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PDM-16QAM 300-km Transmission over Installed High-Crosstalk Step-Index Multi-Core Fibre Cable Employing Unreplicated Crosstalk Canceller

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Abstract. *We propose a low-complexity unreplicated crosstalk canceller (UCC) that eliminates inter-channel interference in a weakly-coupled SDM link. Transmission experiment over installed step-index multicore fibre cables verifies that the UCC tripled the achievable transmission reach for PDM-16QAM signals even with inter-core crosstalk accumulation of -5 dB. ©2022 The Author(s)*

Introduction

Technical breakthrough based on space division multiplexing (SDM) to overcome the capacity limit of standard single mode fibre (SMF) is urgently required toward a future sustainably-developing optical transport network. The spatial multiplexing approaches using optical fibres' cores are categorized into uncoupled and coupled ones, and the former with standard diameter cladding is expected to emerge as an early realization of a SDM system due to its advantages of compatibility with existing technologies of SMFs, optical devices/interfaces, and digital signal processing (DSP). Although a fibre design of multicore fibre (MCF) with a simple step index (SI) profile is appealing in terms of the mass productivity and optical backward compatibility [1], the transmission capacity and/or reach is fundamentally limited by inter-core crosstalk (IXT) under the constraint of fixed cladding diameter [2-4]. One solution to mitigate the IXT impact is the use of multiple-input multiple-output (MIMO) DSP [5].

In this work, to alleviate the IXT-induced limitation of achievable transmission reach over MCF links, we propose a novel unreplicated crosstalk canceller (UCC) that removes IXT by MIMO-DSP without any knowledge of interfering signal waveforms nor laser-originated phase noises, but only requiring (decoded) interfering data streams. The proposed UCC is numerically shown to provide IXT cancellation without laser-phase-synchronization. We also show through MCF transmission experiments that the UCC enables transmission reach for 16QAM signals to be extended to 300 km even over high-crosstalk four-core SI-MCF cable transmission links. To the best of authors' knowledge, this is the first SDM transmission demonstration performing digital IXT cancellation using installed SI-MCF cables.

Proposed: unreplicated crosstalk canceller

We consider an SDM system where N_t spatial channels propagate over a SDM link that mutually interfere with weak couplings, and received by N_r receivers. Assuming the linear coherent transmission, the *i*-th received signal y_i at each sample time is expressed as

$$y_i = h_{ii} x_i e^{j(\varphi_i^t + \varphi_i^r)} + \sum_{j=1, j\neq i}^{N_t} h_{ij} x_j e^{j(\varphi_j^t + \varphi_i^r)} + n_i, \quad (1)$$

where x_p, h_{pq}, φ_p^t, φ_p^r and n_p denote an *p*-th data stream, an (*p*,*q*)-th entry of a transfer matrix, a phase noise from *p*-th Tx laser, a phase noise from *p*-th Rx laser, and a noise for *p*-th spatial channel, respectively. The second term in eq. (1) represents IXT at *i*-th spatial channel from others. As for linear MIMO detection, two approaches are applicable to extract the *i*-th data stream estimate $\hat{x}_i$. If N_r received signals, namely $\boldsymbol{y} = [y_1, \cdots, y_{N_r}]^T$, are available, IXT is suppressed by finding a weight vector $\boldsymbol{w}_i$ through the well-known MIMO equalization: $\hat{x}_i = \boldsymbol{w}_i^T \boldsymbol{y}$, as demonstrated in [5]. This first approach is referred to as *nulling* of interferences (Figure 1(a)) in the context of wireless literatures [6,7]. The proposed UCC scheme in this work focuses on the second approach, known as *cancellation*, directly removing crosstalk components by reconstructing interfering signals in the digital

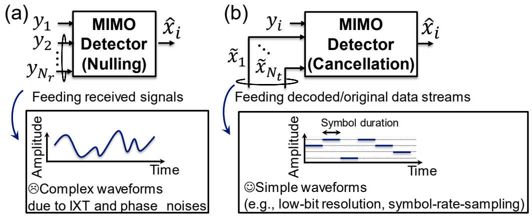

Fig. 1: Comparison of MIMO detection approaches: (a) crosstalk nulling (conventional MIMO equalizer), and (b) unreplicated crosstalk cancellation (proposed).

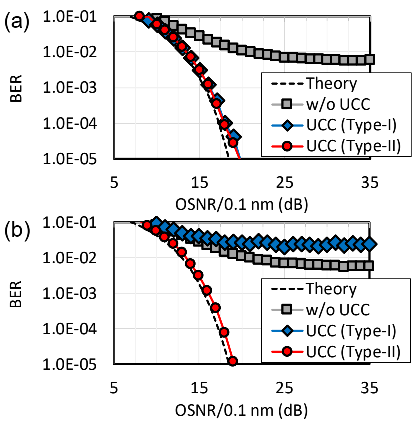

Fig. 2: Numerical BER performance of UCC for (a) phase-synchronized (case1), and (b) phase-unsyncronized systems (case2).

domain (Fig.1(b)). This is accomplished by feeding decoded data stream $\tilde{x}_j$ $(j \neq i)$ (or, original data stream x_j if available) into the canceller. The remaining factor h_{ij} is obtained via, say, adaptive filtering technique including least mean squared adopted unreplicated interference canceller originally designed for mode-multiplexed transmission links [8], and $e^{j(\varphi_j^t+\varphi_i^r)}$ is tracked by digital carrier phase recovery (CPR) schemes including single-input single-output (SISO) CPR or our previously-proposed MIMO-CPR [9]. Accordingly, the application of UCC requires a succeeding input of $\tilde{x}_j$ with low symbol error rate prior to its processing. In particular, this may be possible in uncoupled or weakly-coupling regimes because of low crosstalk impacts. The use of proposed UCC may bring a simplified coherent SDM transceiver architecture in SDM-MIMO transmission, because it requires no knowledge of complex interfering signal waveforms nor requirement on Tx/Rx-laser synchronization between spatial channels.

We evaluate the performance of UCC by a numerical simulation where 2×1 10-GBaud signals generated/received by light sources with a linewidth of 100 kHz are mutually mixed by a crosstalk matrix, and then processed with UCC. We assume that the detection of the 16QAM-modulated data stream x_1 is performed by the prior knowledge of AWGN-modulated x_2 which impacts as an origin of IXT of -15 dB. UCC performs crosstalk cancellation with MMSE-based deterministic weight vector either with SISO-CPR (type-I) or MIMO-CPR (type-II). Also assumed is two cases where Tx lasers are case1) phase-synchronized (i.e., $\varphi_1^t = \varphi_2^t$) and case2) unsynchronized. Figure 2 represents the BER results of x_1. BER improvement w.r.t. OSNR was saturated due to crosstalk from x_2. Remarkably, in the case 1, both types of UCC correctly output $\hat{x}_1$ only using y_1 and x_2 as input signals (Fig.2(a)). In the case2, however, type-I UCC fails to detect x_1 because of the presence of multiple phase noises (i.e., φ_1^t and φ_2^t), which cannot be dealt by SISO-CPR (Fig.2(b)). On the contrary, type-II UCC still provides high detection performance even for the case2. These results inform us that crosstalk cancellation for signals generated from phase-unsynchronized transmitters are enabled only by type-II UCC.

Experimental setup

The setup for MCF transmission link is shown in Fig. 3. Ten WDM channels were loaded with 12.5-GHz channel spacing by spectrally shaping ASE source through a wavelength-selective switch [10], located from 1549.627 nm to 1550.529 nm. The test channels were generated via two independent transmitter sets comprising 25-kHz-linewidth free-running external cavity lasers, arbitrary waveform generators (AWGs), IQ-modulators, and PDM emulators with a 295-ns delay for decorrelation. One generated 12-GBaud PDM-16QAM signals for inputs of core#1 and #3 with a 567-ns delay, and other was used for 12-GBaud PDM-QPSK signal generation into core#2 and #4 with a 1733-ns delay. Note that two AWGs are 10-MHz clock-synchronized. For both modulations, the transmission frame was the LDPC-coded 33360 symbol-length frame with overheads (OHs) of 25% for FEC decoding defined in DVB-S2 standard and 1.4% for the training sequence. To perform long-distance signal transmission, a four-fold recirculating loop system was constructed. The transmission fibre cable had 125-μm-cladding-diameter step-index homogeneous four-core MCFs with a span length of 30 km, core pitch of 40 μm, and measured IXT including fan-in/fan-out devices of less than -15.7 dB/span at 1550 nm [11]. The optical power

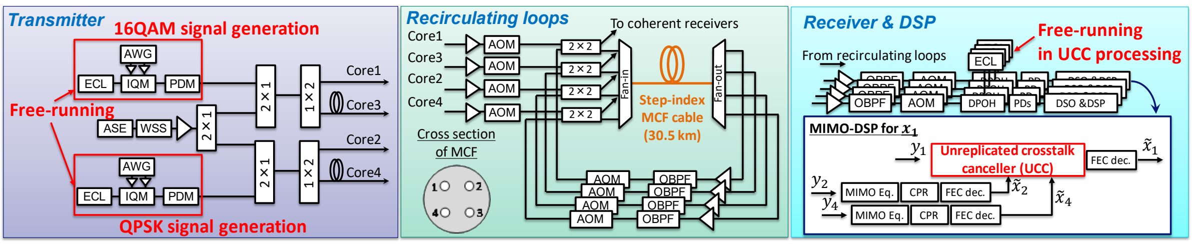

Fig. 3: Experimental setup for SDM-MIMO transmission over installed step-index four-core MCF cable.

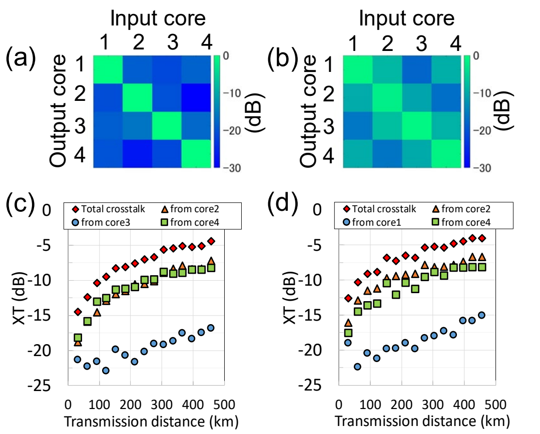

Fig. 4: Inter-core crosstalk analyses. Crosstalk matrices at (a) 30.5 km and (b) 457.5 km. Crosstalk accumulation at (c) core#1 and (d) core#3.

launched into the MCF was set to -5 dBm/λ/core.

After the transmission, signals were detected and stored by coherent receivers for offline processing, performing front-end error correction, chromatic dispersion compensation and MIMO CPR-embedded UCC. The strategy for demonstrating UCC performance is to firstly recover crosstalk-robust QPSK signals propagating over core#2 and #4 *without MIMO-structured DSP* (except for processing between polarisation), then LDPC-decoding them to rebuild and inject these data streams of x_2 and x_4 into UCC processing for the recovery of 16QAM signals propagating over core#1 and #3. Hence UCC recovered signals at core#1 by the inputs of $\{y_1, \tilde{x}_2, \tilde{x}_4\}$, and those at core#3 by $\{y_3, \tilde{x}_2, \tilde{x}_4\}$.

Experimental results

We start the analysis with IXT behaviour. For its purpose, (linear-scaled) IXT from *j*-th core to *i*-th core was obtained as $XT_{ij} = |h_{ij}|^2/|h_{ii}|^2$using the channel transfer matrix that was estimated from the weight matrix of conventional MIMO equalizer. Figures 4(a) and (b) show the crosstalk matrices at 30.5 km and 457.5 km, respectively, indicating that IXT at each core mainly attributes to interference from its adjacent cores. IXT accumulation in longer transmission reach were depicted in Fig.4(c) (at core#1) and Fig.4(d) (at core#3). Total IXT from all cores at the first span was around -15 dB, which was well agree with optically measured data. From the figures, we also noticed that total IXT exceeded -10 dB after 100-km transmission, which is not allowable especially for high-order QAM signal transmission. We then performed long-haul transmission, whose BER results for 16QAM signals at the centre channel (1550.057 nm) are summarized in Figure 5. Although not shown in the figure, even without any crosstalk cancellation, QPSK signals propagating over core#2 and #4 were perfectly reconstructed with no symbol error after LDPC decoding over a distance up to 305 km. 16QAM signals at core#1 and #3 were heavily affected by IXT, resulting in achievable reach of 91.5 km. The decoded QPSK symbol patterns $\{\tilde{x}_2, \tilde{x}_4\}$ together with each received signals for core#1 and core#3 were then used for UCC processing. The use of the UCC remarkably extended the achievable transmission reach to 305 km, corresponding to the distance with IXT of -5 dB (see Figs.4(c)-(d)). For a reference purpose, the detection performance of crosstalk nulling (i.e., conventional MIMO equalizer) that requires not only the inputs of received signal waveforms at the core under test and at neighbouring cores, but also Rx-laser phase synchronization is also plotted in Fig.5, showing a deviation between the BER curve for UCC. This might be a penalty of imperfect reconstruction of interference terms that were provided by UCC.

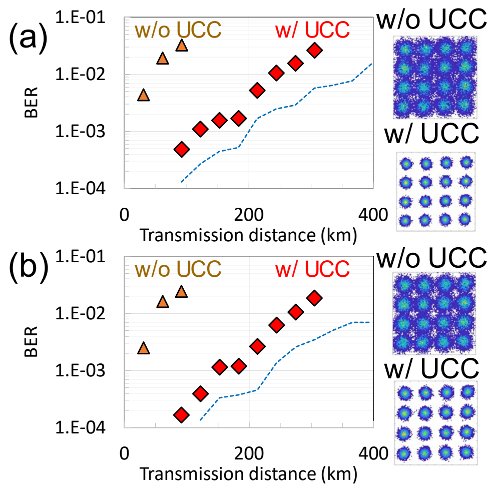

Fig. 5: BERs in long-haul 16QAM MCF transmission obtained by MIMO-DSP without UCC (triangle), with UCC (diamond) for (a) core#1 and (b) core#3. BERs by conventional MIMO equalization are also plotted for a reference (broken line).

Conclusions

We proposed unreplicated crosstalk canceller (UCC) to address the performance-limiting inter-core crosstalk (IXT) in multicore fibre links. Conducted transmission experiments using installed step-index multicore fibre cables showed that UCC scheme compensated for IXT only using decoded signals propagating adjacent cores, hence allowing PDM-16QAM signals to successfully transmit over 300 km even with high IXT presence of -5 dB.

Acknowledgements

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