Sub-band Pairwise Coding for Inter-Channel-Interference Mitigation in Superchannel Transmission Systems

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Abstract *By pairing the mid and edge sub-bands of each channel, the penalty due to inter-channel-interference can be mitigated for a superchannel. Experimental results show that the proposed method offers 1.5-dB* Q^2 *improvement after 3840-km transmission with 1GHz channel overlap.*

Introduction

Superchannels are a promising candidate for spectrally-efficient next-generation coherent optical communication systems[1]. A near rectangular signal spectrum allows close to symbol rate channel spacing without impairment from inter-channel-interference (ICI). Several studies[2-4] have shown an optimal superchannel symbol rate of 4 to 5 Gbaud for dispersion-unmanaged, long-haul links. As such, it is desirable to generate multiple sub-bands from commercial optical I/Q modulators that typically have 20-30 GHz bandwidths.

However, ICI is inevitable if separate lasers are used as carriers, as they can drift by several GHz. The drift is especially critical if the sub-band symbol rate is optimal (a few Gbaud). Because there is a lack of effective ICI suppression methods, a sufficient OSNR margin must be added for laser frequency drift.

With multiple sub-bands in each channel, ICI mainly affects the edge sub-bands, which we call "edge sub-band selective fading". For per-channel reception, with access to both the edge ('deep fade') and the middle ('good') sub-bands, pairwise coding[5,6] can be applied to reduce the ICI penalty. Pairwise coding has been demonstrated as an effective method to maximize the overall system performance when there is signal-to-noise-ratio (SNR) imbalance between polarizations, due to polarization dependent loss[5]. Importantly, pairwise coding does not reduce the data rate of a channel as it has no overhead. It is also computationally efficient as it only operates on pairs of channels, rather than across the whole channel set.

In this paper, we show that by pairing the edge and middle sub-bands, the penalty due to ICI can be reduced. The proposed method is demonstrated in a superchannel experiment, with 16 PDM-QPSK channels, each carrying four sub-bands. We show about 1.5-dB Q^2 improvement after 3840-km transmission with channel overlap of 1GHz.

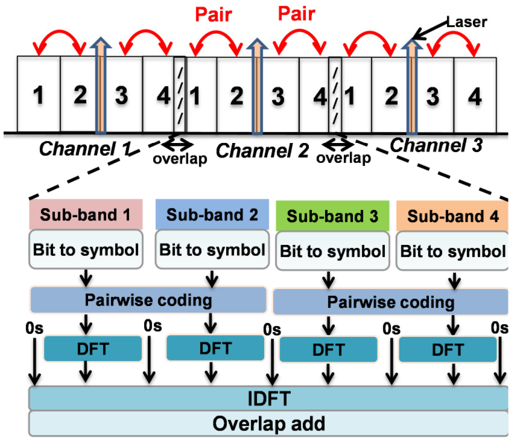

Fig. 1: Structure for sub-band pairwise coding

Sub-band pairwise coding and de-coding

Figure 1 shows the structure of the proposed sub-band pairwise coding scheme. Each channel (each with a laser) contains four sub-bands, so ICI would only affect edge sub-bands 1 and 4 if the relative random frequency drift is less than the sub-band symbol rate, while the middle sub-bands 2 and 3 remain unaffected.

The digital generation of each channel is based on DFT-S-OFDM[2,7]. After bit-to-symbol mapping, the adjacent edge and middle sub-bands are paired, and pre-coding is applied to these two sub-band pairs before DFT operation. After band mapping, IDFT converts the signal to the time domain, and overlap-add is used to create a continuous signal by spreading the samples across the IDFT boundaries.

The pairwise pre-coding and de-coding procedures are shown in Fig. 2(a) and (b), respectively. For each sub-band, a constant phase shift (i.e. angular rotation) is first applied to the data symbols. After this, the in-phase and quadrature components are interleaved to generate the signals for each sub-band: $\mathbf{Tx}_e = \Re(\mathbf{T}_e) + j\Re(\mathbf{T}_m), \mathbf{Tx}_m = \Im(\mathbf{T}_e) + j\Im(\mathbf{T}_m)$, where $\Re(\cdot)$ and $\Im(\cdot)$ represent the I and Q parts of the signals, respectively.

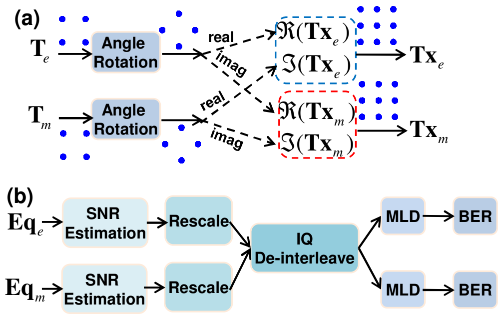

Fig. 2: (a). Transmitter sub-band pairwise pre-coding, (b). receiver sub-band pairwise de-coding.

Although the rotation angle should ideally track the signal-to-interference-noise ratio (SINR) imbalance between the received edge and middle sub-bands, practically this can be difficult to predict due to the random laser drift, which prevents us using the exact optimal angle at the transmitter. Fortunately, 45° provides most of the benefit for a wide range of imbalances[7]; so will be used in this work. With QPSK modulation and a 45° phase shift, pre-coding produces 9-point constellations.

The receiver first implements standard digital signal processing techniques to remove I/Q imbalance, channel distortion, frequency offset and phase noise. SINR is then estimated separately for each sub-band based on the constellation variance, subsequently the equalized signals are rescaled differently according to the estimated SINR. Notably, the SINR difference may change due to varying ICI, therefore the SINR estimation should be updated periodically, in accordance to the laser drift rate. After I/Q de-interleaving, maximum likelihood detection[5] is used to make symbol decisions for bit error rate (BER) calculation.

The essential idea of the pairwise coding is to transform the SINR difference between the paired sub-bands into an I/Q noise imbalance for both of the sub-bands. Subsequently, constellation rotation and rescaling produces optimal decision thresholds to attain the best detection performance.

Experimental demonstration

Figure 3 shows the experimental set-up. The transmitter comprised of 8 external cavity lasers (ECLs), power equalized by a Finisar Waveshaper (WS), and then modulated by electrical signals generated from an Agilent 64 GSa/s DAC. A 16-Gbaud QPSK signal was generated per channel (4 Gbaud per sub-band). An odd-and-even superchannel structure was achieved by power splitting the 8 modulated channels into two arms, delaying one arm and frequency shifting before recombining with the through arm. The signal was frequency shifted to modify the odd and even channel overlap, and the laser carrier frequency spacing was set to twice of the frequency shift, resulting in different levels of ICI. The insets (a)-(d) of Fig. 3 show the spectra (captured by an Agilent High Resolution Spectrometer) of a single channel and its frequency shifted version for 16.1 GHz, 15.5-GHz, 15-GHz and 14-GHz shifts, respectively. These shifts correspond to a 100 MHz guard band, 500-MHz, 1-GHz and 2-GHz channel overlap, respectively. The ICI doubles when all channels are present (i.e. Fig. 3e.). The 3-dB high peaks correspond to the spectrally overlapped channels (marked 'ICI').

Polarization division multiplexing (PDM) was emulated by splitting the signals into two equal arms, delaying one arm and then recombining using a polarization beam combiner (PBC). The signals then passed through a fibre recirculating loop, consisting of two acousto-optic modulators, four 80-km spans of standard single mode fibre (SSMF), a WS for gain flattening and five erbium doped fibre amplifiers (EDFAs). The signal spectrum after 3840-km transmission with 15.5-GHz frequency shift is depicted as inset (e) of Fig. 3. The receiver consists of a WS for channel selection and a 25-GHz coherent

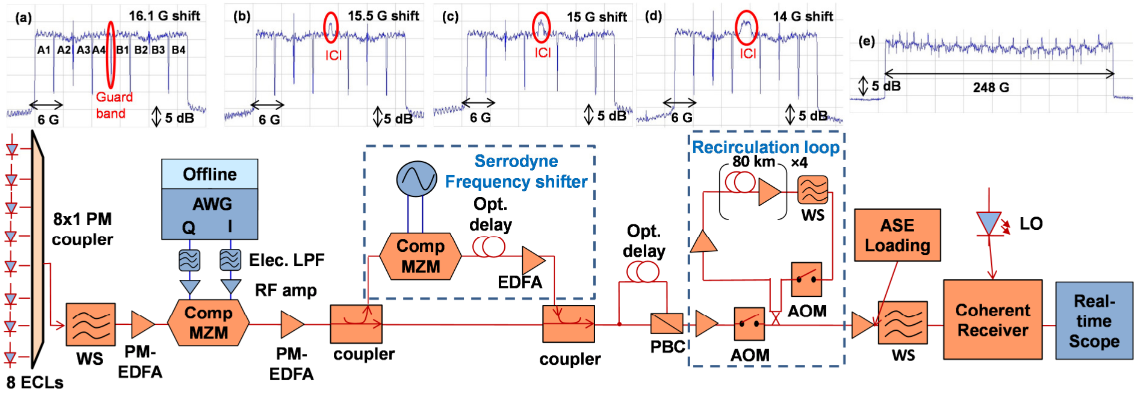

Fig. 3: Experimental setup, signal spectra are shown as the insets (a)-(e).

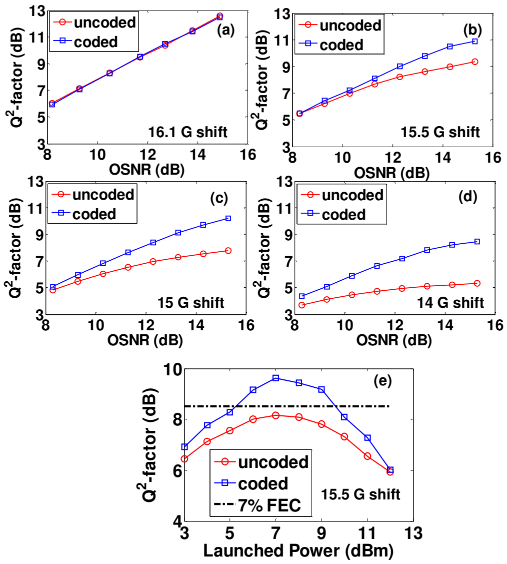

Fig. 4: (a)-(d): B2B OSNR measurements, (e): Results after 3840-km fibre with 15.5 GHz channel spacing.

receiver attached to a 40-GS/s real-time oscilloscope. ASE was added for back-to-back measurements. The offline DSP[7] included frequency offset compensation, DFT operation, overlap-add band demultiplexing with dispersion compensation, and per sub-band signal recovery based on constant modulus algorithm adaptive equalizer and Viterbi-Viterbi phase estimation. Extra decoding was needed for the pairwise coded signals.

For B2B transmission, the measured Q^2-factor ($Q^2(dB) = 20\log_{10}(\sqrt{2}erfc^{-1}(2BER))$) versus OSNR in 0.1-nm resolution is shown as Fig. 4(a)-(d) for different ICI cases. With a 16.1-GHz channel spacing, the coded and uncoded signals show similar performance, which illustrates that the pairwise coding does not introduce an extra penalty. When the spectral overlap is introduced and increased, the coded system shows much better performance than the uncoded system; with 15-dB OSNR, for 15.5/15/14 GHz spacing, the Q^2 penalty is 3.6/5.1/7.6 dB, while it reduces to 2/2.7/4.4 dB when pairwise coding is applied. Figure 4(e) shows the performance of the 8th (centre) channel with 15.5-GHz spacing after 3840-km; the coded signals have an advantage of 1.5-dB Q^2 over the uncoded signals at the optimal launched power.

Figures 5(a) and (b) show the constellation diagrams of the equalized uncoded signals at sub-bands 1 and 2, showing that the BER is dominated by the edge sub-band. Figure 5(c) and (d) shows the equalized coded signals for sub-bands 1 and 2, similar to uncoded case, sub-band 1 has poorer SINR performance. After rescaling and I/Q de-interleaving, similar BER can be observed for both sub-bands, as shown in Fig. 5(e) and (f). In this experiment, the in-phase component of the decoded signals of both sub-bands suffered more interference than the quadrature components, therefore the imaginary axis of the decoded signals has been ‘stretched’ to allow the two clusters sit on the imaginary axis further from the ‘horizontal’ noise from the two clusters that sit on the real axis.

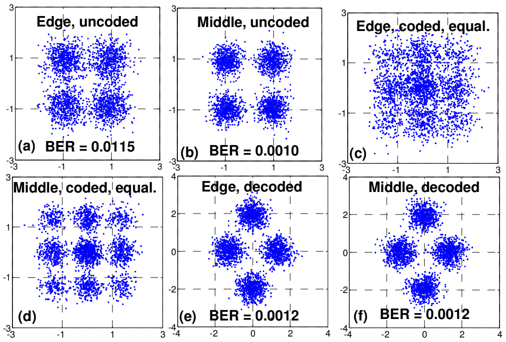

Fig. 5: Constellation diagrams for equalized signals with and without pairwise coding.

Conclusions

We have experimentally demonstrated that by pairwise pre-coding across the edge and middle sub-bands, the ICI penalty is converted into I/Q noise imbalance for both sub-bands and therefore can be significantly reduced.

Acknowledgements

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