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Mode-Group-Division Multiplexing over a Deployed 15-Mode-Fiber Cable

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Abstract: We experimentally demonstrate transmission over a subset of up to 4 spatial modes of a deployed 15-mode Graded-index Fiber Cable. © 2023 The Author(s)

1. Introduction

Mode-division-multiplexed (MDM) transmission over multimode fibers (MMFs) has been proposed as a candidate to overcome the capacity limits of single-mode fiber communication systems [1]. Multimode fibers with a standard 125 μm cladding diameter can support >100 modes, and a number of key components to build optical networks, like efficient optical amplifiers [2–4] and wavelength selective switches (WSSs) [5, 8] compatible with MMF fibers have been demonstrated. Recent in-lab demonstrations have also shown transmission using up to 55 spatial modes [6]. In order to support the transmission over a large number of modes, complex multiple-input multiple-output (MIMO) based receivers are required, and it is therefore desirable to start transmitting over MMFs by using a subset of modes, [9, 10] and scale the capacity as needed over time. In practice, however, the transmission performance and reach of these approaches are limited by the mode coupling and mixing and the differential group delay (DGD) between mode groups, which strongly depend on the deployment conditions, like cabling, and field splices. In this work, we demonstrate transmission over a subset of up to 4 spatial modes over a 15-mode fiber that has been deployed by professional installers as a cable in a multi-service underground tunnel in the city of L'Aquila, Italy. The span under test consisted of 48.8 km link that included 17 field splices, and is therefore representative for a real-world environment. Our measurements indicated that by varying the transmission scheme, transmission distances from 48.8 km up to 800 km, and spectral efficiencies ranging from 3 bit/s/Hz up to 24 bit/s/Hz, can be achieved, making MMFs strong contenders for metropolitan networks.

2. 15-Mode Fiber and Cable Description

The MMF has a 28 μm diameter core with a trench assisted graded index profile supporting up to 9-LP modes (15-spatial modes) [11]. The fiber was optimized for a low DGD, low attenuation, and low bend losses. The cable consisted of two separate cables with a length of 3.9 km and 2.2 km, spliced together in the tunnel to form a 6.1 km long cable with both ends ending in the lab. The cable is 13 mm in diameter, and in addition to reinforcing components and protective sheathing, the cable contains six 2.2 mm diameter tubes, two of which contained four 15-mode fibers each. The fibers from each tube end were spliced together in the lab as shown in Fig. 1a to yield a total span length of 48.8 km of 15-mode fiber. All fibers were spliced by a commercial field splicer by professional telecom installers, and the splice quality was evaluated using an optical time-domain reflectometer (OTDR).

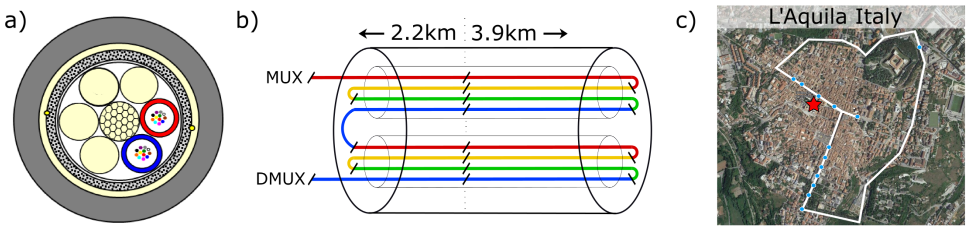

Fig. 1. a) Diagram of the deployed cable cross section b) Diagram of cable with two tubes containing four 15-mode fibers (r/y/g/b) each with splice points in 48.8-km span indicated by a black slash. c) Map of L'Aquila: deployed fiber route shown in white, location of L'Aquila University shown by the red star.

To couple light both into and out of the 15-mode fiber, the two ends of the span are spliced to a pair of commercial mode multiplexers (Cailabs Proteus-C), one used as a multiplexer (MUX) the other a demultiplexer (DMUX).

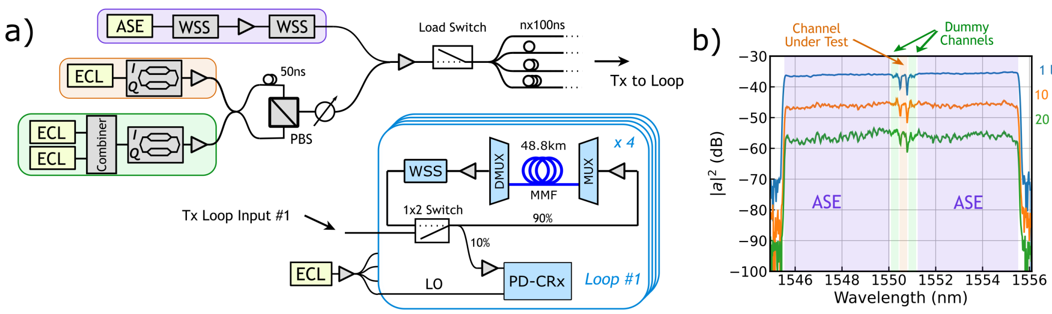

Fig. 2. a) Mode-multiplexed MIMO transmission setup. b) Channel spectrum after 48.8, 488, and 976 km.

We compared the loss and total modal crosstalk of the LP_{01} mode of the system with the MUXs spliced back-to-back to that of the MUXs spliced to the span. The loss of the LP_{01} mode after propagation through the MUXs alone was 7.36 dB. After splicing the MUXs to the 15-mode fiber as shown in Fig. 1a, the loss was 19.66 dB including all 17 splices, resulting in a total span loss of 12.3 dB (or 0.25 dB/km) for the LP_{01} mode. We launched light into the LP_{01} mode on the MUX and measured the total modal crosstalk, as defined by a comparison of the received power on the LP_{01} mode to the total combined output power from all higher order modal outputs of the DMUX. In a MUX-DMUX back to back configuration, the average modal crosstalk was -15.8 dB. Including the 15-mode fiber (MUX+span+DMUX) the crosstalk of the total span increased to -5.9 dB.

3. MIMO Transmission Experiment

Figure 2a describes the experimental transmission setup. For our transmitter, we used three external cavity lasers (ECLs) with 100-kHz linewidth spaced at 33.3 GHz. The laser lines were then modulated by using two dual nested Mach-Zehnder modulators (MZMs) driven by four independent high speed digital-to-analog converters (DACs) operating at 60 GS/s, creating Nyquist shaped QPSK and 16QAM modulated signals at 30 Gbaud. The central channel modulated by the first MZM, acted as chanel under test whereas the external channels modulated by the second MZM represented dummy channels. The signals from the MZMs are combined after amplification, and a polarization multiplexing emulation stage with a delay 50 ms generated polarization multiplexed signals. To emulate a full system spectrum surrounding the test and dummy channels, we used an amplified stimulated emission (ASE) source with the center of the spectrum filtered out using a wavelength selective switch (WSS). The ASE bandwidth is 1267.7 GHz, which would be equivalent to emulating 38 channels at a 33.33 GHz spacing. The ASE and the modulated channels are combined and the resulting spectrum is shown in Fig. 2b.

The signal was then split into four paths, with 100 ns relative delay between each path. Four solid-state 1x2 switches were used to insert each delayed signal copy into a recirculating loop. Each loop began by sending the signal into the second stage of two-stage EDFA. The amplified signal then passed through the MUX to launch the proper LP mode into the 15-mode fiber and the DMUX was used to couple light back out of the MMF span. The signal then passed through the first stage of the EDFA, a WSS, a loop switch, and a 90:10 coupler. Each loop was path length matched to within <1 cm. The transmitted signal was extracted from each recirculating loop by a 90:10 coupler and each sent to one of four polarization diverse coherent receivers (PD-CRx). The signal was captured on a 16-channel digital sampling scope operating at 40 GS/s and processed using off-line MIMO digital signal processing (DSP). The DSP consisted of a resampling of the data to two samples per symbol, frequency offset compensation, chromatic dispersion compensation, followed by a 1000 symbol-spaced tap frequency domain equalizer, operated first in data-aided mode to achieve the convergence of the equalizer, followed by a constant modulus (CMA), or multi-modulus (MMA) algorithm, for QPSK and 16QAM signals, respectively. The equalizer is followed by phase recovery and subsequent bit-error-rate (BER) evaluation.

We demonstrated transmission over a subset of up to 4 spatial modes shown in Table 1, with 15 dBm launch power into each spatial mode. The average intensity impulse response is obtained by a MIMO channel estimation and averaging over all individual output intensity impulse responses. The impulse responses from transmission over each subset of modes are shown in Fig. 3a for transmission distances from 48.8 km to 488 km. In all curves, the signal primarily remains in a central peak at t=0, showing most of the energy resides in the same modes that were launched. Broadening of the impulse response occurs as the transmission distance is increased.

4. Mode-Multiplexed Transmission Results

The impulse response of the LP_{01} mode is shown in Fig. 3 (subset 1), and the crosstalk from the higher order modes can be seen appearing on the right side of the main peak. For subset 2, we primarily see an increase of the crosstalk on the left side of the main peak. Subset 3 we begin to see a more symmetric effect of crosstalk. In the last plot of Fig. 3a, we show the impulse response for subset 3, including LP_{01} and $LP_{11a,b}$. We compensated for

Table 1. Transmission over subsets of LP modes, and spatial multiplicity within that subset.

Subset Used in Transmission	Utilized LP Modes	Spatial Multiplicity
Subset #1	LP_{01}	1
Subset #2	LP_{11a}, LP_{11b}	2
Subset #3	LP_{02}, LP_{21a}, LP_{21b}	3
Subset #4	LP_{31a}, LP_{31b}, LP_{12a}, LP_{12b}	4
Subset #5	LP_{01}, LP_{11a}, LP_{11b}	3

the differential mode group delay (DMGD) between LP_{01} and LP_{11} by adding a 78 cm (equivalent to 4.3 ns) long fiber to the recirculating loop for LP_{01} mode.

We evaluated the MIMO transmission performance by measuring the bit-error rate (BER) and calculated Q^2 factors from the measured BER. The Q^2 factors are shown in Fig 3(b,c) as a function of transmission distance for both QPSK and 16QAM signals. In the following, we assume that the signals are recovered by using a state-of-the-art forward-error correction (FEC) with an overhead 20% and a threshold of $Q^2 > 5.7$ dB, that is marked as dotted line in Fig. 3b,c), resulting in spectral efficiency of 3 bits/s/Hz/spatial mode and 6 bits/s/Hz/sptial mode, for QPSK and 16QAM signals, respectively. The total spectral efficiency is then found by multiplying with the spatial multiplicity given by Table 1. For both modulation formats, transmission over subset 5 is only slightly worse than subset 1, but shows 3 times the spectral efficiency. For both subsets, the maximal reach is 800 km and 400 km, for QPSK and 16QAM, respectively. The largest total spectral efficiency of 24 bits/s/Hz is achieved by sending 16QAM over subset 4, which reduces the reach to 48.8 km. The transmission performance of subset 3 and 4 is most likely limited by the mode dependent loss (MDL), which is found to be the largest in those configurations.

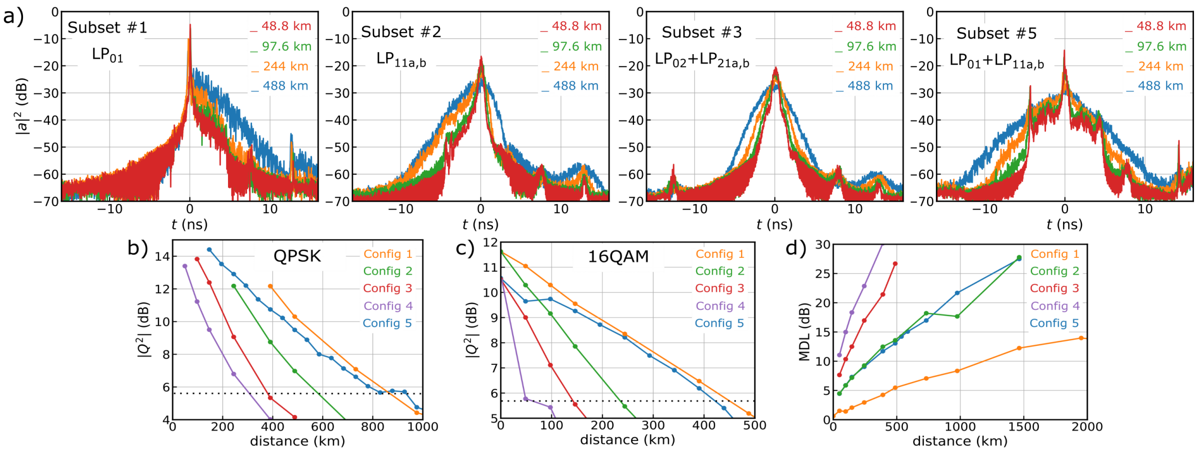

Fig. 3. (a) Intensity-impulse responses of the 15-mode fiber as a function of distance for mode subsets from Table 1. (b,c) Q^2-factors as a function of transmission distance for both QPSK (b) and 16QAM signals (c) for various transmitted mode subsets from Table 1, (d) Mode dependent loss (MDL) as a function of transmission distance.

5. Conclusions

We show mode-multiplexed transmission over a subset of up to 4 spatial modes of a deployed 15-spatial-mode graded-index fiber cable. Transmission distances from 48.8 km up to 1000 km, and spectral efficiencies from 3 bit/s/Hz up to 24 bit/s/Hz are demonstrated, confirming the potential of multimode fibers for metro networks.

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