Experimental Investigation of Reduced Complexity MIMO Equalization in a 55-Mode Fiber SDM Transmission System

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Abstract: We investigate the MIMO equalizer complexity reduction by selective filter deactivation in a 25.9 km 55-mode SDM transmission system. We demonstrate a 21.5% equalizer complexity reduction at the cost of a 4.9% decrease in data rate.

1. Introduction

Space division multiplexing (SDM) has been considered a viable solution to sustain the exponential growth of data traffic in optical transmission networks [1]. Coupled SDM transmission over multi-core fibers (MCFs) and multi-mode fibers (MMFs) requires multiple-input multiple-output (MIMO) equalizers to compensate for channel coupling, introduced by non-ideal devices and fiber propagation [2]. MIMO digital signal processing (DSP) is often implemented with finite impulse response (FIR) filters [3]. The complexity of MIMO equalizers depends on the number of coupled channels and the required length of FIR filters, determined by the total channel delay spread [4–6]. MIMO equalization in high-mode-count SDM transmission can become very complex even for short-distance transmission with low delay spread.

An N-mode transmission with strong coupling between all modes requires an 2N$\times$2N MIMO equalizer with $(2N)^2$ FIR filters to receive the 2N-transmitted signals including spatial and polarization orientations. MMFs typically have a structure, where a number of modes are arranged into MGs, as indicated in Fig. 1(a). Modes within the same MG experience strong coupling, while coupling between modes belonging to different MGs can be orders of magnitude lower. This is indicated by the MG-averaged crosstalk matrices, shown in Fig. 1(b),(c) after 25.9 km transmission in a graded-index 55-mode fiber [7]. The prominent diagonal in the crosstalk matrix indicates a mode-group selective transmission regime, in which the signal power is concentrated around the main diagonal with decreasing coupling levels to MGs further away from the main diagonal.

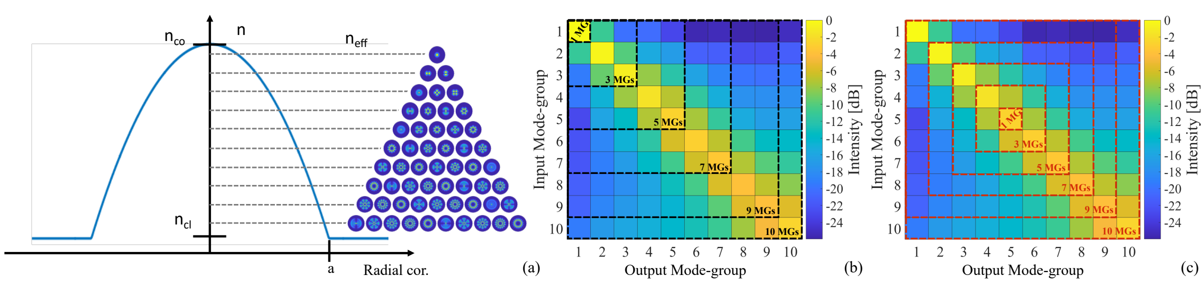

Figure 1. (a) Refractive index profile of a graded-index, 55-mode fiber and the corresponding mode-group (MG) structure. (b) and (c) MG-averaged crosstalk matrices after 25.9 km transmission in a 55-mode fiber [7]. The dashed squares indicate the investigated MG selections employed for equalization to recover (b) MG #1 and (c) MG #5.

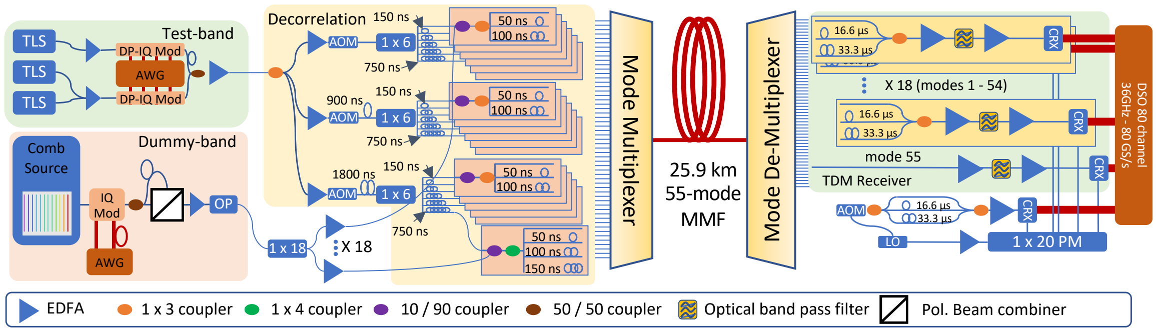

Figure 2. Experimental setup for the 55-mode SDM transmission system.

In this paper, we investigate the potential of reducing the MIMO equalizer complexity in a 55-mode fiber transmission system [7] by strategically deactivating FIR filters corresponding to MG combinations with low coupling. We evaluate the recovering of a certain output MG considering MIMO equalization with a reduced set of input MGs. The input MGs are selected as those whose propagation constants are closest to that of the equalized output MG [8]. As an example, Fig. 1(b) indicates the 2, 4, 6, 8, and 9 closest neighbors of MG #1, whereas Fig. 1(c) shows the 2, 4, 6, 8, and 9 closest neighbors of MG #5.

2. Experimental 55-mode transmission setup

The experimental setup used in this paper is shown in Fig. 2 [7]. A total of 184 WDM channels are generated, comprising a test-band and a dummy-band. The test-band is generated from three 25-GHz-spaced tunable laser sources, modulated in two dual-polarization IQ-modulators. The dummy band is generated in a separate IQ-modulator, using 25 GHz-spaced laser lines from an optical comb source. Test- and dummy-band modulators were driven by 49 GSa/s arbitrary waveform generators (AWGs), producing root-raised cosine-shaped 16-QAM signals with a 0.01 roll-off factor. In this paper, only a single WDM channel at 1543 nm is investigated. 55 copies of the test-band are generated in a three-stage split-and-delay setup, where the 55 signals are delayed by multiples of 50 ns to emulate independent data signals within the delay-spread of the MMF. A multi-plane light-conversion (MPLC) based mode-selective multiplexer (MUX) [9] is used to launch the 55 input signals into the 55 modes of a 25.9 km long, graded-index 55-mode fiber. After transmission, another MPLC MUX is used to demultiplex the signals into 55 SMFs. A time-domain multiplexed (TDM) receiver setup [10] is employed to receive groups of three signals in a single coherent receiver, hence a total of 18 coherent receivers are used to receive the signals transmitted over the first 54 modes, with an additional coherent receiver used for the signal in the 55th mode. A similar TDM setup including another coherent receiver is used for the local oscillator (LO) path to detect the relative phase changes of the LO laser across the three time slots of the TDM receiver. An 80 channel real-time oscilloscope with an electrical bandwidth of 36 GHz, operating at 80 GSa/s, is used to digitize the electrical signals from the 20 coherent receivers. Further details on the transmission system can be found in [7].

The DSP module starts with front-end imperfections removal and frequency offset estimation. MIMO equalization is performed by a time-domain dynamic equalizer that was initialized in a data-aided mode, followed by a decision-directed mode for signal performance assessment. Each of the 10 output MGs is obtained from the equalization of the desired MG itself, along with its 2, 4, 6, 8, and 9 nearest neighboring MGs, maintaining the length of the FIR filters fixed for all the cases. For the MGs at the extremes, MG #1 and MG #10, the nearest neighbors are selected in just one direction (increasing or decreasing propagation constants), as exemplified by the black squares in Fig. 1(b) for MG #1. For intermediate MGs, neighboring MGs are chosen in both directions, as indicated by the red squares in Fig. 1(c) for MG #5. The complexity of MIMO equalization is assessed in terms of the number of active FIR filters. The transmission performance is evaluated based on the data rate estimated from generalized mutual information (GMI).

3. Results and discussion

The average data rate as a function of the number of input MGs used for equalization is shown in Fig. 3(a). For the sake of clarity, only the curves for MGs # 1, 2, 3, 4, 9, and 10 are shown. As expected, lower-order MGs exhibit a higher data rate per mode compared to high-order MGs. The curves indicate a steep increase in the average data rate going from 1 to 3 input MGs used for equalizing low-order MGs. This indicates that low-order MGs couple little to other MGs and have a higher potential for complexity reduction. Higher-order MGs, however, couple more to other MGs, requiring a significant amount of adjacent input MGs to achieve an increment in data rate. From

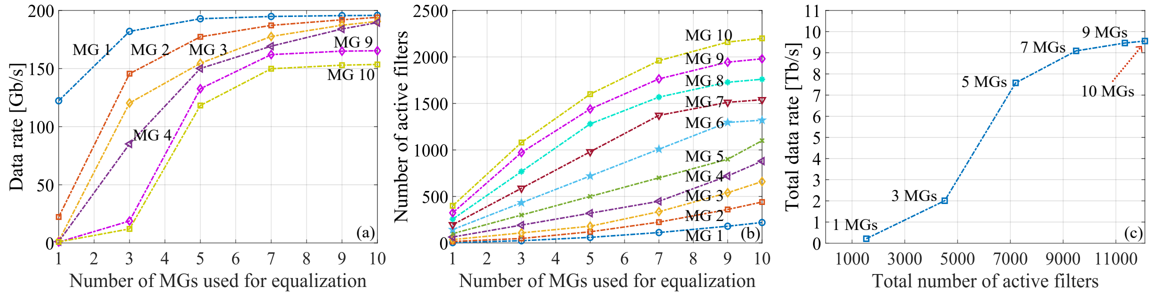

Figure 3. (a) Mode-group (MG)-averaged, GMI-based data rate for different output MGs as a function of the number of input MGs, used for MIMO equalization. (b) Number of active filters for the 10 MGs as a function of the number of input MGs used for equalization. (c) System GMI-based data rate as a function of the number of active filters.

7 MGs, the average data rate remains roughly stable with a gradual increment until reaching the maximum value when all 10 MGs are used for equalization.

Fig. 3(b) shows the number of active FIR filters as a function of the number of MGs used for equalization, for the 10 MGs. If only one input MG is used for equalization, the number of active filters that compose the MIMO equalizer is 4, 16, 36, 64, 100, 144, 196, 256, 324, and 400 for MGs from 1 to 10, respectively. The number of active filters increases with the number of MGs employed for equalization at a higher derivative for higher-order MGs. Fig. 3(a) and Fig. 3(b) show that although lower-order MGs couple less to neighbors and therefore can allow deactivation of a significant portion of its FIR filters, the impact of this deactivation on the overall complexity is limited, as low-order MGs contain relatively few modes, and thus contribute little to the overall system complexity.

Fig. 3(c) shows the overall data rate and the total number of active filters employed in each studied case. A data rate of 9.6 Tb/s is achieved by employing a full MIMO equalizer consisting of 110×110 = 12100 active FIR filters. Employing 7 input MGs for equalization of each output MG requires 2608 fewer filters for a system data rate of 9.1 Tb/s, equivalent to a data rate decrease of 4.9%. Using 5 input MGs per output MG reduces the number of active filters to 7200, leading to a data rate decrease of 20.7%.These results show that the data rate may be flexibly traded with the number of active filters to allow a new dimension for optimization of MMF based SDM systems. Although not investigated here, we note that, further complexity reductions may also be achieved by using a different selection of neighbouring MGs or by simultaneously reducing the FIR filter length.

4. Conclusion

High-mode-count, coupled SDM transmission requires highly complex and computationally expensive MIMO equalizers for signal separation. This paper investigates the potential of reducing their complexity in an experimental 55-mode fiber SDM transmission system, by using only subsets of the received mode-groups (MGs) for MIMO equalization. In the employed 25.9 km long, graded-index 55-mode fiber, low-order MGs couple little with other MGs, but also contribute little to the overall data rate and complexity. On the other hand, high-order MGs couple more with other MGs, and also contribute significantly to the overall data rate and complexity. Our investigation shows that a 21.5% complexity reduction can be achieved with only a 4.9% data rate reduction by selective filter deactivation based on understanding of the MIMO characteristics.

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