On the Equalisation Requirements for Scalable SDM Transmission

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Abstract: We review our recent work on principal modes for high-capacity coherent SDM transmission. The number of spatial data tributaries is scaled up with reduced equalisation complexity under mode-dependent loss and modal dynamics.

1. Introduction

Space-division multiplexing (SDM) has been widely investigated as a platform to accommodate future capacity demands expected to exceed single-mode fibre (SMF) capabilities. Among several approaches, mode-division multiplexing (MDM) over multimode fibres (MMFs) offers the highest potential for integration gains in both system and component levels. However, conventional architectures require detecting and processing the full spatial domain supported by the fibre to guarantee low system outage probability, leading to limited scalability with the number of supported modes. In [1] and [2], we investigated SDM transmissions based on a selective mode vector excitation to weaken this requirement. We explored the basis formed by principal modes (PMs) to reduce channel memory and crosstalk (XT) at the receiver front-end. In this scenario, the number of transmitted data tributaries N_T over a MMF with M spatial and polarisation modes can be increased progressively, while the number of transceiver front-ends follow N_T, importantly, when $N_T < M$. In this work, we review our recent achievements on PM-based SDM transmissions. Firstly, we describe the transmission paradigm followed by an analysis on how XT and equalisation requirements scale with the number of spatially multiplexed data tributaries. We show that reduced equalisation complexity, compared to the full multiple-input multiple-output (MIMO) case, can be achieved by using PMs even under mode dependent loss (MDL) and environmental-induced channel drift.

2. SDM Transmission with Principal Modes

PMs are characterised by having field distribution and GDs that are frequency independent to 1^{st} order (over a coherence bandwidth) [3, 4]. They correspond to the eigenstates of the group delay (GD) operator defined as $\mathbf{G}(\omega) = j\mathbf{H}^{-1}(\omega)\partial_\omega\mathbf{H}(\omega)$ [5], where $\mathbf{H}(\omega)$ is a $M \times M$ matrix representing the MMF channel. The eigenvectors and eigenvalues of $\mathbf{G}(\omega)$ are the set of PMs at fibre *input*, arranged as columns of the $M \times M$ matrix $\mathbf{U}$, and their GDs $\tau_1, \tau_2, \cdots, \tau_M$, respectively. The set of PMs at fibre *output* $\mathbf{V}$ can be determined by forward-propagating $\mathbf{U}$. Note that each *input* PM has its corresponding *output* PM, forming an exclusive PM pair.

The modal basis formed by the PMs is orthogonal, but this characteristic is partially lost in the presence of MDL [6]. Nevertheless, interference between PMs can still be weak and one can take advantage of this for XT suppression in SDM transmissions. Fig. 1 illustrates a transmission system that uses PMs. By exploiting the feedback of channel state information (CSI) from receiver to transmitter, modal multiplexing and demultiplexing can be performed following $\mathbf{U}$ and $\mathbf{V}$, respectively. When the mappings described by $\mathbf{U}$ and $\mathbf{V}$ are implemented in the optical domain, e.g. using multi-plane light conversion (MPLC) [7], channel memory and XT can be reduced at the receiver front-end [1]. This strategy opens the possibility of reducing to N_T (or $N_T/2$ for dual pol. receivers) the number of transceiver front-ends needed to transmit N_T spatial data tributaries. Moreover, mismatches between the set of PMs and the MMF channel subject to environmental-induced drift can also cause XT. Eventually, equalisation is necessary to reduce the impact of such impairment on system performance.

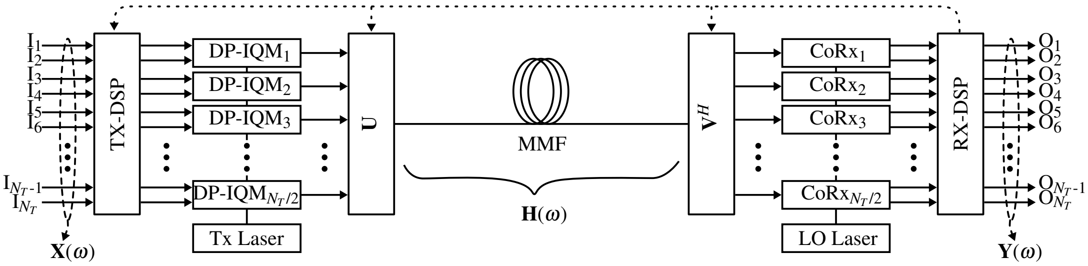

Fig. 1. Schematic diagram of the optical transmission system with selective mode vector launch and detection.

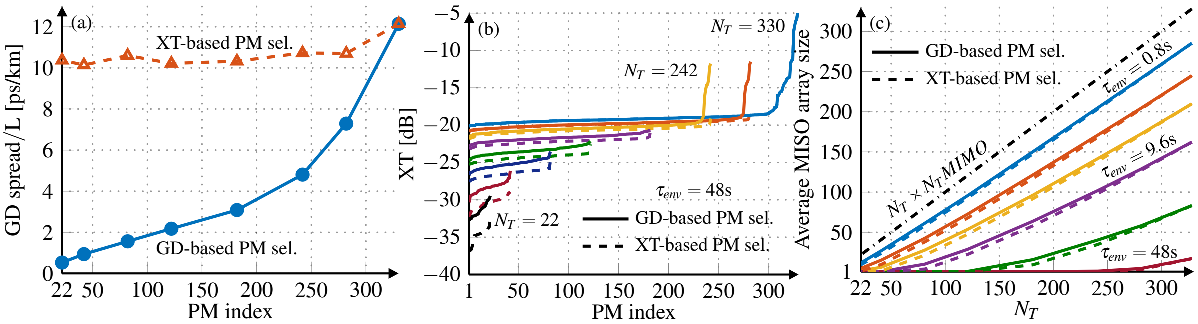

Fig. 2. (a) GD spread versus PM index. (b) XT versus PM index. (c) Average MISO array size versus N_T. Solid and dashed lines correspond to GD- and XT-based PM selection. Results adapted from [2].

3. Scaling of Crosstalk and Equalisation Requirements

In this section, assuming a dynamic channel, we investigate how XT and equalisation requirements behave for transmission of different N_T data tributaries (using N_T transceiver front-ends) over a 10-km MMF with $M = 342$ modelled as in [2, 8]. Due to macrobend loss, only 330 modes are useful for transmission. PM pairs are estimated using the exact calculated channel $\mathbf{H}(\omega)$ at an instant $t = t_0$ and, after the round-trip time t_{rtt} – given the CSI feedback, used for transmission over a drifted channel $\mathbf{H}_{drifted}(\omega)$. The latter is modelled according to [9], considering all fibre sections dynamic and with full channel matrix decorrelation after a period of τ_{env} (see Eq. (6) in [9]). Given $M > N_T$, a strategy is required to choose which PMs form the best composition for transmission. Here, we consider two strategies. PMs are selected to minimise either (1) the GD spread or (2) the average XT. For a channel of interest, XT is the sum of the power of all *interfering terms* divided by the power of the respective channel. Note that, the XT-based selection produces groups with higher GD spread, as it can be seen in 2(a).

Fig. 2(b) shows the XT as a function of PM index for $\tau_{env} = 48$s and $N_T = [22, 42, 82, 122, 182, 242, 282, 330]$. Results are presented in ascending order using solid and dashed lines for the selection strategies based on GD and XT, respectively. As N_T grows, the overall level of XT within the group also grows. Interestingly, the XT-based PM selection does not reduce significantly the overall XT. To translate XT into equalisation requirements, we count the respective *interfering terms* to each PM, neglecting the smallest group of terms that amount to a XT below -20 dB. Note that, in this case, an SNR of 20 dB is achievable if channel additive noise allows. Fig. 2(c) shows the average array size for multiple-input single-output (MISO) equalisers as a function of N_T considering $\tau_{env} = [48, 24, 9.6, 4.8, 2.4, 0.8]$s. With both allocation strategies, average MISO array size scales sub-linearly with N_T. For slower drifts (larger τ_{env}), single-input single-output (SISO) equalisers are sufficient to recover over 100 tributaries under the assumptions made in terms of XT and SNR. Although the XT-based PM selection reduces slightly the MISO array size, longer training sequences and equalisers with higher number of taps would be required to deal with the *residual channel impulse response spread* given the increased GD spread observed for the groups generated according to such strategy.

4. Conclusion

In this work, we reviewed our recent studies on PM-based SDM transmissions. PM selection based on minimisation of GD spread and average XT were investigated. The SDM scheme shown here opens a scalable path to increase the number of spatial tributaries in SDM transmissions while achieving equalisation complexity savings compared to the full MIMO case.

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