as the EWSS has a quite symmetric roll-off response. If the signal propagates through more loops, the ΔSINR increases, due to the accumulated ICI on the edge sub-carriers (1 and 4). The optimal rotation angle for pairwise pre-coding is defined as: $\tan^{-1}[(\Delta SINR-1)-\sqrt{[(\Delta SINR-1)^2-\Delta SINR]}]$ for $\Delta SINR>4.7$ dB and 45° for $\Delta SINR\leq 4.7$ dB [7]. It has also been shown that 45° rotation provides reasonable gain over a wide range of ΔSINRs [5]. The Q^2 results ($Q^2(\text{dB})=20\log_{10}[\sqrt{2}\text{efrc}^{-1}(2\text{BER})]$) based on averaged BER of all sub-carriers for the system with or without pairwise coding are depicted in Fig. 3(b), only BER>10^{-5} is shown in this experiment, which occurs after 2 loops for uncoded system and 3 loops for coded system. Pairwise coding using a set 45° rotation achieves more than 2-dB Q^2 gain than the uncoded system, and using the optimal rotation angle leads to extra 0.5 dB coding gain. At 7% FEC threshold, the number of reachable ROADM nodes can be extended from 4 to 8 by with a fixed 45° pairwise coding, and further 2 nodes can be supported by implementing the optimal rotation angle. Therefore we can tradeoff between either using 45° as a fixed rotation at the transmitter with sub-optimal receiver performance, or implement optimal angle adaptively to maximize the performance, which requires receiver feedback information.

Figure 3(c)/(d) and (e)/(f) depict the equalized signals of edge/middle sub-carriers for uncoded and coded systems with 45° rotation after 4 loops, respectively. Clearly both systems have similar SINR values on the sub-carriers. After rescaling and I/Q de-interleaving, the decoded signals are shown as Figs. 3(g) and (h), indicating improved performance. The decoded signals with 45° and optimal angle rotations after 8 loops are depicted in Figs. 3(i) and (j), respectively. With optimal angle rotation, the decoded signals are more squeezed on the vertical (imaginary) axis than the 45° case, due to much heavier noise on the horizontal (real) axis that experienced by the edge sub-carrier, which carries the original real components of both the edge and middle sub-carriers. If ΔSINR is increased further, the decoded signals with optimal rotation angle would be more aligned to the vertical axis, and eventually become a PAM signal at infinite ΔSINR, as the PAM signal is immune to the real valued noise.

4. Conclusion

We have employed pairwise coding for superchannel transmission, to improve the system optical filtering tolerance. We experimentally demonstrated the proposed concept with 16 QPSK superchannels, each with four 3-Gbaud sub-carriers, passing through a EWSS embedded recirculation loop which emulates different number of ROADM nodes. Pairwise coding is able to double the tolerable ROADM induced ICI at 7% FEC threshold.

Acknowledgement

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