Experimental Analysis of Receiver Failure For 19-Core Randomly Coupled Core Fibre Transmission

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Abstract: We experimentally investigate the impact of the failures of spatial channel receivers on the transmission performance of a randomly coupled 19-core fiber system. Severe penalties are observed when a spatial channel receiver fails. © 2024 The Author(s)

1. Introduction

The potential of space-division multiplexing (SDM) [1] to increase the per-fiber transmission throughput by exploiting multiple spatial paths inside a single fiber has been demonstrated in various transmission experiments [2–5]. For coupled systems, such as multi-mode fibers or randomly coupled multi-core fibers, multiple-input multiple-output (MIMO) equalization at the receiver is required to undo the mixing that occurs during transmission. Any residual mode mixing after equalization results in added crosstalk to the spatial channels and reduces the system's performance. Additionally, different losses of coupled spatial paths during propagation result in mode-dependent loss (MDL), which reduces the system's capacity [6]. In SDM systems with coupled spatial modes, the performance of spatial channels, multiplexed into a spatial superchannel, can be highly correlated. For example, the failure of a single coherent receiver may highly affect the demultiplexing of several or all spatially multiplexed signals due to coupling during transmission [6].

For transmission using a randomly coupled 19-core multi-core fiber (RC-19-MCF) system, 19 coherent receivers are required to fully unmix the spatial channels. In this work, we investigate the impact of a malfunctioning coherent receiver on the transmission throughput of an RC-19-MCF when transmitting 64-ary quadrature amplitude modulation (QAM) signals. In this case, the MIMO equalizer cannot correctly undo mixing between spatial channels as the receiver can no longer access information from all the required coherent receivers. By means of experimental demonstrations, we show that a single faulty coherent receiver results, for this scenario, in a throughput reduction of 35 % (or 1.8 Tb/s in absolute value). The outcomes are confirmed using simulations and modeling. These results highlight the importance of considering the full receiver reliability when designing and operating coupled SDM systems.

2. Experimental Setup For Spatial Channel Input Receiver Failure Analysis

To analyze the impact of a coherent receiver failure on the transmission performance of a RC-19-MCF, the SDM transmission system given by Fig. 1 was implemented. This system was the same as the one used in [5]. A 3-channel test band comprised three tunable lasers with a linewidth of less than 10 kHz that were modulated in two dual-polarization IQ-modulators (DP-IQMs). These modulators were driven by a 4-channel 49 GS/s digital-to-analog converter (DAC) that produced 24.5 GBd 64-QAM signals with a root-raised cosine shape with 0.01

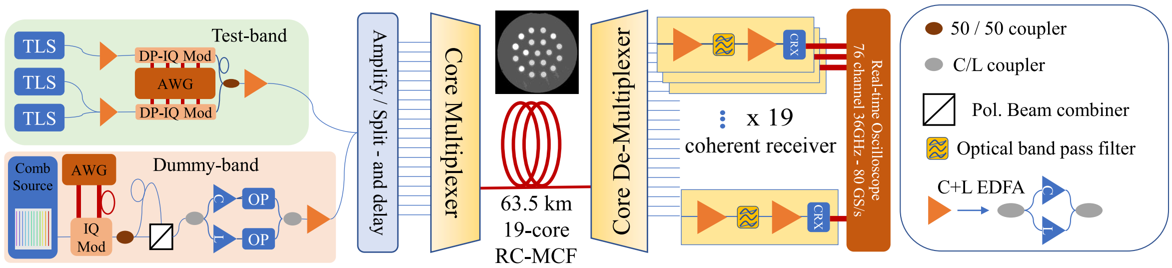

Fig. 1: Experimental setup used for transmission over 63.5 km of RC-19-MCF.

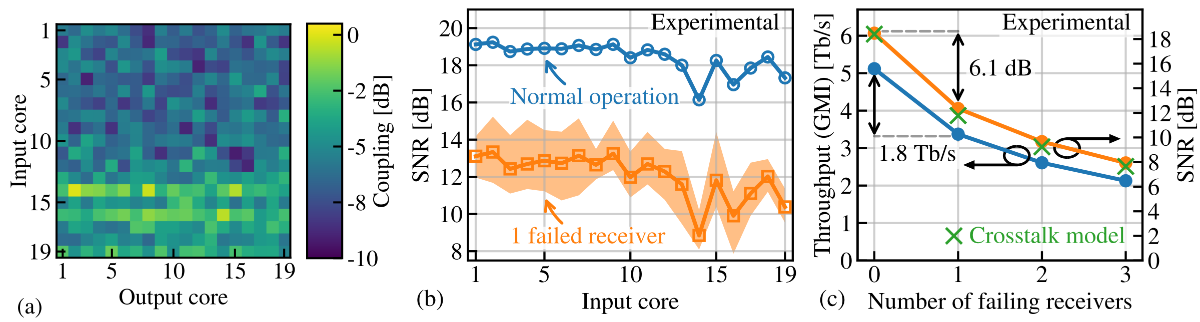

Fig. 2: Experimental results, showing in **(a)** the coupling matrix obtained from the MIMO equalizer. **(b)** shows the SNR per spatial signal for normal operation and 1 failed coherent receiver and **(c)** shows the reduction in throughput and SNR when coherent receivers fail to operate correctly.

roll-off. For wavelength-division multiplexing (WDM) dummy channel generation, the output of an optical comb source with 25 GHz channel spacing was modulated in a single-polarization IQ modulator, followed by a polarization multiplexing emulation stage. 19 de-correlated copies of the combined test- and dummy-band were generated in a split-and delay setup. This added multiples of 150 ns delay between the 19 signals before transmission over the RC-19-MCF. The signals were amplified to 21 dBm per core using erbium-doped fiber amplifiers (EDFAs) and launched into the fiber through 3-D laser inscribed core-multiplexers with less than 0.8 dB loss [7]. After 63.5 km RC-19-MCF, a similar device was used as a demultiplexer before signals were received in a 19-channel SDM receiver. Each of the 19 spatial channel receivers comprised two stages of EDFAs around a tunable filter to select a WDM channel under test followed by coherent receivers in which the signals were mixed with the light of another tunable laser with less than 60 kHz linewidth. The resulting electrical signals were digitized in a 76 channel, 36 GHz, 80 GS/s real-time oscilloscope. Offline digital signal processing (DSP) mainly consisted of a 38×38 time-domain data-aided least means squares (LMS) MIMO equalizer with 101 half-symbol-duration-spaced taps. A data-aided phase compensation algorithm was running within the equalizer loop.

The coherent receiver failure is emulated by digitally removing the data of a received input signal from a capture containing all 19 received input signals. As a result, the receiver DSP does not have any knowledge about the information in that specific input channel and cannot fully unmix all the spatially multiplexed signals into 19 outputs.

3. Experimental Results of Receiver Failure

The experimental coupling matrix obtained from the taps of the MIMO equalizer for the wavelength channel at 1550 nm is shown in Fig. 2a. The matrix qualitatively shows strong coupling between all the cores. There seems to be more coupling for input cores 14, 16, and 19, which is attributed to unequal input powers into the 19 cores of the RC-19-MCF. Figure 2b presents the signal-to-noise ratio (SNR) after equalization per spatial signal. The SNR for normal operation confirms the assumption of unequal input power into all the cores, as these cores show a lower SNR. Figure 2b also shows the SNR per spatial signal for 1 failed receiver. The filled area represents the spread of the SNR when scanning the failed receiver over the 19 coherent receivers, while the markers indicate the resulting average SNR. Figure 2b confirms that all spatial signals experience a similar drop in SNR, independent of the specific coherent receiver that fails. The variation in SNR per failing receiver in Fig. 2b is attributed to the combination of non-uniform coupling and different per-core input powers. Figure 2c shows the average throughput and SNR for different numbers of failing receivers. The throughput here is the spatial super-channel throughput calculated from the generalized mutual information (GMI). No difference in throughput is observed when evaluating different combinations of failing receivers, as is expected for a fully coupled system. Figure 2c shows that a single failing receiver results in a throughput penalty of 1.8 Tb/s (or 35 % of the normal operation throughput), resulting from imperfect equalization. Figure 3a shows the throughput for all 381 wavelength channels spread across the C- and L-band. The throughput penalty related to receiver failure is shown to vary versus wavelength, which is attributed to the already varying transmission performance without failing receivers, as also observed in [5].

4. Simulation, Analytical Modelling and Discussion

To support the experimental findings, transmission over the RC-19-MCF is simulated using the multisection model proposed in [8]. 38×38 coupling matrices are generated to simulate transmission over a randomly coupled 19-core fiber using polarization-multiplexed 64-QAM at 24.5 GBd. We simulate MDL-free transmission, and the spatial-mode dispersion was set to 10.8 ps/$\sqrt{\text{km}}$, as was previously characterized for the RC-19-MCF in [5]. The optical signal-to-noise ratio (OSNR) was set to match the OSNR obtained from the experimental implementation described previously. A MIMO equalizer was updated using a data-aided LMS algorithm to undo the mixing

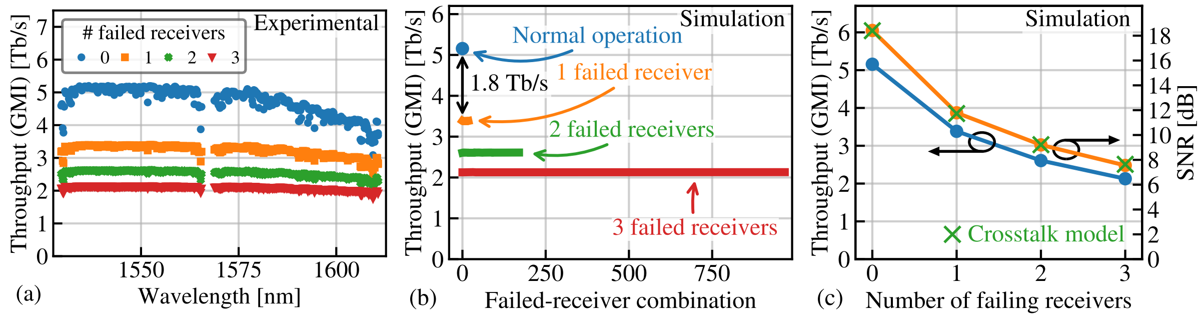

Fig. 3: **(a)** Experimentally measured throughput versus wavelength channel for failing receivers. **(b)** and **(c)** show the simulated reduction in throughput and SNR when receivers fail to operate.

between spatial channels and compensate for modal dispersion.

The coherent receiver failure effect is investigated in Fig. 3b. *Failed-receiver combination* refers to the (arbitrary) possible combination out of 19 receivers to obtain one (19 combinations), two (171 combinations), or three (969 combinations) faulty coherent receivers. It shows that the specific combination of failed receivers does not influence the throughput penalty, which is expected for such a randomly coupled system. Figure 3c presents the throughput and SNR versus the number of failing coherent receivers, showing that throughput penalty increases with the number of failed receivers, and matches the experimental results shown in Fig. 2c.

To model the impact of spatial channel receiver failure on the SNR of the spatial superchannel, we assume that every failing coherent receiver contributes to crosstalk introducing additional noise having a normalized power of $1/N_{spatial\ channels}$. The SNR of the spatial superchannel can then be modelled as $SNR = \left[SNR_0^{-1} + (N_{failed\ rx}/N_{spatial\ channels})\right]^{-1}$, where SNR_0 is the SNR without receiver failure. Figures 2c and 3c also show the modelled SNR. The good alignment with the SNRs obtained from experiments and simulations indicates that crosstalk might be the origin of the reduced performance. This model also shows that for coupled SDM systems with fewer spatial channels than the one discussed here, the SNR penalty for a failing receiver is increased.

Both simulation and experimental results show a severe throughput penalty (1.8 Tb/s for 64-QAM at 24.5 GBd) when only a single coherent receiver fails. This penalty increases when more receivers are failing. These results show that a single failing coherent receiver results in throughput reduction for the entire spatial superchannel when not handled appropriately. One could envision multiple strategies to reduce the impact on transmission throughput, such as hardware redundancy of spatial channel receivers or changing to lower-order modulation formats, which are more tolerant to additional crosstalk. Additionally, other equalization techniques such as the vertical Bell Labs Layered Space-Time (V-BLAST) architecture [9] or other successive interference cancellation (SIC) techniques [10] might help to reduce the impact of spatial channel receiver failure.

5. Conclusion

We experimentally demonstrated the throughput penalty of coherent receiver failures for transmission using a randomly coupled 19-core multi-core fiber. It is shown that the failure of even a single spatial channel receiver results in a throughput reduction of 35 % for the investigated scenario. Furthermore, a crosstalk model indicates that unremoved crosstalk might be the source of reduced performance. These results show the importance of considering coherent receiver reliability in designing and operating coupled SDM systems.

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