Mitigation of Inter-Subcarrier Linear Crosstalk with Groupwise Fixed FDE assisted MIMO

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Abstract: We experimentally demonstrated inter-subcarrier linear crosstalk mitigation of five-subcarrier 10-GBaud RRC-PM-16QAM using Groupwise fixed FDE assisted MIMO. The proposed method enabled 6.3% tighter subcarrier spacing over 120 km SSMF, compared to conventional 2x2 MIMO.

1. Introduction

The accelerating growth in data center demand has triggered blooming research on metro applications. For this application, higher spectral efficiency (SE) using high-order modulation and constellation shaping techniques are a promising approach on typical distances in the range of 600 km. Indeed, with the fast evolution of digital coherent technology, state of the art digital signal processors (DSP) are now featuring 64 quadrature amplitude modulation (QAM) to enable 600-Gbps real-time transmission [1]. Dense WDM with tight carrier spacing is another way to increase SE, at the expense of the linear crosstalk between adjacent carriers. To overcome this, Nyquist pulse shaping with small roll-off factor is commonly used for averting linear crosstalk, however additional guard band is required to reduce the residual filtering penalty. Super-Nyquist filtering with minimum mean square error based receiver [2] has been advocated for mitigating linear crosstalk to realize the Nyquist spaced subcarrier transmission. Further increasing SE, polybinary shaping with maximum-likelihood sequence estimation [3] has been proposed to achieve sub-Nyquist spaced transmission.

Likewise, Multiple-input-multiple-output (MIMO) based inter carrier interference (ICI) mitigation [4-6] has been investigated to realize sub-Nyquist spacing [5-6], as it is modulation-independent and requires moderate circuit resource [6]. It has already been demonstrated for dual-subcarrier polarization multiplexing (PM)-64QAM in a transmission experiment with Sub-Nyquist channel spacing [6]. For cases of more than three subcarriers (N>3), the crosstalk of the target PM subcarrier of index n can be mitigated by using $n\pm1$ inputs for MIMO, as it mainly comes from the adjacent subcarriers. However, $n+1$ and $n-1$ are corrupted by the crosstalk from their respective adjacent subcarriers $n+2$ and $n-2$; thus to achieve the best performance, the information of all subcarriers should be used, which requires more computation resource [4]. Moreover, the filter convergence for full MIMO processing might fall into local minima when using the conventional methods, such as the constant modulus (CMA) or least mean squared algorithms, which remains problematic. Therefore, limitation to the use of $n\pm1$ inputs is preferable, whereas the penalties from $n\pm2$ have not been experimentally quantified so far.

In this paper, we experimentally study the penalty from non-adjacent subcarriers for our previously reported fixed frequency domain equalizer (FDE) assisted MIMO based ICI mitigation [6]. We propose Groupwise fixed FDE assisted MIMO equalizer for five subcarriers to enable narrower subcarrier spacing. We experimentally demonstrate our method with 10-GBaud root-raised-cosine (RRC)-PM-16QAM five subcarrier, which enables 6.3% tighter subcarrier spacing, compared to the conventional 2x2 MIMO after 120 km transmission over SSMF.

2. Groupwise fixed FDE assisted MIMO equalizer

The concept of MIMO based ICI mitigation used in this study is shown in Fig. 1. The fixed FDE assisted MIMO

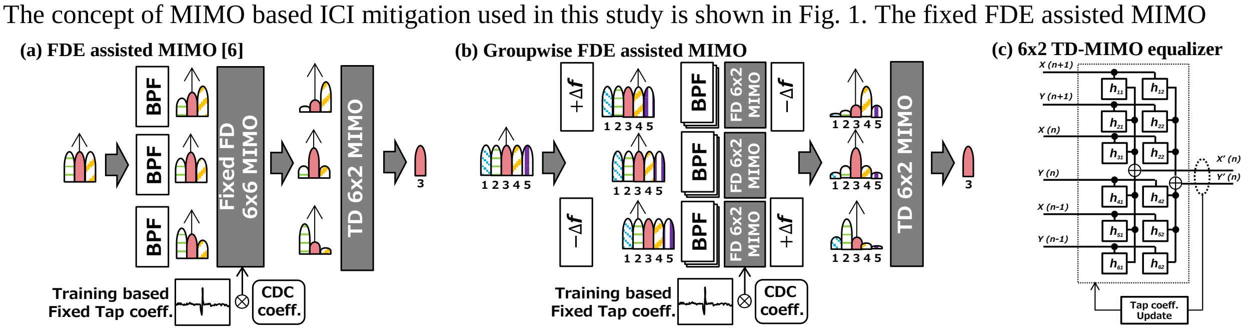

Fig. 1. Concept of MIMO based ICI mitigation (a) FDE assisted MIMO, (b) Groupwise FDE assisted MIMO, (c) 6x2 TD-MIMO equalizer

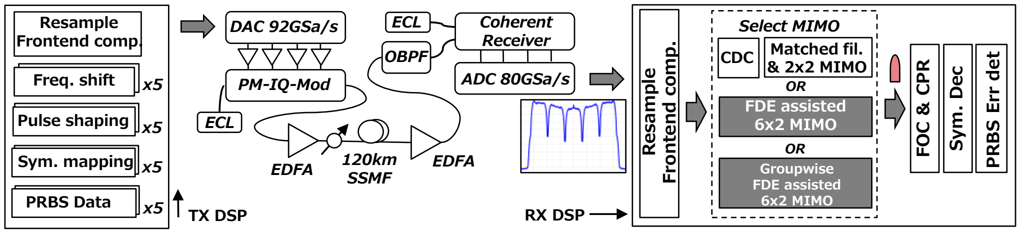

Fig. 2. Experimental setup and offline DSP

based ICI mitigation for N=3 Nyquist shaped subcarrier [6] is described on Fig. 1 (a). To detect each subcarrier, digital bandpass filter (BPF) is applied before MIMO equalizer. Nevertheless, as ICI variations between subcarriers are slow evolving phenomena, fixed 6x6 MIMO equalizer into the frequency domain is selected for the first stage, taking advantage of resource efficient linear equalization circuit implementation with static long impulse response, need for Nyquist shaped signal. In addition, chromatic dispersion compensation (CDC) is performed jointly in the same FDE. In order to address the remaining ICI deviation, we use a time domain equalizer (TDE) with a limited number of taps. Note that the filter coefficients for fixed FD-MIMO are obtained by training signal, which we used PM-quadrature phase shift keying (QPSK) with pseudo random binary sequences (PRBS) since CMA enables blind and robust convergence of long impulse response MIMO equalizer. Notably, TD-MIMO processing with separated CDC is used in the training mode for convergence. Since polarization rotation is a dynamic phenomenon, polarization and the remaining linear crosstalk are adaptively demultiplexed by cascaded TD-MIMO equalizer, 6x2 configuration in Fig. 1 (c), to equalize center carrier. The TDE pre-converge is achieved by CMA before switching to radially directed equalization (RDE).

For N=5 subcarriers, mitigating linear crosstalk from non-adjacent carrier $n\pm2$ by using full FDE assisted MIMO, would require a 2Nx2N (10x10) FD-MIMO configuration, which would increase required computation resources. Nevertheless, the numbers of FIR filter and interconnection for MIMO would exponentially increase with respectively $(2N)^2$ and $2x(2N)^2$. Although advanced CMOS technology may allow to realize it in the future, the issue of circuit placement and routing due to interconnection complexity among circuitries is still prohibitive in the current state of the art. Therefore, we propose to split our FDE assisted MIMO method as a novel Groupwise fixed FDE assisted MIMO equalizer, replacing a fixed 2Nx2N FD-MIMO by three parallel fixed 6x2 FD-MIMO, as shown in Fig. 1 (b). The baseband frequency for each FDE inputs are shifted by subcarrier spacing to set center of $n-1$, n and $n+1$ subcarriers. Each FDE output is shifted back to the original baseband, fed into the cascaded 6x2 TD-MIMO. With this configuration, we can efficiently reduce the complexity of circuit placement and routing, avoid local minima for filter convergence since each MIMO processing takes into account center and adjacent subcarriers only. The remaining for the process is similar to standard FDE assisted MIMO.

3. Experimental setup for evaluation of ICI mitigation

Fig. 2 shows the experimental setup and offline DSP for five-subcarrier 10-GBaud-RRC-PM-16QAM transmission (N=5). External cavity lasers (ECL) with a 100 kHz linewidth were used for both signal source and local oscillator (LO) set at 192.1 THz. On the TX side, the five-subcarrier signal was modulated with a PM-IQ modulator and four DAC. Five sets of de-correlated PRBS 15 were generated and mapped onto the each 16QAM symbol, then RRC filtering with roll-off factor of 0.25 at two oversampling ratio was performed individually. The decorrelation between adjacent subcarrier was kept wider than the MIMO equalizer depth. Next, frequency shift, detuning to evaluate the linear crosstalk, was applied for each subcarrier, on both side of the center frequency between 0.85 and 1.3 times the symbol-rate. After compensation of the frontend imperfections, the five-subcarrier signal was resampled to 92-GSa/s.

For back-to-back characterization, ASE was loaded on the signal before the optical bandpass filter (OBPF) to adjust OSNR. For transmission experiments, we used 120 km SSMF and with EDFA amplification. The fiber launch power was set to 1 dBm for five-subcarrier signal to reduce the penalties due to the fiber nonlinearity, resulting in a received OSNR for five-subcarrier of 28.4 dB/0.1nm.

On the RX side, the five-subcarrier signal was captured by the single coherent receiver and following four 80-GSa/s ADC converted it to the electrical domain. The received signal was firstly resampled and filtered to compensate frontend imperfections. Following MIMO processing was detailed in the previous section. The equalized center subcarrier was then processed for frequency offset compensation (FOC), carrier phase recovery (CPR) by blind phase search algorithm and symbol decision. Finally error counting was performed on the central subcarrier (n=3 for N=5), which is the limiting one. For a reference conventional 2x2 MIMO processing for polarization demultiplexing only, CDC was applied in the frequency domain for the central subcarrier, and matched Nyquist filtering was applied before 2x2 MIMO equalizer.

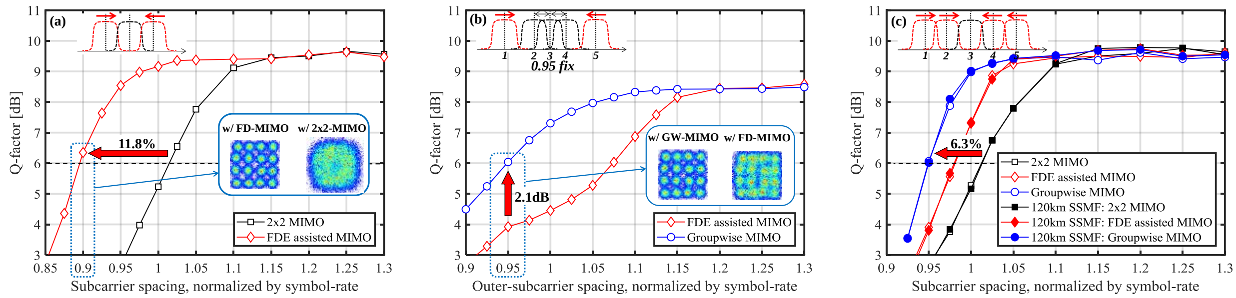

Fig. 3. Experimental results (a) three subcarrier, (b) five subcarrier, fixed subcarrier spacing for center three subcarriers, (c) five subcarrier

4. Results and Discussion

First, we investigated the case N=3: we evaluated fixed FDE assisted MIMO detection for three-subcarrier signal, and compared it with 2x2 MIMO in back-to-back for the reference of this work. As expected, the three-subcarrier signal suffers more from linear crosstalk than a dual-carrier signal [6]. In Fig. 3 (a), the Q-factor is plotted as a function of the subcarrier spacing. We optimized the number of taps to 97 taps for the fixed FD-MIMO equalizer, and to 21 taps for TD-MIMO. The OSNR for the three-subcarrier was set to 21.77 dB/0.1nm. Clearly, FDE assisted MIMO outperformed 2x2 MIMO detection. The negligible Q-penalties were observed larger than Nyquist spacing, then penalties were gradually increased as linear crosstalk increase. It enabled 11.8% tighter subcarrier spacing at the Q-factor of 6 dB, compared to 2x2 MIMO.

Next, we evaluated wider channel for N=5. We quantified the penalty caused by non-adjacent subcarriers onto FDE assisted MIMO and we compared with the proposed Groupwise fixed FDE assisted MIMO based ICI mitigation for five-subcarrier signal. Due to the additional implementation penalties for five-subcarrier signal, OSNR for the five-subcarrier was set to 25 dB/0.1nm to adjust to constant Q-factor between N=5 and N=3. In Fig. 3 (b), the subcarrier spacing for center three subcarriers are set to 0.95 times the symbol-rate, and the Q-factor is plotted as a function of the outer subcarrier spacing. The optimized number of tap for Groupwise MIMO was same as that of FDE assisted MIMO, keeping the circuit scale in reasonable range. As linear crosstalk from the outer subcarriers *(n=1, n=5)* was increased, the performance of FDE assisted MIMO was reduced even for wider spacing than Nyquist. In contrast, Groupwise MIMO successfully mitigated the linear crosstalk from not only adjacent subcarriers *(n=2, n=4)*, but also non-adjacent subcarriers *(n=1, n=5)*, Q-factor was significantly increased by 2.1 dB at subcarrier spacing of 0.95 times the symbol-rate, compared with FDE assisted MIMO.

Finally, we evaluated Groupwise MIMO detection for five subcarrier signal both in back-to-back and 120 km SSMF transmission. In Fig. 3 (c), the Q-factor is plotted as a function of uniform subcarrier spacing. In order to compare our results with the back-to-back cases, OSNR was adjusted to 25 dB/0.1nm after transmission. Compared with three-subcarrier case, the performance of FDE assisted MIMO was degraded in the presence of non-adjacent subcarriers, whereas Groupwise MIMO effectively mitigated the linear crosstalk at the same condition. Moreover, the performance was not affected by SSMF transmission and joint CD compensation. Our method enabled 6.3% tighter subcarrier spacing at the Q-factor of 6 dB, compared to the conventional 2x2 MIMO.

5. Conclusion

We have quantified the penalty caused by crosstalk from non-adjacent subcarriers. We have experimentally demonstrated the linear crosstalk mitigation for 10-GBaud RRC-PM-16QAM five-subcarrier signal, by using fixed FDE assisted 6x2 MIMO and the proposed Groupwise fixed FDE assisted 6x2 MIMO equalizer. We have shown that Groupwise MIMO improved Q-factor of 2.2 dB at subcarrier spacing of 0.95 times the symbol-rat compared to previously reported FDE assisted MIMO, mitigating for some crosstalk from non-adjacent subcarriers. Furthermore, Groupwise MIMO keeps the complexity of circuit placement and routing lower than full set MIMO. Finally, our method enabled 6.3% tighter subcarrier spacing, compared to the conventional 2x2 MIMO after 120 km transmission over SSMF with joint CD compensation.

Acknowledgements

Part of these research results was obtained within “The research and development of innovative optical network technology as a new social infrastructure” of the Ministry of Internal Affairs and Communications, Japan.

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