Reduction of Modal Dispersion in a long-haul 15-Mode Fiber link by means of Mode Permutation

Giammarco Di Sciullo(1,2), Menno van den Hout(1,3), Georg Rademacher(1,4), Ruben S. Luís(1), Benjamin J. Puttnam(1), Nicolas K. Fontaine(5), Roland Ryf(5), Haoshuo Chen(5), Mikael Mazur(5), David T. Neilson(5), Pierre Sillard(6), Frank Achten(6), Jun Sakaguchi(1), Chigo Okonkwo(3), Antonio Mecozzi(2), Cristian Antonelli(2), and Hideaki Furukawa(1).

(1) NICT, Koganei, Tokyo, Japan, giammarco.disciullo@graduate.univaq.it
(2) University of L'Aquila and CNIT, L'Aquila, Italy,
(3) High Capacity Optical Transmission Lab, Eindhoven University of Technology, The Netherlands,
(4) INT, University of Stuttgart, Stuttgart, Germany,
(5) Nokia Bell Labs, New Providence, NJ, USA,
(6) Prysmian Group, France and The Netherlands.

Abstract *We experimentally investigate mode permutation schemes to mitigate the impact of differential mode delay in a long-haul 15-mode fiber link. These schemes reduce the rate at which the link intensity impulse response duration increases with transmission distance, which results in a decreased MIMO DSP complexity.*

Introduction

Space-division multiplexing (SDM) is considered a promising approach to avoid a capacity crunch of the global fiber-optic network[1],[2]. In particular, multi-mode fibers (MMFs), where independent data signals are multiplexed onto different spatial modes, are suitable candidates as the next-generation transmission medium for future SDM systems. MMFs can accomodate a large number of spatial channels within the same 125 µm cladding diameter as standard single-mode fibers (SMFs), thereby preserving the fiber mechanical reliability as well as compatibility with current cabling and manufacturing processes[3]. However, the accumulation of differential mode delay (DMD) directly affects the required temporal memory for the time-domain multiple-input multiple-output (MIMO) equalizer[4], which may result in limitations on mode count and transmission reach. To mitigate DMD accumulation, strong mode coupling can be intentionally introduced in the MMF link. This approach is based on the notion that modal dispersion accumulates proportionally to the square root of propagation distance in the regime of strong mode mixing, whereas it accumulates proportionally to propagation distance in the regime of no-to-weak mode coupling[5],[6]. A practical scheme to achieve strong mode coupling is the one based on inserting lumped mode scramblers along the fiber link[6]. Cyclic mode permutation (C-MP) and cyclic mode-group permutation (C-MGP) are recently proposed implementations of this scheme[7]–[10].

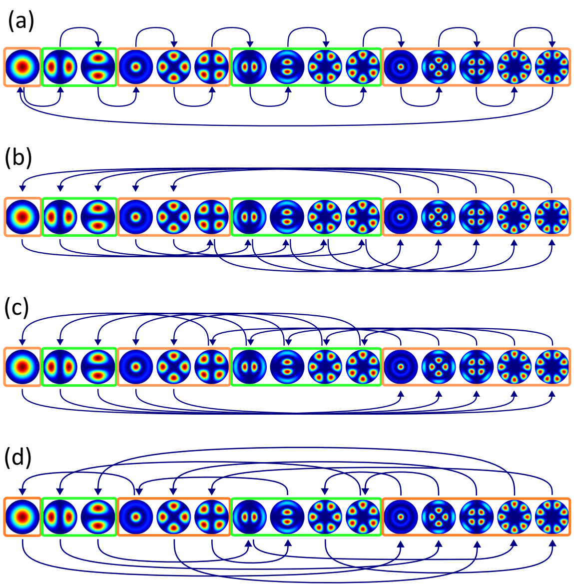

Fig. 1: Illustration of (a) C-MP, (b) Clockwise C-MGP, (c) Counter-clockwise C-MGP and (d) NC-MGP.

In this work, we experimentally investigate the effectiveness of four different mode permutation schemes in a recirculating-loop-based long-haul 15-mode fiber link. At the end of each loop, mode permutation is implemented by means of a multiplexer/de-multiplexer device pair, where the first device is used to separate the multi-mode field at the output of the MMF in single-mode fields which are then cross-connected at the input of the second device. Use of these permutation schemes enabled to increase the transmission reach from 530 km to 1178 km with a considerably reduced complexity of the receiver MIMO

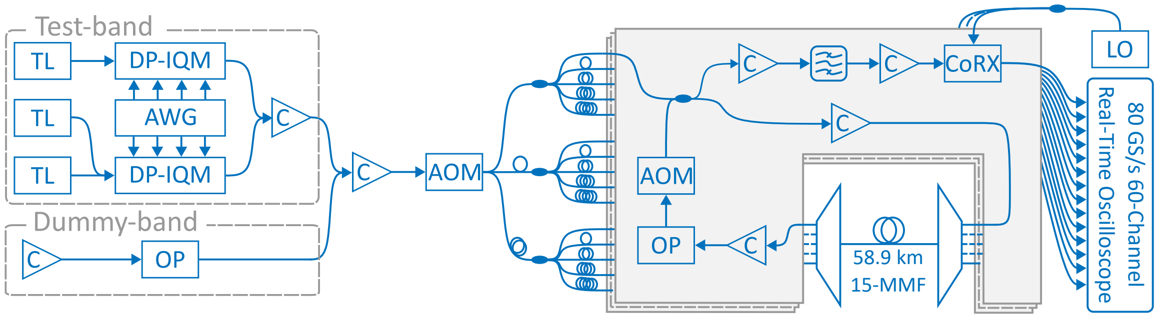

Fig. 2: Experimental setup of the recirculating-loop-based long-haul 15-mode fiber link used to test the effectiveness of the considered mode-permutation schemes.

digital signal processing (DSP). At 530 km, a reduction in the duration of the MMF link intensity impulse response (IIR) by more than 65% was observed. The measured IIR duration increased proportionally to the square-root of transmission distance, indicating operation in the strong mode-coupling regime. In contrast, in the absence of mode permutation the IIR duration increased linearly with transmission distance, prior to transitioning to a sub-linear increase at approximately 400 km. The investigated schemes showed similar performance, although mode-group permutation was found to reduce the wavelength dependence of the IIR duration.

Mode permutation schemes

The permutation schemes that we investigated are illustrated in Fig. 1. The first scheme[7] (Fig. 1a) is based on unitary C-MP, namely the 15 spatial modes are cyclically shifted by one position toward higher order modes at each permutation stage. In the second[10] and third schemes, the 15 spatial modes are cyclically shifted clockwise (Fig. 1b) and counter-clockwise (Fig. 1c) by five positions, respectively, corresponding to the largest mode-group size. These schemes are characterized by a periodic pattern, where the spatial modes return to their initial configuration after either 15 or 3 permutation stages. The fourth scheme (Fig. 1d), which is considered for the first time in this work, avoids this periodicity by introducing controlled inter mode-group permutation. In this scheme, which we refer to as non-cyclic mode-group permutation (NC-MGP), the spatial modes of a given mode group are mapped onto other spatial modes belonging to the remaining mode groups, while minimizing multiple mappings between two mode groups.

Experimental setup

The experimental setup used to demonstrate the effectiveness of the analyzed permutation schemes is depicted in Fig. 2. A three-channel test-band was generated by modulating carriers produced by three tunable lasers (TLs) using two dual-polarization IQ-modulators (DP-IQMs) driven by a 65 GS/s 4-channel arbitrary waveform generator (AWG). The modulated signals were dual-polarization quadrature phase-shift keying (DP-QPSK) signals, with 1% roll-off root-raised cosine pulse shape, and transmitted at a rate of 24.5 GBd. A dummy-band was generated by spectrally flattening amplified spontaneous emission noise produced by an erbium-doped fiber amplifier using an optical processor (OP). The combined signal comprising both test- and dummy-band was split and delayed to produce 15 uncorrelated replicas with a relative delay of 150 ns to be fed into 15 parallel path-length aligned recirculating loops. The signals related to each of the different 15 loops were amplified and then multiplexed using a multi-plane light converter (MPLC) before the multiplexed signal was launched into a 58.9 km long span of 15-mode MMF[11]. The outputs of the MPLC de-multiplexer were connected to the single-mode loops according to the proposed permutation schemes, before entering a second amplification stage followed by OPs to compensate for amplifier gain tilts. For signal reception, the 15 outputs of the parallel loops were amplified, then the channel of interest (COI) was filtered and amplified again prior to being received by 15 coherent receivers (CoRXs) sharing the same local oscillator (LO). The electrical signals were acquired by an 80-GS/s 60-channel real-time oscilloscope, storing traces for offline DSP, which consisted mainly of a time-domain 30×30 MIMO equalizer.

Experimental results

Figure 3a shows the IIR of the 15-mode fiber link at 1545.7 nm in the absence of mode permutation for different transmission distances. In this case, the inherently weak inter-mode-group coupling is responsible for a linear increase of the IIR duration with transmission distance. The growth rate of the IIR duration reduces as inter-group

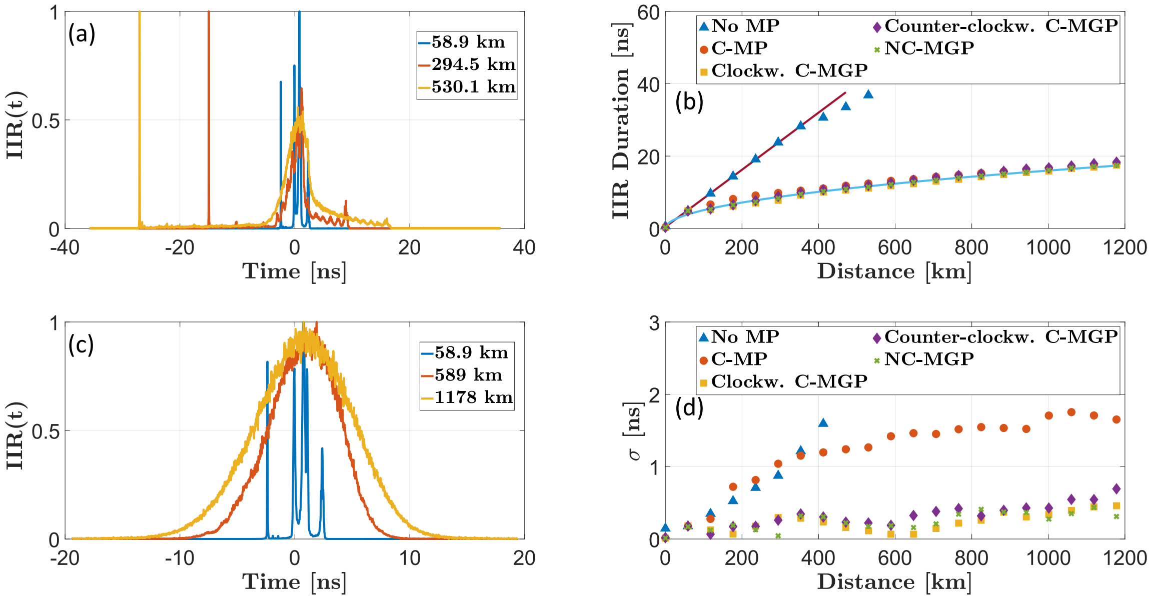

Fig. 3: Intensity impulse response at 1545.7 nm for different transmission distances (a) in the absence of mode permutation and (c) with NC-MGP. (b) Wavelength-averaged IIR duration in the cases of no mode permutation, unitary C-MP, clockwise C-MGP, counter-clockwise C-MGP, and NC-MGP. (d) Standard deviation of the IIR duration for each mode permutation scheme versus transmission distance.

coupling becomes non-negligible. This transition can be observed in Fig. 3b, where the measured IIR duration is plotted by triangles as a function of transmission distance, along with a linear fit. Here we define the IIR duration as the time interval in which 98% of the IIR energy is contained. Each data point was obtained by averaging the duration of the IIR of the MMF link for five different wavelength channels spanning the C-band. Figure 3b also shows a plot of the IIR duration measured for each of the considered mode permutation schemes along with a square-root fit. No significant difference in performance between schemes can be observed, and a reduction in the IIR duration of approximately 65% is achieved at 530.1 km. The excellent agreement between the data and the square-root fit is an indication of the fact that the MMF link is operating in the regime of strong mode coupling, which demonstrates the effectiveness of the considered permutation schemes in introducing inter-mode-group coupling. This result is further confirmed in Fig. 3c, where the IIR measured at 1545.7 nm in the case of NC-MGP is clearly seen to become Gaussian-shaped, as expected in systems with strong mode mixing[12],[13]. We note that the linear increase of the IIR duration with propagation distance in the absence of mode permutation may partly result from some loop artifacts, such as path-length misalignment between single-mode loops, which are unavoidable in practical transmission systems. If this were the case, our results show that mode permutation can effectively mitigate the impact of these artifacts. Finally, we analyzed the wavelength dependence of the IIR duration. To this end, we evaluated the standard deviation, σ, of the IIR duration measured at five different wavelength channels spanning the C-band, for each permutation scheme. The resulting values of σ are plotted versus transmission distance in Fig. 3d. The plot shows a weak wavelentgh dependence of the IIR duration, with the largest fluctuations being observed for the C-MP scheme.

Conclusions

We have experimentally investigated the impact of periodic mode permutation on the accumulation of DMD in a long-haul 15-mode fiber link. We considered four permutation schemes and demonstrated their effectiveness in introducing random coupling between all the fiber modes. We showed that in the presence of mode permutation, the MMF link intensity impulse response duration increases proportionally to the square root of transmission distance, rather than proportionally to transmission distance, thereby considerably reducing the complexity of the receiver MIMO-DSP. The considered schemes have similar performance and negligible wavelength dependence. Our results suggest that in-line mode permutation is an effective solution to mitigate the accumulation of DMD in MMF links and it constitutes a promising design strategy for future long-haul optical communication systems based on MMFs.

Partial funding is from the INCIPICT and FIRST projects and from the KPN-TU/e Smart Two program.

References

[1] P. J. Winzer and D. T. Neilson, "From Scaling Disparities to Integrated Parallelism: A Decathlon for a Decade", *Journal of Lightwave Technology*, vol. 35, no. 5, pp. 1099–1115, 2017. DOI: 10.1109/JLT.2017.2662082.

[2] B. J. Puttnam, G. Rademacher, and R. S. Luís, "Space-division multiplexing for optical fiber communications", *Optica*, vol. 8, no. 9, pp. 1186–1203, 2021. DOI: 10.1364/OPTICA.427631.

[3] S. Matsuo, K. Takenaga, Y. Sasaki, *et al.*, "High-Spatial-Multiplicity Multicore Fibers for Future Dense Space-Division-Multiplexing Systems", *Journal of Lightwave Technology*, vol. 34, no. 6, pp. 1464–1475, 2016. DOI: 10.1109/JLT.2015.2508928.

[4] R. Ryf, S. Randel, A. H. Gnauck, *et al.*, "Mode-Division Multiplexing Over 96 km of Few-Mode Fiber Using Coherent 6 $\times$ 6 MIMO Processing", *Journal of Lightwave Technology*, vol. 30, no. 4, pp. 521–531, 2012. DOI: 10.1109/JLT.2011.2174336.

[5] C. Antonelli, A. Mecozzi, M. Shtaif, and P. J. Winzer, "Stokes-space analysis of modal dispersion in fibers with multiple mode transmission", *Opt. Express*, vol. 20, no. 11, pp. 11 718–11 733, 2012. DOI: 10.1364/OE.20.011718.

[6] S. Ö. Arik, K.-P. Ho, and J. M. Kahn, "Group Delay Management and Multiinput Multioutput Signal Processing in Mode-Division Multiplexing Systems", *J. Lightwave Technol.*, vol. 34, no. 11, pp. 2867–2880, 2016.

[7] K. Shibahara, T. Mizuno, D. Lee, *et al.*, "DMD-Unmanaged Long-Haul SDM Transmission Over 2500-km 12-Core × 3-Mode MC-FMF and 6300-km 3-Mode FMF Employing Intermodal Interference Canceling Technique", *J. Lightwave Technol.*, vol. 37, no. 1, pp. 138–147, 2019.

[8] K. Shibahara, T. Mizuno, H. Ono, *et al.*, "Long-Haul DMD-Unmanaged 6-Mode-Multiplexed Transmission Employing Cyclic Mode-Group Permutation", in *Optical Fiber Communication Conference (OFC) 2020*, Optica Publishing Group, 2020, Th3H.3. DOI: 10.1364/OFC.2020.Th3H.3.

[9] K. Shibahara, M. Hoshi, and Y. Miyamoto, "10-spatial-mode 1300-km Transmission over 6-LP Graded Index Few-Mode Fiber with 36-ns Modal Dispersion", in *Optical Fiber Communication Conference (OFC) 2023*, Optica Publishing Group, 2023, M2B.2.

[10] M. van den Hout, G. Di Sciullo, G. Rademacher, *et al.*, "273.6 Tb/s Transmission Over 1001 km of 15-Mode Fiber Using 16-QAM C-Band Signals", in *Optical Fiber Communication Conference (OFC) 2023*, Optica Publishing Group, 2023, Th4B.5.

[11] P. Sillard, D. Molin, M. Bigot-Astruc, K. de Jongh, and F. Achten, "Low-Differential-Mode-Group-Delay 9-LP-Mode Fiber", in *Optical Fiber Communication Conference*, Optica Publishing Group, 2015, p. M2C.2. DOI: 10.1364/OFC.2015.M2C.2.

[12] R. Ryf, S. Randel, A. H. Gnauck, *et al.*, "Space-division multiplexing over 10 km of three-mode fiber using coherent 6 × 6 mimo processing", in *Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2011*, Optica Publishing Group, 2011, PDPB10. DOI: 10.1364/OFC.2011.PDPB10.

[13] A. Mecozzi, C. Antonelli, and M. Shtaif, "Intensity impulse response of SDM links", *Opt. Express*, vol. 23, no. 5, pp. 5738–5743, 2015. DOI: 10.1364/OE.23.005738.