Scaling Spatial Multiplexing with Principal Modes

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***Abstract* — We assess the robustness of a principal modes approach to scalable space-division multiplexing transceivers in the presence of mode-dependent loss. Results show resilience to several mode-dependent loss regimes.**

Keywords* — *Principal modes, multimode fibres, mode-dependent loss.

I. Introduction

Space-division multiplexing (SDM) has been proposed as a strategy to meet future capacity demands and to cope with sustainable cost- and energy-per bit. Amongst the candidate solutions, the transmission over multimode fibres (MMFs) offers the highest spatial information density and potential integration gains in transceivers, wavelength selective switches, optical amplifiers and both fibre- and chip-to-fibre interfaces. The multitude of modes adds new linear impairments, namely group delay (GD) spread [1, 2], stemming from the interplay between differential mode delay (DMD) and linear mode coupling, and mode-dependent loss (MDL) [3]. The GD spreading can be undone using multiple-input multiple-output (MIMO) equalisation. However, conventional transceivers require all guided modes to be detected and processed for successful equalisation, binding the number of coherent front-ends required to that of the fibre modes. This limits the deployment of fibres with higher number of modes. A spatially scalable multimode transceiver would unlock MMFs approaching 1000 spatial and pol. modes [4, 5].

In MMFs, a set of modes that are frequency independent to 1st order can be identified. These modes are referred to as principal modes (PMs) and have initially been proposed as a way to overcome modal dispersion in direct detection systems [6, 7]. In [8], we consider the use of PMs as a platform for scaling the number of spatial tributaries in MMFs coherent optical systems in line with traffic demand. T spatial and pol. tributaries are transmitted over a M-mode fibre ($T < M$) by exciting T PMs and using T (or $T/2$ dual pol.) receivers. In the present work, we assess the robustness of such approach in the presence of different MDL regimes, since link MDL can considerably affect the PMs orthogonality and bandwidth [9, 10].

II. SDM Transmission using PMs

The coherent SDM transmission system considered for transmission simulations in this work is shown in Fig. 1. To estimate the $M \times M$ matrix $\mathbf{H}(\omega)$ that describes the MMF channel, a least-square approach based on frequency-domain training sequences (TSs) with 4096 symbols is used. $\mathbf{H}(\omega)$ can also include impairments of the transmission link. Estimates of the *input* principal modes, $\mathbf{U}_e$, and their corresponding group delays can be calculated as the eigenvectors and eigenvalues, respectively, of a group delay operator defined as $\mathbf{G}(\omega) = \mathrm{j}\,\partial_\omega \mathbf{H}_e(\omega)\,\mathbf{H}_e^{-1}(\omega)$ [11], where $\mathbf{H}_e(\omega)$ is the estimate of the MMF channel. The *output* PMs, $\mathbf{V}_e$, can be calculated using $\mathbf{H}_e(\omega)$ and $\mathbf{U}_e$. The frequency independent characteristic of PMs allows to assume, over a certain frequency interval, that $\mathbf{H}_e(\omega) = \mathbf{V}_e \boldsymbol{\Lambda}_e(\omega) \mathbf{U}_e^H$ [6], where $(\cdot)^H$ is the Hermitian and $\boldsymbol{\Lambda}(\omega)$ is a diagonal matrix accounting for the overall group delays and mode gain/loss. Estimates of mode gain/loss can be obtained as the logarithm of the eigenvalues of $\mathbf{D}(\omega) = \mathbf{H}_e(\omega)\mathbf{H}_e^H(\omega)$. The estimation of PMs are sensitive to artefacts on $\mathbf{H}_e(\omega)$. As in [8], we also modify the output PMs by zero-forcing the residual channel, i.e. the end-to-end channel obtained after using the PMs for transmission. This new set of PMs (including both input and output PMs) is indicated as PMs* hereafter.

Assuming that channel state information can be fed back from the receiver to the transmitter, as depicted in Fig. 1, the input PMs (or PMs*) $\mathbf{U}_e$ are exploited for mode multiplexing. At the channel output, the output PMs (or PMs*) $\mathbf{V}_e$ are used for mode demultiplexing. Both $\mathbf{U}_e$ and $\mathbf{V}_e$ are applied in the optical domain by an ideal programmable mode multiplexer [5, 12]. This approach reduces channel memory and partially suppresses mode coupling at the receiver front-end [8], an effort focused at reducing to T (or $T/2$ for dual pol. receivers) the number of

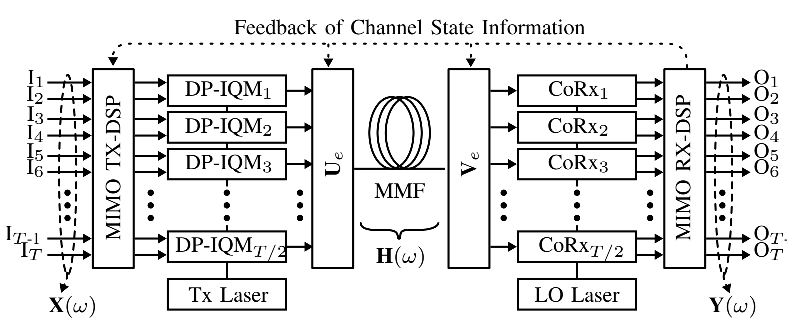

Fig. 1. Schematic diagram of the optical transmission system.

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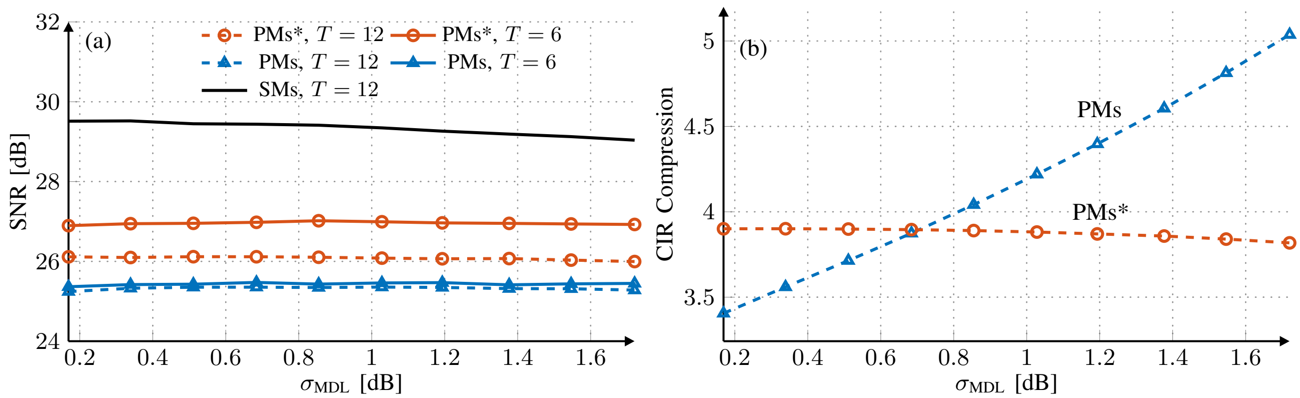

Fig. 2. (a) Average SNR of the received constellations versus σ_{MDL}. (b) CIR compression versus σ_{MDL}. SMs (solid line), PMs (lines with triangles) and PMs* (lines with circles) are used. Solid lines with markers for the 6 PMs case and dashed lines with markers for the 12 PMs case.

optical front-ends necessary to transmit&detect T spatial tributaries ($T < M$). We then transmit T tributaries by exciting T PMs with the lowest GDs. At the receiver, the residual channel is estimated using TSs transmitted by only the T tributaries, and MMSE MIMO equalisation is then carried out. However, and because, PMs are affected by DMD and MDL, we evaluate their performance against the optimal basis provided by the Schmidt modes (SMs). SMs are obtained through singular value decomposition of $\mathbf{H}_e(\omega)$ [9]. Although forming an optimal multiplexing basis, SMs are not readily suitable for optical domain implementation due to their frequency dependent nature, thus mode coupling and channel memory reduction would not be achieved at the receiver front-end.

We assume a 50-km graded-index MMF with $M = 12$ spatial and pol. modes – optimised following [13, 4]. To account for larger link MDL, the mode attenuation vector is varied by changing the core doping contrast. The fibre parameters are available in the underlying data (see footnote). Transmission considers the semi-analytical channel model in [1], with a linear mode coupling of -20 dB/km. Receiver includes quantisation to 7 bits. We transmit 16-QAM signals at 33 GBd, and consider as performance metrics the signal-to-noise ratio (SNR) of the received constellations (averaged over T, $1/T \sum_{i=1}^{T} E|X_i|^2/E|X_i - Y_i|^2$). Furthermore, the channel intensity impulse response (CIR) at the receiver front-end is estimated, considering the pulse RMS width, to evaluate to what extent channel memory is reduced by the PMs. All results are obtained for an optical SNR of 35 dB.

Fig. 2(a) shows the SNR of the received constellations as a function of the standard deviation of the accumulated MDL, σ_{MDL}. Performance is shown for $T = 12$ and for the transmission using the best 6 PMs ($T = 6$). The results show that correcting the PMs (by zero-forcing) improved performance by 0.7 dB and 1.5 dB for $T = 12$ and $T = 6$, respectively. The SNR gap between PMs (or PMs*) and SMs is mainly due to errors in the estimation of $\mathbf{H}(\omega)$ and/or errors in the eigendecomposition of $\mathbf{H}_e(\omega)$. Finally, it can be observed that the PMs and PMs* performance are not significantly affected by MDL (for the regimes tested).

Fig. 2(b) shows the CIR compression achieved by using PMs (or PMs*) as a function of σ_{MDL} – taking as reference CIR related to $\mathbf{H}_e(\omega)$ without pre- or post-compensation. It can be seen that CIR compression of 4 times can be achieved for the MDL regimes tested.

III. Conclusion

We have shown a PMs approach can successfully reduce end-to-end channel memory and suppresses mode coupling at the receiver front-end for several MDL regimes. Therefore, this is a promising technique to exploit a subset of the fibre spatial and pol. modes while keeping the number of optical front-ends to that of tributaries transmitted.

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