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# Experimental validation of MDL emulation and estimation techniques for SDM transmission systems

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**Abstract** We experimentally validate a mode-dependent loss (MDL) estimation technique employing a correction factor to remove the MDL estimation dependence on the SNR when using a minimum mean square error (MMSE) equalizer. A reduction of the MDL estimation error is observed for both transmitter-side and in-span MDL emulation.

## Introduction

Space-division multiplexing (SDM) provides a significant capacity increase over the use of single-mode fiber (SMF), by transmitting over multiple modes or cores in a single fiber.<sup>[1]</sup> Mode-dependent loss (MDL) and mode dependent gain (MDG) are known to limit the performance of SDM transmission and can even cause system outage<sup>[2][3]</sup>. MDL/MDG are generated by unequal attenuation and/or amplification of the guided modes in amplifiers, spatial (de)multiplexers, switches, fibers, connectors and splices.

At a component level, MDL can be characterized by means of an optical vector network analyzer (OVNA)<sup>[4],[5]</sup> or digital holography techniques<sup>[6],[7]</sup>, while at a system level, the MDL is usually estimated from the channel transfer function obtained by the multiple-input multiple-output (MIMO) equalizer. In [8], we showed that the MDL estimation based on minimum mean square error (MMSE) MIMO equalizers depends on the signal-to-noise ratio (SNR), resulting in an underestimation of the MDL at low SNR. We also proposed a correction factor that improves the estimation process for moderate levels of MDL.

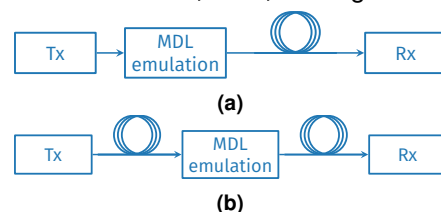
MDL can be artificially introduced by purposely attenuating or amplifying the fiber modes by different factors. For example, by using multi-mode amplifiers with an inherent MDG or by changing the powers of the single mode tributaries of mode (de)multiplexers using amplifiers or attenuators. As a benefit, the latter allows controlling the powers of the modes individually and hence to vary the induced MDL, which is not possible by using a multi-mode amplifier as there is no control over the individual gains of the modes. MDL

emulation by varying individual mode powers can be done by placing an MDL emulator stage directly after the transmitter<sup>[9]</sup> (Fig. 1a), or in-span (Fig. 1b). Compared to emulation at the transmitter side, in-span configuration enables a more approximate emulation of the MDL introduced by SDM components like multi-mode amplifiers, optical switches, spatial (de)multiplexers and multi-mode fiber (MMF), as the powers of the modes are varied after the modes have mixed.

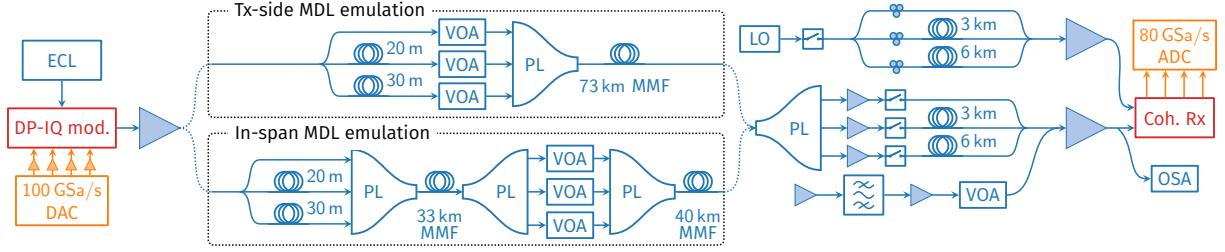
The correction factor that improves the MDL estimation was initially proposed in [8] and experimentally validated in [10] for a back-to-back and single span transmission scheme using an MDL emulator at the transmitter side. In this work, we extend the experimental validation and show that the correction factor reduces the MDL estimation error both for the case of MDL emulation at the transmitter side, as well as for the in-span MDL emulation scenario.

## MDL estimation correction factor

The peak-to-peak MDL of a transmission link can be computed from the ratio between the maximum and minimum eigenvalues  $\lambda_i^2$  of the operator  $\mathbf{H}\mathbf{H}^H$ , where  $\mathbf{H}$  is the channel transfer matrix and  $(\cdot)^H$  denotes the Hermitian transpose operator<sup>[2]</sup>. The relation between the channel transfer matrix and the MMSE equalizer transfer matrix depends on the SNR, then, the eigenvalues ob-



**Fig. 1:** Schematic representation of MDL emulation at the transmitter side (a), and in-span MDL emulation (b).



**Fig. 2:** Experimental setup for MDL emulation in 3-mode transmission. The transmitter generates 16-QAM symbols at 25 GBd, which are subsequently split and delayed to create the input tributaries for the photonic lantern (PL). Variable optical attenuators (VOAs) are placed directly after the transmitter or in the fiber span in order to emulate MDL. The multi-mode signal is transmitted over in total 73 km of MMF<sup>[11]</sup>. At the receiver, a time-domain multiplexed space-division multiplexing (TDM-SDM) scheme is employed, and a noise-loading stage is used to vary the optical signal-to-noise ratio (OSNR).

tained from the equalizer  $\lambda_{i, \text{MMSE}}^2$ , are related to the actual eigenvalues  $\lambda_i^2$ , as<sup>[8]</sup>

$$\lambda_{i, \text{MMSE}}^2 = \left[ \frac{(\lambda_i^2)^{-1}}{\text{SNR}^2} + \frac{2}{\text{SNR}} + \lambda_i^2 \right]. \quad (1)$$

For a known SNR, this relation can be inverted, resulting in

$$\lambda_i^2 = \frac{[\text{SNR}^2 \lambda_{i, \text{MMSE}}^2 - 2 \text{SNR}] \pm \sqrt{[\text{SNR}^2 \lambda_{i, \text{MMSE}}^2 - 2 \text{SNR}]^2 - 4 \text{SNR}^2}}{2 \text{SNR}^2}, \quad (2)$$

where the positive solution of (2) is a correction factor proposed to recover  $\lambda_i^2$ <sup>[8]</sup> and improve the estimation for moderate levels of MDL.

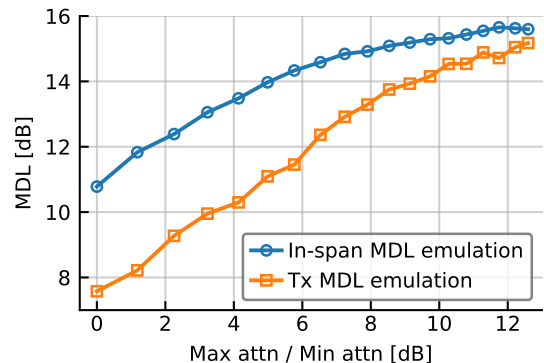
### Experimental setup

The experimental setup used for MDL emulation is depicted in Fig. 2. At the transmitter, a pseudorandom bit sequence (PRBS) of  $2^{16}$  polarization-multiplexed 16-QAM symbols is generated at 25 GBd. Pulse shaping at the transmitter is done using a root-raised-cosine (RRC) filter with  $\beta = 0.01$ . The shaped signal is converted to the analog domain by a 100 GSa/s digital-to-analog converter (DAC) followed by RF-amplifiers. The resulting signal modulates the output of an external cavity laser (ECL) operating at 193.4 THz using a dual-polarization in-phase and quadrature modulator. After modulation, the signal is amplified by an erbium-doped fiber amplifier (EDFA), split and delayed by 0 m, 20 m and 30 m to generate three decorrelated data streams that are multiplexed by a mode-selective photonic lantern (PL)<sup>[12]</sup>. The output of the PL is connected to a 73 km fiber link consisting of 16 spools of 50  $\mu\text{m}$  core diameter graded-index MMF<sup>[11]</sup> with lengths varying from 1.2 km to 8.9 km. At the receiver side, a mode-selective PL is used as mode de-multiplexer.

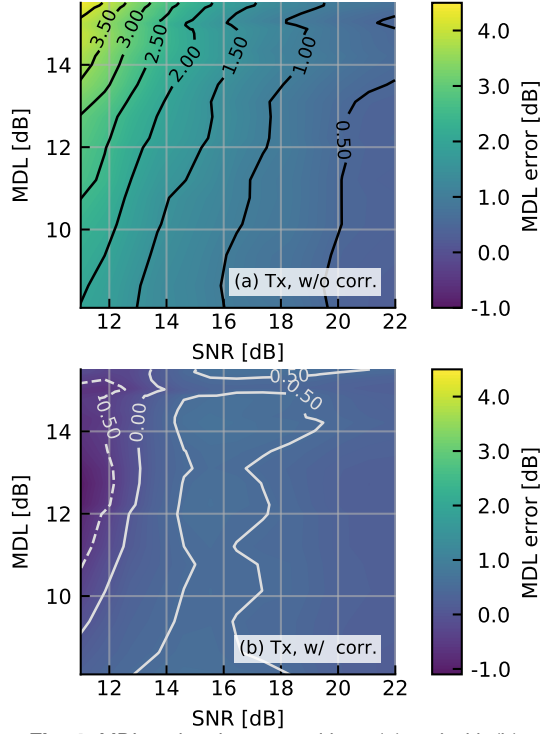
In order to emulate MDL, two different schemes are employed (see Fig. 2). For transmitter side MDL emulation, variable optical attenuators (VOAs) are placed between the decorrelation

fibers and the inputs of the transmitter PL. In-span MDL emulation is achieved by placing two mode-selective PLs connected by VOAs after 33 km of MMF.

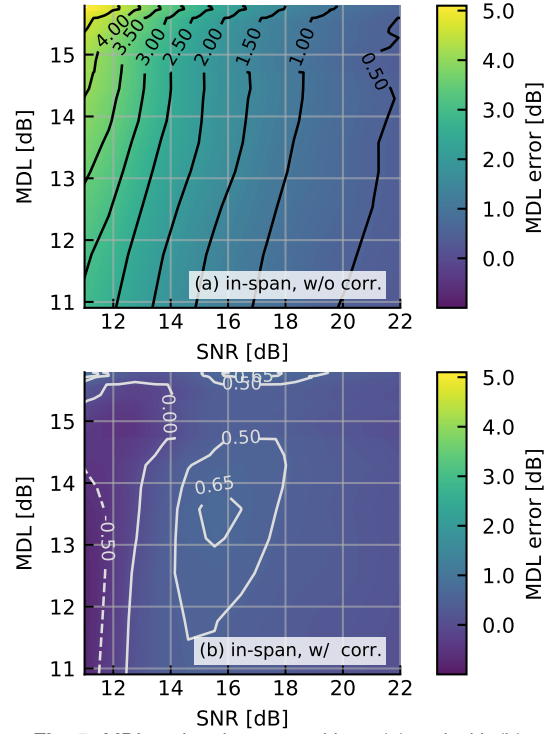
The receiver employs a time domain multiplexed (TDM)-SDM scheme<sup>[13]</sup> that delays two flows by 3 km and 6 km of SMF to reduce the required amount of coherent receivers. After the TDM-SDM stage, a noise-loading stage composed of two EDFAs, a wavelength selective switch (WSS) and a VOA is placed to vary the optical signal-to-noise ratio (OSNR) at the coherent receiver input. This noise-loading setup places a 250 GHz wide noise-band around the 193.4 THz carrier. The average OSNR is measured by an optical spectrum analyzer (OSA) after the last amplification stage. The average SNR at the receiver input is computed as  $\text{SNR} = \text{OSNR} (T_s \times 12.5 \text{ GHz})$  where  $T_s$  is the symbol time<sup>[14]</sup>. The noisy signal is amplified and converted from the optical to the electrical domain by the receiver front-end that integrates a second ECL as local oscillator (LO). The TDM electric signals are fed into 80 GSa/s analog-to-digital converters (ADCs) to be digitized. In the DSP block, the TDM streams are parallelized and down-sampled to two samples per symbol. Next, dispersion is digitally compensated and frequency offset is estimated and compensated for. The signal is matched-filtered by a RRC filter, and, finally, fully supervised MMSE equalization is applied and MDL is calculated from the MIMO equalizer taps.



**Fig. 3:** MDL versus attenuation ratio between the LP<sub>01</sub> and LP<sub>11</sub> modes. No noise loading is used.



**Fig. 4:** MDL estimation error without (a) and with (b) correction, as a function of the actual MDL and the SNR. The MDL is emulated at the transmitter side.



**Fig. 5:** MDL estimation error without (a) and with (b) correction, as a function of the actual MDL and the SNR. The MDL is emulated at 33 km in the transmission fiber span.

## Results

First, the ability of the two MDL emulation schemes to introduce MDL is verified by varying the attenuation of the VOAs and estimating the MDL. In order to keep the launch power constant, the three VOAs are initialized at an attenuation of  $-5$  dB and the attenuation of the  $LP_{11}$  modes is gradually increased, while decreasing the attenuation of the  $LP_{01}$  mode. In Fig. 3, the estimated MDL for different attenuation ratios between the  $LP_{01}$  and  $LP_{11}$  modes is shown, indicating the capability of MDL emulation for both schemes. Due to the two extra PLs in the transmission link for the in-span MDL emulation compared to the transmitter side MDL emulation, the initial MDL is about 2.5 dB higher for the in-span scheme.

Next, the MDL estimation correction factor is verified by sweeping the MDL and SNR. The MDL estimation error is defined as the difference between the estimated MDL in the setup without noise loading (with OSNRs of 40.1 dB and 38.4 dB for the transmitter and in-span emulation schemes, respectively) and the estimated MDL with noise loading. Figs. 4a and 5a show the obtained MDL estimation error for both emulation schemes. The estimated MDL without noise loading is assumed to be the true system MDL, as for high SNR, according to (1),  $\lambda_i^2 \approx \lambda_{MMSE}^2$ . As can be seen from these figures, the MDL estimation

error increases for low SNR, which is expected from (1). A maximum error of up to 5 dB is seen, indicating an underestimation of the system MDL.

The eigenvalues used to calculate the MDL in Figs. 4a and 5a are now corrected by the correction factor given in (2) and the resulting MDL estimation error is given in Figs. 4b and 5b for the transmitter and in-span MDL emulation scheme, respectively. It is seen that the MDL error is reduced to below 0.5 dB for the transmitter emulation scheme and to below 0.65 dB for the in-span emulation scheme. For SNRs below 14 dB, for both schemes, a small negative MDL estimation error is seen, resulting in an overestimation of the system MDL.

## Conclusions

We have experimentally demonstrated an MDL estimation technique employing a correction factor that removes the estimation dependence on the SNR. When using an MDL emulator at the transmitter or an MDL emulator placed in the fiber span, the MDL estimation correction factor reduced the estimation error, indicating the ability of the technique to improve the MDL estimation based on MMSE MIMO equalizers.

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