Frequency-Comb Enabled Interchannel Crosstalk Mitigation with Reduced Complexity

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Abstract *We propose and demonstrate a comb-based multi-channel equalization scheme using only two receivers for three channels, achieving a similar joint processing gain to a three-receiver diagram and reducing the DSP complexity.*

Introduction

In wavelength division multiplexing (WDM) systems using external cavity lasers (ECLs), interchannel guard bands of a few GHz[1],[2] are employed to cope with the frequency drift at the expense of spectral efficiency (SE). By using frequency-locked carriers provided by optical frequency combs, the required guard bands is reduced by ten times[3],[4]. To further reduce the guard bands, aggressive pulse-shaping[5] or multi-channel equalization using three receivers[6],[7] can be applied, enabling high-SE superchannel systems. In the case of multi-channel processing comb-based receivers are required to maintain the frequency coherence between the detected channels and facilitate the joint DSP.

In this paper, we propose a comb-based multi-channel equalization scheme that reduces the number of receivers required for joint processing-based interchannel interference cancellation (ICI) to two. In contrast to the three-receiver architecture that applies a 6x2 multiple-input-multiple-output (MIMO) equalizer[7], the three channels are detected in two receivers by separating half the center-channel spectrum into each side-channel receiver. A following 4x2 MIMO equalizer operating at 2 samples per symbol (SPS) is applied to mitigate the ICI. We observe in the noise loading and after 80 km SMF that the two-receiver architecture achieves equivalent joint processing gain to the conventional diagram and reduces the required number of receivers from 3 to 2.

Proposed Comb-Based Joint Equalization

To mitigate the linear crosstalk efficiently, the neighboring three wavelength channels need to be detected jointly. In practice, the effective number of bits (ENOBs) of analog-to-digital converters decreases as a function of frequency[8],[9], limiting the performance of broadband detection using a single receiver. Alternatively, each channel can be detected independently and digitally stitched to regenerate the superchannel using spectral slicing[10]. Here, comb-based local oscillators (LOs) must be employed to provide stable and known channel spacing. However, the stitching requires an estimation of the receiver response and phase in each channel. Moreover, parallelizing the stitched ultra-high bandwidth signal can be tricky for hardware implementations. A less complex scheme for signal reconstruction and ICI mitigation can be implemented by a 6x2 MIMO equalizer[7], as shown in Fig.1 (a), which automatically performs the amplitude and phase estimation. Under closer investigation, we see that half the spectrum from the center channel (l) is captured in each side-channel ($l-1$, $l+1$) receiver, resulting in redundant detection. In this three-receiver diagram, the separate and joint processing uses the information from the center and all three channels, respectively.

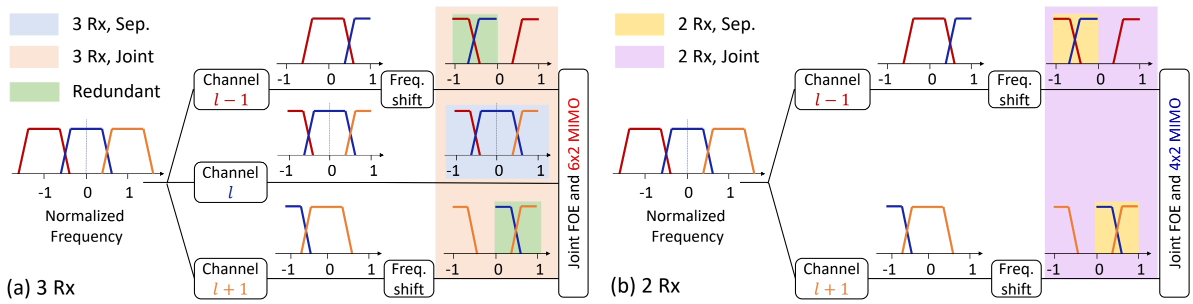

Fig. 1: Multi-channel processing enabled by (a) Three receivers, (b) Two receivers. The green bars in (a) highlight the redundant detection of the center channel l. The processing operates at 2 SPS. Sep.: separate processing; Joint: joint processing.

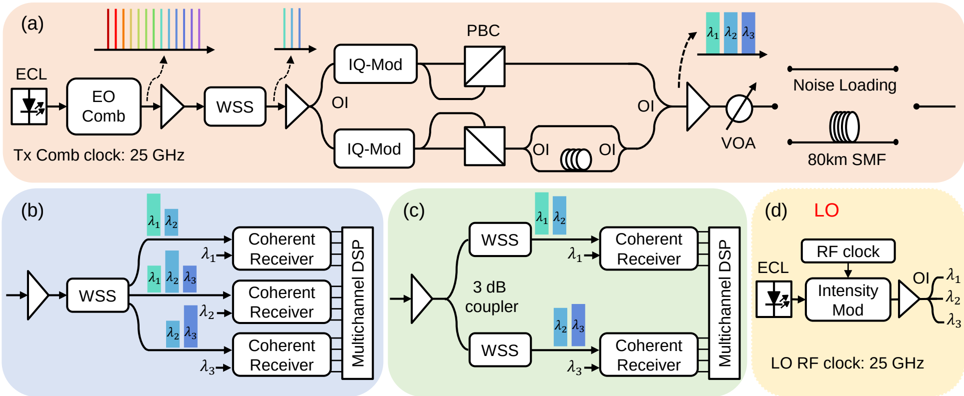

Fig. 2: Experimental setup. (a) Transmitter and channel, (b) Three receivers diagram, (c) Two receivers diagram, (d) LO setting.

By removing the center-channel receiver, we find the proposed two-receiver diagram can still detect the full spectrum as shown in Fig 1 (b). After signal detection, frequency shifting, and joint FOE, the 4x2 MIMO equalizer is applied to superimpose the center channel and perform ICI mitigation. Different from spectral slicing that requires upsampling to 3 SPS, the shift in this scheme is performed within the bandwidth of the 2 SPS window. Since the center channel is divided into two parts, a data-aided equalizer needs to be employed to enable accurate signal reconstruction. Here, separate processing only uses half the center-channel spectrum (highlighted by the yellow bars) in each receiver to reconstruct the center channel using the equalizer, while joint equalization includes all received spectral information (highlighted by the pink bars) to mitigate the ICI.

Experimental setup

The experimental setup is shown in Fig. 2. The optical signal is generated by an ECL operating at 1554.12 nm. We used a 25 GHz clock to drive an electro-optic frequency comb. The equally-spaced carriers were sent to two erbium-doped fiber amplifiers (EDFAs) for amplification. A wavelength selective switch (WSS) was applied to filter and flatten three lines before using an optical interleaver (OI) to separate the signal into center and side channels. We employed 16-, 32-, and 64-QAM signal pulse-shaped with a 10%-roll-off root-raised-cosine filter. The symbol rate varied from 24 to 26 Gbaud to change the effective guard bands. The electrical signals generated by four digital-to-analog converters were fed to two IQ-modulators, modulating odd and even channels. We used the split-delay-combine method to perform polarization multiplexing and employed another pair of OIs to decorrelate the third channel. The signals were then combined and amplified. We used a variable optical attenuator to adjust the OSNR in the noise loading measurements and the launch power in the 80 km SMF experiment.

In the three-receiver diagram shown in Fig. 2 (b), we employed a WSS to separate the channels with a filtering bandwidth of 0.2 nm. An independent receiver is employed for each channel. For the two-receivers diagram in Fig. 2 (c), the signal was divided into two paths and filtered by two WSSs with a bandwidth of 0.4 nm. We use receivers with 30 GHz electrical bandwidth for both schemes. As shown in Fig. 2 (d), three LOs were generated by driving an intensity modulator with a 25 GHz clock. The LOs were then amplified and separated into corresponding receivers with cascaded OIs. The received signal is sampled by 80GS/s oscilloscopes. After digitally filtering and downsampling to 2 SPS, multi-channel joint processing[7],[11] is performed to mitigate ICI. We measure the achievable information rate (AIR) by including the guard band and QPSK pilot overhead. The optimized pilot overhead is 2.3%.

Results

For the proposed two-receivers scheme, a comparison between the separate and joint processing (performed following Fig.1 (b)) in the noise loading measurements is shown in Fig. 3. We note that separate processing indicates superimposing the center channel without ICI mitigation, while joint equalization means including side channels as well to remove the crosstalk. First, for 16-QAM, we observe that the optimum symbol rate increases from 25 to 25.5 Gbaud with joint processing, achieving a super-Nyquist superchannel. The maximum AIR at 40 dB OSNR is only 0.05 bits/s/Hz lower than the theoretical limit at 25.5 Gbaud when including the pilot overhead, indicated by the black dashed line. We notice that negligible improvement is achieved by joint equalization for 24 and 24.5 Gbaud. This originates from the fact that there is little spectral overlap be-

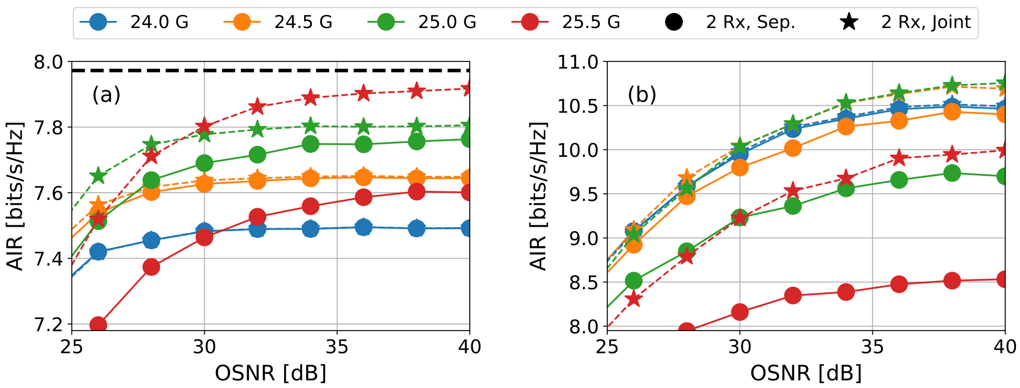

Fig. 3: Achievable information rate of the center channel versus OSNR for (a) 16-QAM, (b) 64-QAM. Both separate and joint equalization is performed with the proposed two-receivers architecture as shown in Fig. 1 (b).

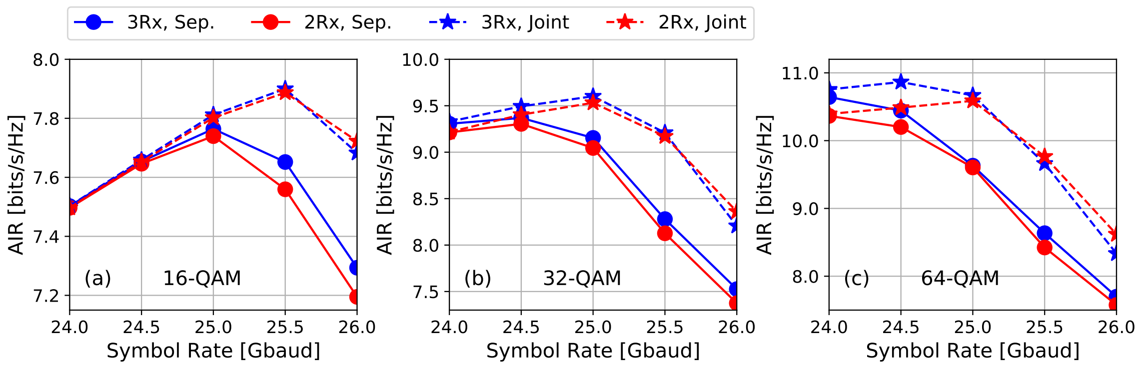

Fig. 4: Achievable information rate of the center channel versus symbol rate after 80-km SMF. The proposed two-receivers diagram (2Rx, performed following Fig.1 (b)) is compared with the three-receivers diagram (3Rx, performed following Fig.1 (a)) in terms of separate and joint processing.

tween the channels and the AIR is already very close to the theoretical maximum. For 64-QAM, the joint equalization performs better than independent processing at high OSNRs for all tested symbol rates except for 24 Gbaud. We observe a joint gain of around 0.35 and 1 dB for 24.5 and 25 Gbaud, respectively, in the high-OSNR region, enabling a maximum AIR of around 10.75 bits/s/Hz with joint processing. In contrast to 16-QAM, the joint processing gain for 64-QAM is much higher. This is because ICI results in more penalties for high-order modulation formats due to the decreased Euclidean distance between the symbols. Furthermore, the limited ENOBs significantly degrade the multi-channel equalization, especially for 64-QAM, leading to an optimum symbol rate of around 25 GBaud.

In the 80-km SMF transmission experiment, we include the measurements for the three-receiver (3Rx) architecture for comparison. Fig. 4 (a)-(c) shows the maximum AIR versus symbol rate at the optimum launch power of around 2 dBm. With joint processing, the optimum symbol rate in the two-receiver case increases to 25.5, 25, and 25 Gbaud for 16-, 32-, and 64-QAM, respectively. In the proposed scheme, the joint processing gain and maximum AIR are similar to the three-receiver diagram for 16-QAM and 32-QAM. However, the two-receiver scheme suffers a penalty at 24 and 24.5 Gbaud for 64-QAM for both the separate and joint processing. Due to the trade-off between noise and receiver-TIA nonlinearity, the received optical power is limited, reducing the power spectral density in the proposed scheme with larger detected signal bandwidth. This degrades SNR and therefore the AIR performance, especially for high-order QAM. The AIR for 25, 25.5, and 26 Gbaud is not degraded significantly as they are mainly limited by the ICI.

Conclusions

We have experimentally demonstrated a comb-based multi-channel equalizer with two receivers to mitigate interchannel crosstalk. Compared with the three-receiver architecture, the proposed method reduces the required number of receivers from 3 to 2. Our results indicate that the proposed technique performs similarly to the three-receiver diagram, showing the potential for joint equalization with reduced hardware and DSP complexity.

Acknowledgements

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