# Spatial Light Manipulation for Scalable Spatial Division Multiplexing

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***Abstract*— We review our recent work on spatial manipulation techniques for scalable space-division multiplexing in multimode fiber systems. We demonstrate principal mode-based multiplexing for significant crosstalk suppression and efficient modal control under challenging modal dynamics and mode-dependent loss.**

***Keywords*— *multimode fibers, space-division multiplexing, high-capacity transmission***

## I. INTRODUCTION

Space-division multiplexing (SDM) has emerged as a key solution to overcome the capacity limitations of single-mode fibers (SMFs). SDM technologies have evolved significantly, ranging from SMF bundles and uncoupled multi-core fibres (MCFs) to more advanced coupled-core MCFs (CC-MCFs) and multimode fibers (MMFs). Beyond increased trunk and connectivity density, SDM potential lies in opto-electronic transceiver integration – shared hardware (e.g. laser) and common digital signal processing (DSP) functions across spatial channels. Critically, as spatial channel density increases, so do the opportunities for integration gains. Recently, 1 Pb/s transmission over CC-MCFs has been demonstrated after 1800 km over 19-cores [1]. However, CC-MCFs are unlikely to scale well from 19 cores.

Instead, we have recently explored the potential of MMFs for much larger spatial information density. In [2], we shown that MMFs can support high-capacity transmission up to ~1000 modes DCI distances (~100km) – by pushing the core diameter and index contrast. Nevertheless, the advantages of multimode SDM come with notable challenges, namely, group delay (GD) spread, mode-dependent loss (MDL), and modal dynamics [3-5]. While GD spread can be mitigated by MIMO-DSP [6], MDL leads to an inherent throughput loss.

Despite the promise of multimode SDM fibers to deliver much higher fundamental capacity, efficiently accessing this capacity remains a major hurdle. A major bottleneck in multimode SDM is that conventional MIMO equalization requires detection of all guided modes for proper signal recovery [7], linking the number of fiber modes directly to the number of coherent front-ends at the transceiver. This constraint makes it impractical to deploy high-mode-count fibers, as deploying transceivers with the required number of optical front-ends from the outset is not feasible.

A tantalizing alternative is for the use of all-optical signal processing to untangle light propagation through MMFs using an adaptive MPLC as experimentally demonstrated in [8], albeit for a continuous wave scenario. To tackle this bandwidth issue, we proposed in [6] a selective mode vector launching and detection scheme based on principal modes (PMs). This approach suppresses crosstalk (XT) before coherent detection, reducing equalization complexity and allowing the number of receiver front-ends to scale following the number of transmitted data tributaries, rather than the total number of supported fiber modes. Further avenues to complexity reduction remain to be explored through using machine learning based approaches in the optical domain [9] and/or in the electronic domain [10].

Here we explore the potential of the all-optical PM-based approach to diagonalize the fiber channel and allow a significant reduction in the DSP complexity. We show for a fiber with 342 spatial and polarization modes that less than 1% of full MIMO-DSP complexity is required. Finally, throughput scaling is assessed with channel estimation and equalization limited to the number of tributaries.

## II. PRINCIPAL MODES BANDWIDTH AND TRANSMISSION

PMs are characterized by propagating, on an end-to-end perspective, with well defined GDs, independent of frequency to 1st order. They allow to diagonalize a given fiber channel $\mathbf{H}(\omega)$, as $\mathbf{H}(\omega)\approx\mathbf{V}(\omega_c)\mathbf{\Lambda}(\omega)\mathbf{U}^{H}(\omega_c)$ – where $\mathbf{\Lambda}(\omega)$ represents the diagonalized channel with well defined GDs, at a given frequency $\omega_c$, and $\mathbf{U}(\omega)$ and $\mathbf{V}(\omega)$ represent the input and output pair eigenvector sets – the so-called PMs.

Given the PMs sensitivity to GD spread and MDL, the PMs

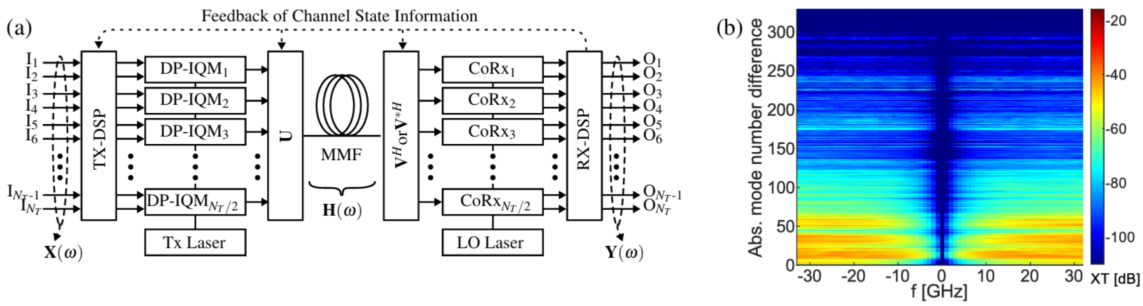


Fig. 1. (a) Transmission system with spatial multiplexing over the PMs. (b) XT versus of frequency and absolute mode number difference for the 10-km 342-mode fibre, when using the PMs in the absence of modal dynamics.

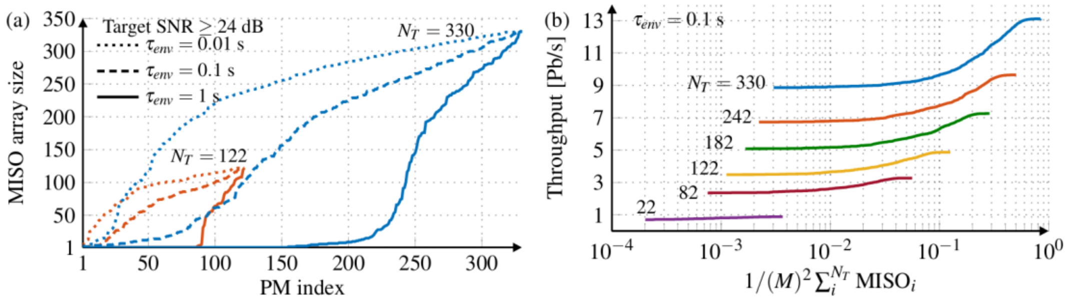


Fig. 2. (a) Required MISO array size for each PM to achieve SNR $\geqslant$ 24 dB. Results are sorted in ascending order. (b) Throughput (for a WDM bandwidth of $\approx$5 THz) versus the sum of MISO array sizes of each PM normalized by the 342x342 MIMO case.

have a limited coherence bandwidth [11] specific to channel conditions but in general it reduces with the GD spread – algorithms to extend the PMs bandwidth have been proposed [11]. Even though, many of the PMs have a spectral width comparable to that of the modulated signals and in many cases smaller, interference between PMs can still be weak, or limited to a few PMs. The latter can be exploited in SDM transmission given low-order MISO equalization.

Fig. 1(a) depicts the SDM system considered. The number of coherent transceivers used for transmission is determined by that of data tributaries, $N_T$. Taking advantage of CSI (albeit outdated due to channel modal dynamics [4]), modal multiplexing and demultiplexing is conducted implementing **U** and **V**, respectively. Programmable mode (de)multiplexers based on multi-plane light conversion (MPLC) allow for the implementation of such types of mappings [8] (i.e., **U** and **V**). The actual set of output PMs is modified in this work such that the residual channel at $\omega_c$, $\mathbf{H}_{\mathbf{res}}(\omega_c) = \mathbf{V}^{\mathrm{H}}\mathbf{H}(\omega_c)\mathbf{U}$, is perfectly diagonalized – other approaches for extended bandwidth / reduced crosstalk offer further potential [11].

Fig. 1(b) shows an analysis of the residual XT obtained despite using PMs due to the fiber MDL (even in the absence of channel modal dynamics) – that breaks the PMs orthogonality. The XT is obtained from the residual channel $\mathbf{H}_{\mathbf{res}}(\omega)$ for all mode pairs (i, j) as a function of frequency and averaged for pairs with the same absolute mode number distance (i.e. $|i - j|$). As expected, XT is negligible for the central frequency in all cases, but for a significant number of adjacent PMs, the bandwidth over which XT is negligible can be quite narrow, although XT rapidly flattens out at around −20 dB. Conversely, over PMs sufficiently far apart (GD-wise), XT can be negligible with little frequency dependency.

Critically, the PM-based approach explored here is subject to limitations due to channel drift. This is, the set of PM pairs obtained are outdated given the CSI acquisition time (and of at least one round-trip time), leading to residual XT. DSP-based equalization is then necessary to mitigate it.

## III. Simulations and Results

Transmission simulations with 22 GBd 256-QAM signals over a 10-km 342-mode MMF were performed. Training sequences (TSs) of 8192 symbols were used for least-square (LS) frequency domain channel estimation **H'**(ω) at the receiver. Then, **U** and **V** are estimated from **H'**($\omega$) and applied for transmission over the drifted channel. The channel drift time is set to $\tau_{env}$ = [0.01,0.1,1]s reflecting typical acquisition time with holography (∼0.1−100s), and the long term stability of PMs reported in [12]. Investigations were conducted scaling the number of tributaries from 22 up to 330 – in each case selecting the PMs with lower GD deviation from the median. Ideal transceivers are considered, and #front-ends limited to $N_T$. OSNR is set to 35 dB independently of $N_T$. For each tributary, MISO equalization is applied considering only the strongest interferes.

Fig. 2(a) shows the required MISO array size for each PM to achieve a target SNR ≥ 24 dB. The results are shown in ascending order for the sake of clarity. The MISO array size increases as $\tau_{env}$ decreases, but many PMs can achieve SNR ≥ 24 dB with SISO. Despite the vulnerability to channel drift, the results indicate that PMs can be used for coherent transmission yet leading to reduction of equalization complexity compared to full MIMO case.

Fig. 2(b) shows the throughput for $\tau_{env}$ = 0.1s as a function of MISO complexity normalized to that of full MIMO case. Fig. 2(b) suggests that one can increase throughput by addressing more modes, while equalization complexity per tributary remains at similar levels. For instance, with an equalization complexity significantly smaller than that of the $M$×$M$ MIMO case, it is possible to transmit from roughly 1 to 9 Pb/s with 256-QAM by increasing the number of addressed modes from 22 to 330. Also, the results indicate that for a given target throughput, one can operate with either fewer PMs at higher DSP complexity, or more PMs (larger number of coherent front-ends) but lower DSP complexity.

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