Multi-Channel Equalization for Comb-Based Systems

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Abstract: We propose and demonstrate a frequency comb-enabled joint DSP. With joint processing, the required guard-bands decreases and the optimal roll-off factor increases, reducing penalties from non-ideal transceiver electronics while simultaneously increasing the spectral efficiency.
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1. Introduction

Maximizing the spectral efficiency (SE) requires maximizing both the per-channel SE and minimizing the inter-channel guard-bands. Using higher-order modulation formats and constellation shaping, the per-channel SE is within fractions of a dB away from theoretical bounds, leaving little room for further increase. In traditional WDM systems, the largest guard-bands are required for routing. Flex-grid networks and superchannels can overcome this limitation by improving SE with up to 30% [1]. Guard-bands for coping with laser frequency drift still cause about 10% loss in SE for superchannels using standard external cavity lasers (ECLs) and baud-rates around 30 GBaud [2]. Forming superchannels using frequency-locked carrier originating from an optical frequency comb, so called comb-based superchannels, overcomes this issue. Comb-based superchannels with sub-GHz guard-bands have therefore been frequently used in recent record-SE experiments [3, 4]. The spacing is then limited by linear crosstalk and in order to reach the ultimate spectral efficiency, crosstalk mitigation is required [5].

In this work we report the first transmission experiment using joint comb-enabled receiver-side multi-channel DSP for inter-channel crosstalk mitigation. We show that by exploiting unique capabilities of frequency comb-based superchannel receivers, system performance can be improved by enabling inter-channel cross-talk mitigation. The standard dynamic equalizer, used for e.g. polarization demultiplexing, is re-designed to exploit the unique coherence provided by the comb source, enabling processing beyond that of systems with traditional laser arrays. Each channel is detected using individual coherent receivers and by exploiting frequency aliasing, it is sufficient to sample each channel with two samples-per-symbol (2SPS) and no further up-sampling is required. Using the proposed equalization scheme, the tolerance to channel crosstalk is significantly improved, enabling denser channel spacing. We also observe an increase in optimal roll-off factor from 1% for single channel processing to 5-10% for our proposed joint processing DSP.

2. Comb-Enabled Joint Equalization

A sketch of the proposed receiver architecture is shown in Fig. 1(a). To enable linear crosstalk to be cancelled beyond that of a classical system, multiple channels need to be detected in parallel and processed jointly. While superchannel detection using a single broadband receiver has been proposed [6], this approach is not scalable to many wavelengths due to receiver bandwidth limitations. It is therefore essential to be able to detect each channel using individual receivers. Using free-running LOs, coherent information exchange between signals detected on independent receivers is not possible, due to the unknown relative frequency drifts. However, if all LOs originates from a common frequency comb and its spacing is known, the complete frequency grid can be reconstructed using spectral splicing [7]. However, spectral splicing requires pre-calibration, and therefore knowledge of all receiver components and precise phase

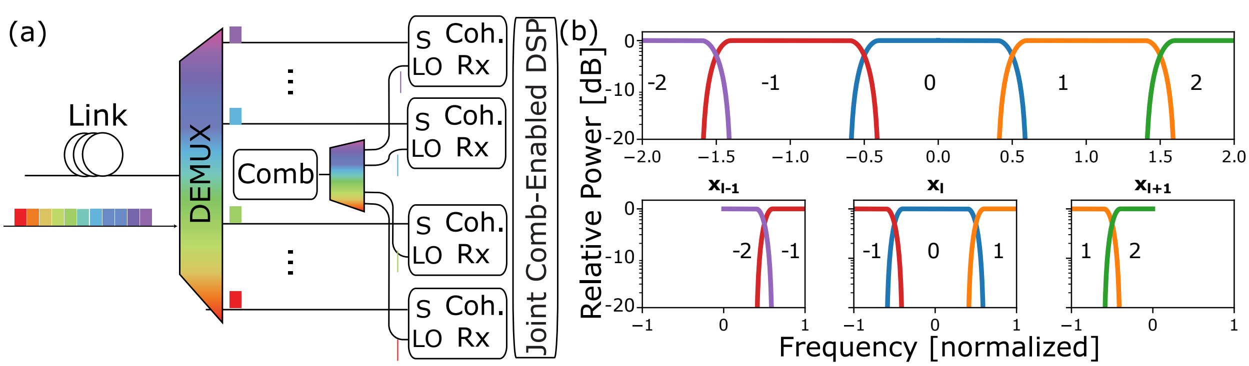

Fig. 1: (a) Principle sketch for a comb-based superchannel receiver. Each channel is detected using independent receivers with all LOs originating from a common frequency comb enabling joint DSP. (b) Frequency grid and inputs to the multi-channel equalizer using aliasing of the side channels to avoid upsampling. Each channel is sampled at 2SPS, or less, and stitched by the equalizer.

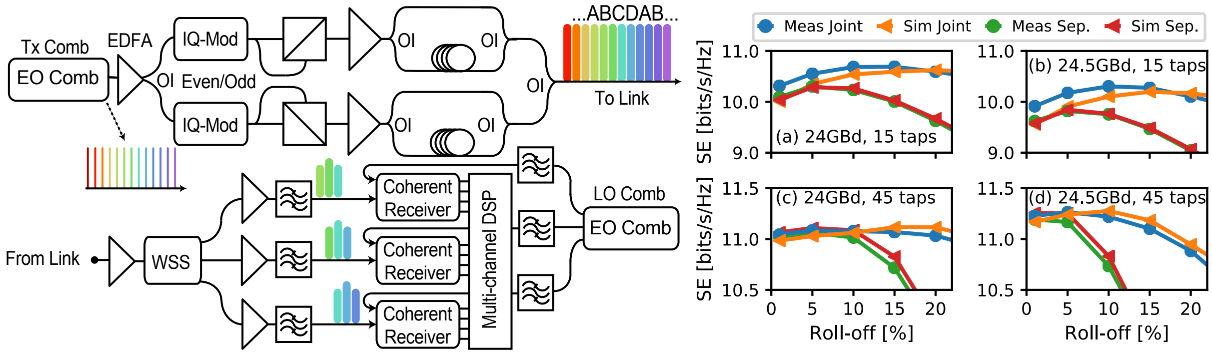

Fig. 2: (left) Experimental setup for the 64QAM comb-based superchannel transmitter and receiver using multiple independent receivers. EO: Electro-optic. OI: Optical interleaver. WSS: Wavelength selective switch. (right) Back-to-back measurements and numerical simulations of joint versus separate processing. Spectral efficiency vs. transmitter side roll-off factor is shown in (a) 24GBaud with 15 taps, (b) 24.5GBaud with 15 taps, (c) 24GBaud with 45 taps and (d) 24.5GBaud with 45 taps, respectively.

alignment to properly stitch the detected channels. Alternatively, a dynamic equalizer can be used to find the delays and align the phases between the signals [8]. In addition, prior to stitching, each waveform needs to be upsampled sufficiently to span the spectral width of the full signal, independent of how the signals are aligned.

By instead including the stitching into the equalizer using separate input streams, the need for complex upsampling or cumbersome stitching prior to equalization can be avoided. This is enabled by expanding the traditional 2×2 multiple-input-multiple-output (MIMO) equalizer to a 6×2, with the three separate polarization-multiplexed wavelength channels as shown in Fig. 1(b). As the input channels are separated, frequency aliasing can be exploited to allow all processing to be done at the initial sampling rate, here taken to be 2SPS. However, only a small overlap is needed and much lower oversampling factors can therefore be used for dense superchannels. Importantly, the proposed equalizer still performs all standard functionalities such as polarization de-multiplexing and equalization of residual dispersion so the previously proposed post-equalizer for crosstalk mitigation can be avoided [5, 9].

3. Experimental setup

The experimental setup is shown in Fig. 2. Two free-running electro-optic (EO) frequency combs seeded by standard ECLs were used as the transmitter and receiver comb, respectively. Each comb was driven by an independent 25 GHz-spaced RF clock and consisted of a phase modulator and an intensity modulator, generating $>$20 comb lines. On the transmitter side, two separate IQ-modulators modulated even-odd data consisting of 64 quadrature amplitude modulated (QAM) signals with varying roll-off factor and symbol rate. Pilot symbols were inserted using a framed structure [10]. Polarization multiplexing (PM) was emulated using two independent split-delay-combine emulation stages with a delay exceeding 250 symbols. Every second odd and even channel was then delayed by about 750 symbols, creating A-B-C-D-A decorrelation prior to recombining all channels to form the superchannel output.

The transmitter was either connected to the receiver for B2B evaluation or to a single 80 km standard single-mode fiber span with about 16 dB span loss for the transmission experiment. At the receiver, a multi-port wavelength selective switch (WSS) filtered out the channels. The filter bandwidth of each receiver filter was 0.3 nm. Three corresponding lines from the LO comb were selected and each channel was independently detected using coherent receivers with 23 GHz analog bandwidth and sampled using three 50 GS/s real-time oscilloscopes. All scopes were synchronized using a common trigger and reference clock, but no path-matching was performed. In addition, the scope sampling clocks were locked to the receiver EO comb for coherent stitching. The offline traces were then processed with the pilot-based DSP outlined in [10] as base. The equalizer was replaced with the 6×2 MIMO equalizer described above and the frequency offset estimation block was performed jointly for all three channels to avoid breaking any coherence between the channels. Pilot overhead optimization was performed, resulting in 2.3% pilots.

4. Results

A comparison between joint and separate equalization for different roll-off factors (amount of crosstalk) in B2B is shown in Fig. 2(b) for symbol rates of 24 and 24.5 GBaud, respectively. The measurements are also compared with numerical simulations to ensure that no artificial gain or penalty from the decorrelation scheme is present. First, as expected, we observe significantly larger tolerance to linear cross-talk for multi-channel processing. The difference is naturally higher for 15 taps but even at 45 taps, after which no gain from further increase was observed, the joint measurements are always better than separate processing. Comparing to the simulations, we observe a very good match and identical trends for separate processing but the experimental measurements with joint processing outperforms the simulations at lower roll-off factors. While, for 45 taps, aggressive roll-off is beneficial for separate processing, the

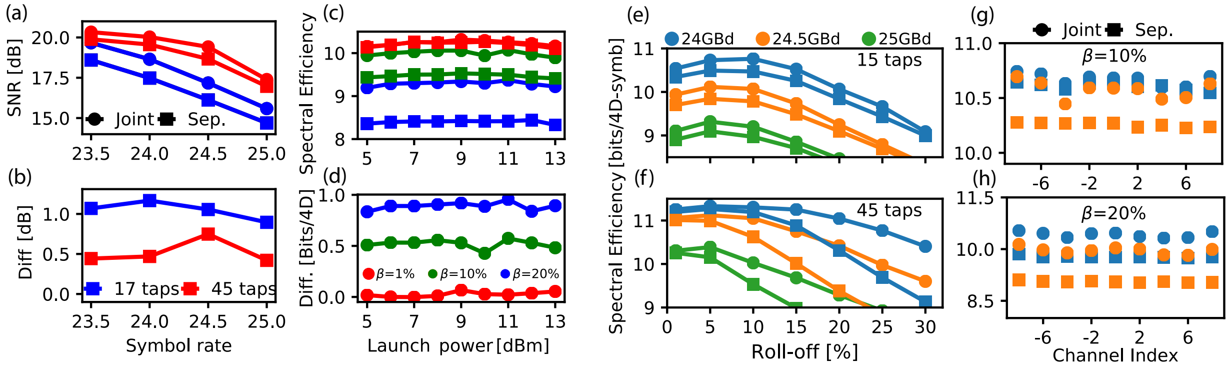

Fig. 3: (a) Estimated SNR for joint and separate processing using 17 (orange) and 45 (blue) T/2-spaced taps. (b) Corresponding difference. (c) Launch power sweep for 25 GBaud with roll-off β =1%, 10% and 20%, respectively. (d) The difference between joint and separate equalization for different launch powers. Spectral efficiency as a function of roll-off factor for 15 (e) and 45 (f) taps, respectively. Performance for 9 evenly spaced test channels with $\beta = 10\%$ (g) and $\beta = 20\%$ (h).

optimal roll-off is between 5% and 10% for joint processing, showing that less aggressive roll-offs improves the overall performance for joint processing. This is because of the non-ideal transceiver components, which increases the penalty from the larger peak-to-average power variations at low roll-off, and the limited ability to implement very rectangular channel shapes using practical components. At optimal roll-offs with 45 taps, the optimal symbol rate is increased from 24 to 24.5GBaud when using joint processing. This trend is furthermore confirmed by analyzing the estimated digital signal to noise ratio (SNR) for joint and separate processing as a function of symbol rate, as shown in Fig. 3(a). The difference is shown in Fig. 3(b) and even at 45 taps, joint processing always outperforms separate with an average SNR improvement of 0.5 dB. A gain of 0.8 dB is observed at 24.5 GBaud, the optimal symbol rate for joint processing.

Launch power sweeps after 80 km for the central channel at 25GBaud is shown in Fig. 3(c) for the case of $\beta = 1\%, 10\%$ and 20% using 45 taps. We observe stable performance and no significant difference in tolerance to fiber nonlinearities between joint and separate processing is observed even at higher-than-optimal launch power. At a roll off factor of $\beta = 1\%$, the difference is marginal although joint processing is generally better. For $\beta = 10\%$ the difference is about 0.5 bit/4D-symbol, as shown in Fig. 3(d). A comparison between different roll-off factors at optimal launch power, being 9 dBm, for 15 and 45 taps is shown in Fig. Fig. 3(e) and (f), respectively. Importantly, the joint processing outperforms traditional separate processing for all roll-offs. We also observe the same trend as for the B2B results presented in Fig. 2(b) with the optimal roll-off being 5-10% for joint processing. Finally, to verify that the performance could be maintained throughout the superchannel, we measured 9 evenly spaced test-channels for with $\beta = 10\%$ and 20%, as shown in Fig. 3(g) and (h), respectively. Very similar gains for all channels are observed.

Finally, we note that multiple DSP operations, such as clock recovery [11] and dispersion estimation [12], perform better for channels with higher roll-off factors. The proposed multi-channel equalization scheme may therefore have significant implications for the overall design of a joint superchannel DSP, and moving to higher roll-offs can be beneficial beyond reducing the penalty from non-ideal transceiver electronics and mitigating inter-channel crosstalk.

5. Conclusions

We have experimentally demonstrated a joint comb-enabled multi-channel equalizer to suppress linear crosstalk and thereby increasing the spectral efficiency for comb-based superchannels. Each channel is detected using independent receivers and combined to a joint multi-channel equalizer, which expands the traditional DSP-based dynamic equalizer. Using multi-channel processing, the required guard-bands are reduced and the optimal roll-off factor increases 5-10%, improving the superchannel spectral efficiency. Our results show the potential for joint DSP to enable comb-based superchannels to reach performance beyond that of classical systems by exploiting unique features of frequency combs.

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