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Field demonstration of mode-division multiplexing upgrade scenarios on commercial networks

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Abstract: We demonstrate three possible scenarios for upgrading current single-mode transmission networks with high capacity few-mode fiber technology using mode-division multiplexing (MDM). The results were obtained from measurements over a number of field-deployed single-mode fiber links with an additional experimental in-line amplified few-mode fiber link. The results confirm the viability of employing MDM using few-mode fiber technology to gradually replace legacy optical systems.

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References and links

1. J. Sakaguchi, B. Puttnam, W. Klaus, Y. Awaji, N. Wada, A. Kanno, T. Kawanishi, K. Imamura, H. Inaba, K. Mukasa, R. Sugizaki, T. Kobayashi, and M. Watanabe, "305 Tb/s space division multiplexed transmission using homogeneous 19-Core fiber," *J. Lightwave Technol.* **31**(4), 554–562 (2013), <http://www.opticsinfobase.org/jlt/abstract.cfm?URI=jlt-31-4-554>.
2. H. Takara, A. Sano, T. Kobayashi, H. Kubota, H. Kawakami, A. Matsuura, Y. Miyamoto, Y. Abe, H. Ono, K. Shikama, Y. Goto, K. Tsujikawa, Y. Sasaki, I. Ishida, K. Takenaga, S. Matsuo, K. Saitoh, M. Koshiba, and T. Morioka, "1.01-Pb/s (12 SDM/222 WDM/456 Gb/s) crosstalk-managed transmission with 91.4-b/s/Hz aggregate spectral efficiency," in European Conference and Exhibition on Optical Communication, OSA Technical Digest (online) (Optical Society of America, 2012), paper Th.3.C.1. <http://www.opticsinfobase.org/abstract.cfm?URI=ECEOC-2012-Th.3.C.1>
3. H. Takahashi, T. Tsuritani, E. L. de Gabor, T. Ito, W. R. Peng, K. Igarashi, K. Takeshima, Y. Kawaguchi, I. Morita, Y. Tsuchida, Y. Mimura, K. Maeda, T. Saito, K. Watanabe, K. Imamura, R. Sugizaki, and M. Suzuki, "First demonstration of MC-EDFA-repeated SDM transmission of 40 x 128-Gbit/s PDM-QPSK signals per core over 6,160-km 7-core MCF," *Opt. Express* **21**(1), 789–795 (2013), <http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-21-1-789>.
4. R. Ryf, S. Randel, N. Fontaine, M. Montoliu, E. Burrows, S. Chandrasekhar, A. Gnauck, C. Xie, R. Essiambre, P. Winzer, R. Delbue, P. Pupalakis, A. Sureka, Y. Sun, L. Gruner-Nielsen, R. Jensen, and R. Lingle, "32-bit/s/Hz spectral efficiency WDM transmission over 177-km few-mode fiber," in Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2013, OSA Technical Digest (online) (Optical Society of America, 2013), paper PDP5A.1. <http://www.opticsinfobase.org/abstract.cfm?URI=NFOEC-2013-PDP5A.1>
5. E. Ip, M. Li, Y. Huang, A. Tanaka, E. Mateo, W. Wood, J. Hu, Y. Yano, and K. Koreshkov, "146λx19-gbaud wavelength- and mode-division multiplexed transmission over 10x50-km spans of few-mode fiber with a gain-equalized few-mode EDFA," in Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2013, OSA Technical Digest (online) (Optical Society of America, 2013), paper PDP5A.2. <http://www.opticsinfobase.org/abstract.cfm?URI=NFOEC-2013-PDP5A.2>
6. V. A. Sleiffer, Y. Jung, V. Veljanovski, R. G. van Uden, M. Kuschnerov, H. Chen, B. Inan, L. G. Nielsen, Y. Sun, D. J. Richardson, S. U. Alam, F. Poletti, J. K. Sahu, A. Dhar, A. M. Koonen, B. Corbett, R. Winfield, A. D. Ellis, and H. de Waardt, "73.7 Tb/s (96 x 3 x 256-Gb/s) mode-division-multiplexed DP-16QAM transmission with inline MM-EDFA," *Opt. Express* **20**(26), B428–B438 (2012), <http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-20-26-B428>.

7. V. Sleiffer, Y. Jung, N. Baddela, J. Surof, M. Kuschnerov, V. Veljanovski, J. Hayes, N. Wheeler, E. Numkam Fokoua, J. Wooller, D. Gray, N. Wong, F. Parmigiani, S. Alam, M. Petrovich, F. Poletti, D. Richardson, and H. de Waardt, "High capacity mode-division multiplexed optical transmission in a novel 37-cell hollow-core photonic bandgap fiber," *J. Lightwave Technol.* **PP**(99), 1 (2013).
8. V. Sleiffer, P. Leoni, Y. Jung, J. Surof, M. Kuschnerov, V. Veljanovski, D. Richardson, S. Alam, L. Grüner-Nielsen, Y. Sun, B. Corbett, R. Winfield, S. Calabrò, B. Sommerkorn-Krombholz, H. von Kirchbauer, and H. de Waardt, "20 × 960-Gb/s MDM-DP-32QAM transmission over 60km of FMF with inline MM-EDFA," in *European Conference and Exhibition on Optical Communication, OSA Technical Digest (online) (Optical Society of America, 2013)*, paper We.2.D.2.
9. V. Sleiffer, Y. Jung, B. Inan, H. Chen, R. van Uden, M. Kuschnerov, D. van den Borne, S. Jansen, V. Veljanovski, T. Koonen, D. Richardson, S. Alam, F. Poletti, J. Sahu, A. Dhar, B. Corbett, R. Winfield, A. Ellis, and H. De Waardt, "Mode-division-multiplexed 3x112-Gb/s DP-QPSK transmission over 80 km few-mode fiber with inline MM-EDFA and Blind DSP," in *European Conference and Exhibition on Optical Communication, OSA Technical Digest (online) (Optical Society of America, 2012)*, paper Tu.1.C.2. <http://www.opticsinfobase.org/abstract.cfm?URI=ECEOC-2012-Tu.1.C.2>
10. D. Richardson, J. Fini, and L. Nelson, "Space-division multiplexing in optical fibres," *Nat. Photonics* **7**(5), 354–362 (2013).
11. M. D. Feuer, L. E. Nelson, X. Zhou, S. L. Woodward, R. Isaac, B. Zhu, T. F. Taunay, M. Fishteyn, J. M. Fini, and M. F. Yan, "Joint digital signal processing receivers for spatial superschannels," *IEEE Photon. Technol. Lett.* **24**(21), 1957–1960 (2012).
12. L. Grüner-Nielsen, Y. Sun, J. Nicholson, D. Jakobsen, K. Jespersen, R. Lingle, Jr., and B. Pálsdóttir, "Few mode transmission fiber with low DGD, low mode coupling, and low loss," *J. Lightwave Technol.* **30**(23), 3693–3698 (2012), <http://www.opticsinfobase.org/jlt/abstract.cfm?URI=jlt-30-23-3693>.
13. Y. Jung, S. Alam, Z. Li, A. Dhar, D. Giles, I. P. Giles, J. K. Sahu, F. Poletti, L. Grüner-Nielsen, and D. J. Richardson, "First demonstration and detailed characterization of a multimode amplifier for space division multiplexed transmission systems," *Opt. Express* **19**(26), B952–B957 (2011), <http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-19-26-B952>.
14. Y. Jung, Q. Kang, V. A. Sleiffer, B. Inan, M. Kuschnerov, V. Veljanovski, B. Corbett, R. Winfield, Z. Li, P. S. Teh, A. Dhar, J. Sahu, F. Poletti, S. U. Alam, and D. J. Richardson, "Three mode Er³⁺ ring-doped fiber amplifier for mode-division multiplexed transmission," *Opt. Express* **21**(8), 10383–10392 (2013), <http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-21-8-10383>.
15. F. Yaman, N. Bai, Y. K. Huang, M. F. Huang, B. Zhu, T. Wang, and G. Li, "10 x 112Gb/s PDM-QPSK transmission over 5032 km in few-mode fibers," *Opt. Express* **18**(20), 21342–21349 (2010), <http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-18-20-21342>.
16. J. D. Downie, J. E. Hurley, D. V. Kuksenkov, C. M. Lynn, A. E. Korolev, and V. N. Nazarov, "Transmission of 112 Gb/s PM-QPSK signals over up to 635 km of multimode optical fiber," *Opt. Express* **19**(26), B363–B369 (2011), <http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-19-26-B363>.
17. M. Kuschnerov, O. Agazzi, V. Veljanovski, J. Slovák, M. Herrmann, C. Hofer, U. Bauer, T. Rieger, S. Camatel, P. Voois, N. Swenson, and M. Bohn, "Recent advances in signal processing for real-time implementation - 40Gb/s, 100Gb/s and beyond," in *Advanced Photonics Congress, OSA Technical Digest (online) (Optical Society of America, 2012)*, paper SpW2B.4. <http://www.opticsinfobase.org/abstract.cfm?URI=SPPCom-2012-SpW2B.4>
18. R. Ryf, S. Randel, A. Gnauck, C. Bolle, A. Sierra, S. Mumtaz, M. Esmaelpour, E. Burrows, R. Essiambre, P. Winzer, D. Peckham, A. McCurdy, and R. Lingle, "Mode-division multiplexing over 96 km of few-mode fiber using coherent 6 × 6 MIMO processing," *J. Lightwave Technol.* **30**(4), 521–531 (2012), <http://www.opticsinfobase.org/jlt/abstract.cfm?URI=jlt-30-4-521>.
19. R. Ryf, N. Fontaine, J. Dunayevsky, D. Sinefeld, M. Blau, M. Montoliu, S. Randel, C. Liu, B. Ercan, M. Esmaelpour, S. Chandrasekhar, A. Gnauck, S. Leon-Saval, J. Bland-Hawthorn, J. Salazar-Gil, Y. Sun, L. Grüner-Nielsen, R. Lingle, and D. Marom, "Wavelength-Selective Switch for Few-Mode Fiber Transmission," in *European Conference and Exhibition on Optical Communication, OSA Technical Digest (online) (Optical Society of America, 2013)*, paper PD1.C.4.
20. H. Chen, V. Sleiffer, F. Huijskens, R. Van Uden, C. Okonkwo, P. Leoni, M. Kuschnerov, L. Grüner-Nielsen, Y. Sun, H. De Waardt, and T. Koonen, "Employing prism-based three-spot mode couplers for high capacity MDM/WDM transmission," *IEEE Photon. Technol. Lett.* **25**(24), 2474–2477 (2013).
21. R. Ryf, N. Fontaine, and R. Essiambre, "Spot-based mode coupler for mode-multiplexed transmission in few-mode fiber," *IEEE Photon. Technol. Lett.* **24**(21), 1973–1976 (2012).
22. M. Kuschnerov, F. Hauske, K. Piyawanno, B. Spinnler, M. Alfiad, A. Napoli, and B. Lankl, "DSP for coherent single-carrier receivers," *J. Lightwave Technol.* **27**(16), 3614–3622 (2009).
23. V. Sleiffer, M. Kuschnerov, R. van Uden, and H. de Waardt, "Differential phase frame synchronization for coherent transponders," *IEEE Photon. Technol. Lett.* **25**(21), 2137–2140 (2013).

1. Introduction

In a fairly short period of time, space-division multiplexing (SDM), using multiple cores [1–3] or multiple modes [4–9] in a single optical fiber, has emerged as a powerful approach to increase the per-fiber-capacity, with impressive aggregate transmission capacities and transmission distances demonstrated [10].

This far work on optical SDM technology has been confined to the laboratory. All the experiments have been performed using only full few-mode fiber (FMF) or multi-core fiber links, largely neglecting many of the practical/commercial constraints set by customers. However it is unlikely that operators will deploy a full SDM-link from day one due to the high costs of fiber installation. More likely they will prefer gradual upgrade steps before a pure SDM-link is established. Therefore it is important to show that current single-mode fiber (SMF) technology is compatible with SDM technology such that congested SMF spans carrying the most data traffic can be replaced first by high capacity SDM spans without the need to immediately deploy a fully end-to-end SDM-link. This has been done to a certain extent in [11] for multi-core fiber links, but up to this moment this has not been done for FMF-links.

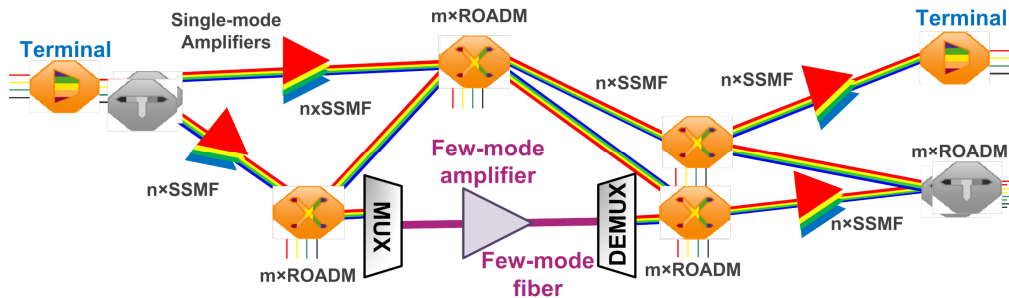


Fig. 1. Schematic of studied network upgrade. One of the spans is exchanged with a few-mode technology span (pink link at the bottom) upgrading the potential capacity of that span.

In this paper we demonstrate three probable field upgrade scenarios, successfully showcasing the interoperability of a live commercial network with two FMF spans including a mid-span few-mode (FM) erbium-doped fiber amplifier (EDFA), as depicted in Fig. 1. First we will explain the link configuration used for all the experiments. Then as a first scenario, single-mode transmission over a regular single-mode network with an additional 120km FMF-link is shown. The second scenario covers the more conventional mode-division multiplexing (MDM) scenario. Three single-mode signals running at the same wavelength are mode-multiplexed after travelling over three different SMFs of equal length. After mode demultiplexing the three signals travel again over three different SMFs of equal length and are received together. The last upgrade scenario considers the case that the three signals are running at the same wavelength but originate from different laser sources and are modulated with different modulation formats. Also the signals have travelled different distances before they are mode multiplexed.

2. Link configuration

The field trial was carried out on the live Coriant hiT7300 system of the A1 Telekom Austria (A1) network running between Salzburg-Klagenfurt-Vienna (link 1) and Vienna-Linz-Salzburg (link 2), both depicted in Fig. 2(A), with different span lengths and fiber types (standard single-mode fiber (SSMF) and non-zero dispersion-shifted fiber (NZDSF)) as listed in Table 1, with a total length of 1,023 km. Additionally, six single-mode dark fibers were available between Salzburg and Bischofshofen (Bhn), indicated by link 3 in Fig. 2(B), each with a ~ 52.2 km length.

The FMF-link was built in Bhn and comprised four spools of FMF supporting the linearly-polarized (LP) LP_{01} and LP_{11} modes [12] and with the properties listed in Table 2. The spool combination was chosen to average out the differential group delay (DGD) between the LP_{01} and LP_{11} modes to within one symbol (summing up the DGDs of the separate spools yields $(0.039 + -0.044 + 0.053 + -0.047) \cdot 30000 = 30$ ps). The total FMF-link was 120 km long with a FM-EDFA [13, 14] placed after 60 km.

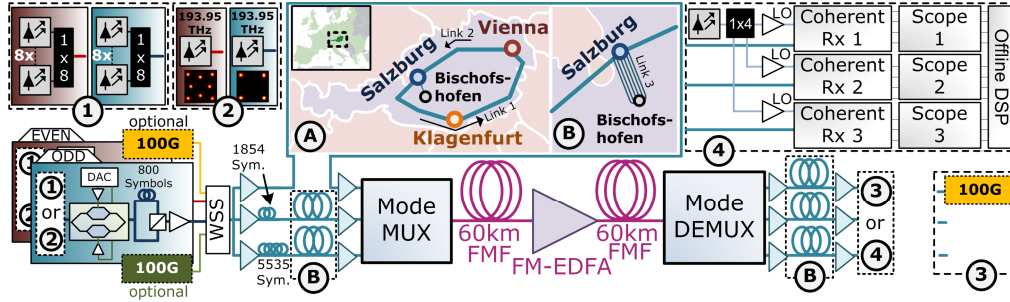


Fig. 2. Field trial and few-mode link setup. The 100G cards are used in Scenario I only. (1) Laser configuration Scenario I and II, (2) Laser configuration Scenario III, (3) Receiver setup scenario I, (4) Receiver setup Scenario II and III. (A) Fiber link across Austria (Salzburg-Klagenfurt-Vienna (660km, link 1) and Vienna-Salzburg (363km, link 2)), (B) Fiber link Salzburg-Bischofshofen (link 3).

At the transmitter side two commercial 100G cards were available for testing, as well as 16 freely tunable C-band ECL-lasers (<100 kHz linewidth) with single-polarization IQ-modulators and digital-to-analog converters to create the modulation formats wanted. At the receiver-side three coherent receivers were employed to receive the (mixed) signals after transmission, thereby enabling any cross-coupling that happened either during mode multiplexing or during transmission over the FMF-link to be undone.

Figure 2 will be used throughout this work to indicate how the scenario under study was tested using the link configuration described.

Table 1. Link data single-mode fibers (@ 1550nm)

	Link 1	Link 2	Link 3
Fiber type	SSMF	NZDSF	SSMF
Distance [km]	660	363	52.2
Avg. Loss [dB/km]	0.23	0.25	0.23
Avg. Disp. [ps/(nm·km)]	17.2	4.4	17

Table 2. The DGD-compensated hybrid FMF span (@ 1550nm)

	Spool 1	Spool 2	Spool 3	Spool 4
Length [km]	30	30	30	30
Mode-coupling [dB]	-26	-26	-25	-26
DGD [ps/m]	0.039	-0.044	0.053	-0.047
Disp. LP ₀₁ [ps/(nm·km)]	19.9	19.8	19.8	19.8
Effective Area LP ₀₁ [μm ²]	96	95	95	95
Disp. LP ₁₁ [ps/(nm·km)]	20.1	20	20	20
Effective Area LP ₁₁ [μm ²]	96	96	95	96

3. Scenario I: Single-mode transmission over FMF

As a first upgrade scenario the performance of a commercial 100G card over a live field-deployed fiber network in combination with an FMF-span was considered. Single-mode transmission over FMF and multi-mode fiber was already demonstrated previously [15, 16]. Both references are showing that single-mode transmission over FMF is feasible. In [15] it is shown that single-mode transmission over FMF might even offer improvements relative to SSMF since the nonlinear tolerance of the FMF is typically better due to the larger effective area of the fundamental (LP₀₁) mode.

The setup for this scenario is depicted in Fig. 3. In Salzburg two 100G coherent cards [17] were run at the frequencies of 193.55 THz and 194.4 THz respectively of the A1 network. Both were multiplexed on a 50 GHz ITU-grid together with eight even and eight odd 256-Gb/s dual-polarization (DP) 16QAM channels (193.6-194.35 THz), which were generated by two separate setups as described later on.

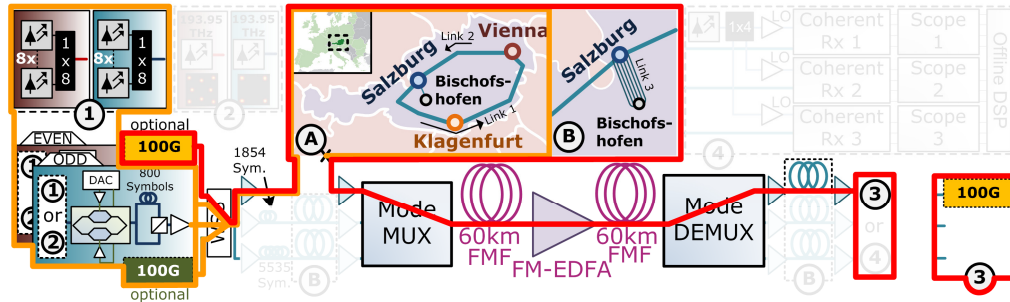


Fig. 3. Scenario I: Single-mode transmission over FMF. Two commercial 100G cards are wavelength-division multiplexed with sixteen 256-Gb/s DP-16QAM channels and transmitted over link 1 and 2 (1,023 km), after which one 100G channel is de-multiplexed and sent over link 3 + the FMF link (1,247 km).

Afterwards the resulting 18 wavelength channels were transmitted over the 1,023 km fiber link comprising of link 1 and link 2. The 100G signal running at 194.4 THz was dropped in Salzburg using an arrayed wave-guide grating (AWG) and subsequently, after amplification, transmitted to Bhn with a 0 dBm launch power. In Bhn the 100G signal was coupled into the 120 km FMF-link incorporating a mid-span FM-EDFA, using the LP₀₁-port of a commercial phase-plate based mode multiplexer (>25 dB extinction ratio). The theory of operation of such a mode-multiplexer is more fully described in reference [18]. At the output of the FMF-link the FMF was spliced to an SMF using a regular SMF splicing procedure, amplified, and transmitted back to Salzburg where the 100G signal was received after travelling 1,247 km (of which was ~10% FMF) using one of the commercial 100G transponder cards, indicated by the insert in Fig. 3. Since it was known from previous work that the FM-EDFA is causing a lot of cross-talk between modes [9], mandrels at the input and output of the FM-EDFA were placed to filter out the higher-order modes.

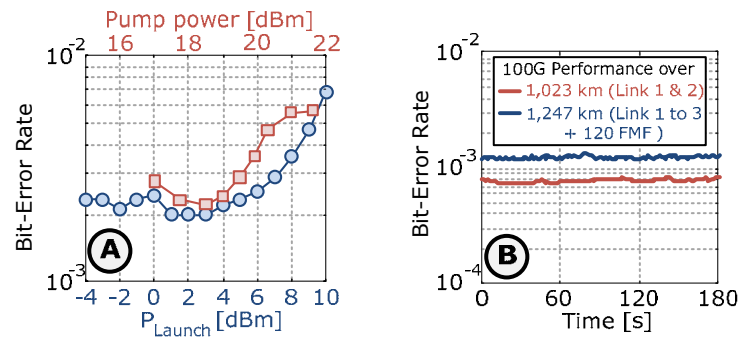


Fig. 4. Scenario I results. (A) Launch power (blue circle) and pump power optimization (red square) (B) 100G BER over time after travelling across Austria (1,023 km), and after 1,247 km including 120 km FMF.

After the 1,023 km commercial link the obtained pre-FEC bit-error rate (BER) was $\sim 8 \cdot 10^{-4}$, as observed in Fig. 4(B) (red curve). After tuning the launch power into the FMF-link and the FM-EDFA pump power, depicted in Fig. 4(A), and placing additional mandrels at the input and output of the FMF-link (as such obtaining better performance than measured in Fig. 4(A)), a pre-FEC BER of $\sim 1.3 \cdot 10^{-3}$ was obtained, as observed from the blue curve in Fig. 4(B), showing zero post-FEC errors over the whole measurement and therefore the viability of using legacy transponders in an interoperability mode over FMF-links. The observed slight increase in BER is caused by the additional 224 km transmission and the signal passing through four additional optical amplifiers in the path.

4. Scenario II: Mid-link mode multiplexing and de-multiplexing of three signals ($3 \times \text{SMF} \rightarrow \text{FMF} \rightarrow 3 \times \text{SMF}$)

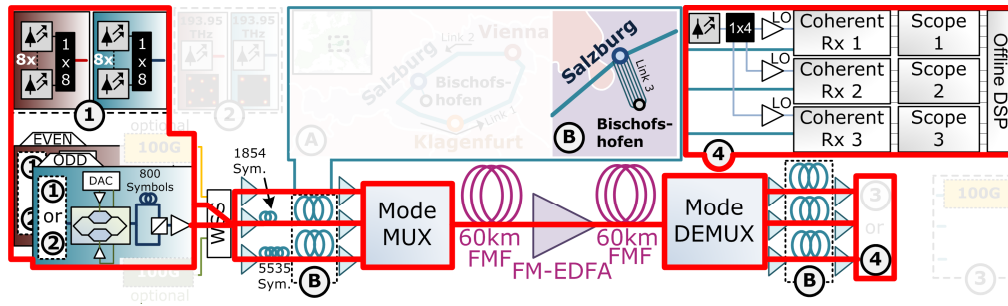


Fig. 5. Scenario II: $3 \times \text{SMF} \rightarrow \text{FMF} \rightarrow 3 \times \text{SMF}$. Eight even and eight odd channels were wavelength division multiplexed, split in to three de-correlated tributaries, and transmitted over link 3. In Bischofshofen the signals were mode multiplexed and transmitted over the FMF-link. After mode de-multiplexing the signals were transmitted over link 3 and received in Salzburg using three coherent receivers and offline 6×6 MIMO-DSP.

The second upgrade scenario considers mode multiplexing three single-mode signals running at the same wavelength after propagating over three separate SMF spans together onto one FMF-link. After the FMF-link the mode de-multiplexed signals are sent over three separate SMF spans again, as depicted in Fig. 5. This scenario targets the possibility of replacing the most congested spans with higher capacity fiber at a lower cost/bit, utilizing cost efficient multi-mode optical amplifiers [13,14] and reconfigurable optical add/drop multiplexers [19], without the need to deploy a pure FMF transmission link.

The signals were generated by the experimental setup depicted in Fig. 5. 16 channels were created by modulating eight lasers running at the even (193.6 THz - 194.3 THz) and eight lasers running at the odd ITU-grid (193.65 THz - 194.35 THz), shown in inset 1 in Fig. 5, with two separate single-polarization IQ-modulators, after passively combining them using 1×8 polarization-maintaining (PM) couplers. The in-phase and quadrature ports of the IQ-modulators were electrically driven by two linearly amplified outputs of a 64 GSamples/s DAC, which generated either 8QAM or 16QAM symbols at 32 GSymbols/s. The voltage swing was tuned to drive the IQ-modulators in the linear regime. For both modulation formats the symbols were created using either three or four 2^{15} long pseudo-random bit sequences (PRBSs), combining them after shifting them over $(n-1) \cdot 8192-1$ bits, with $n = 1,2,3,4$, and mapping them onto the respective symbols.

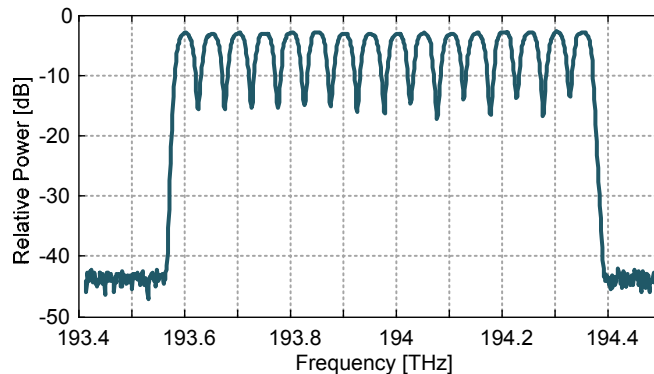


Fig. 6. Optical spectrum before transmission.

Polarization-multiplexing was emulated by splitting the signal out of the IQ-modulators in to two tributaries of equal power, delaying one of them for de-correlation (180 symbols (even))

or 800 symbols (odd)), and combining them again using polarization beam couplers. The resulting DP-signals were multiplexed after amplification using single-mode EDFAs. Subsequently a wavelength selective switch (WSS) was used to equalize the 16 wavelength-division multiplexed (WDM) channels carrying either 192-Gb/s DP-8QAM or 256-Gb/s DP-16QAM on a 50-GHz grid obtaining the spectrum depicted in Fig. 6.

After wavelength division multiplexing the signal was first split into three tributaries and each tributary was delayed with respect to the others for de-correlation (by 1854 symbols and 5535 symbols respectively) to emulate three distinct signals each however carrying the same modulation format (at the same data rate) and produced from the same laser source. These signals were subsequently coupled into three 52.2 km long separate SMF links going from Salzburg to Bhn (link 3).

In Bhn the three single-mode signals were mode multiplexed into the FMF using the packaged phase-plate based mode-multiplexer, depicted in Fig. 7(A), having insertion losses of 3.7 dB, 8.9 dB and 9.1 dB for the LP_{01} , LP_{11A} and LP_{11B} ports, respectively. Following the FMF-link, a spot-launch spatial de-multiplexer, shown in Fig. 7(B) [20, 21], was used to de-multiplex the signals, with a ~ 3.5 dB insertion loss per port. Afterwards the three signals were sent into three separate 52.2 km long SMFs before detection using three coherent receiver front-ends connected to three different time-synchronized digital sampling scopes as illustrated in inset 4 in Fig. 5. The SMFs were carefully measured beforehand assuring the relative time delay arising from length differences was sufficiently small to make sure the signals were captured at the same relative time instance. This is a requisite to enable compensation of the mode coupling using multiple input multiple output (MIMO) digital signal processing (DSP). The scopes were sampling at 40, 50 and 50 GSamples/s and had electrical bandwidths of 20 GHz, 16 GHz and 23 GHz, respectively.

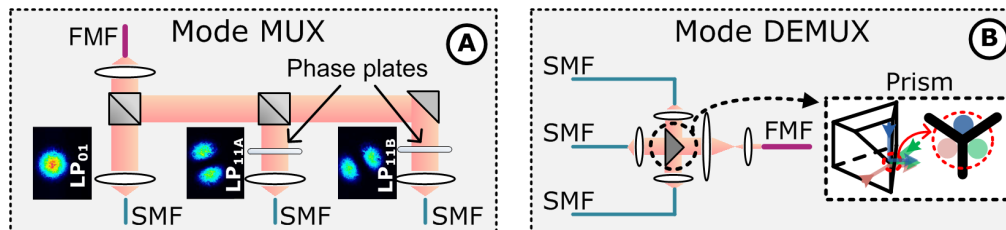


Fig. 7. (A) Mode multiplexer (Mode MUX) and (B) mode de-multiplexer (Mode DEMUX) as used in the experiment. The mode MUX is based on the phase plates, whereas the DEMUX uses spot launch spatial de-multiplexing.

In the offline 6x6 MIMO-DSP [7] firstly all samples were re-sampled to two samples per symbol after which the skew between the I and Q signals was removed. Afterwards frequency-domain chromatic dispersion (CD) compensation [22] was employed followed by feed-forward timing recovery. In the next step, the start of the frames was determined using a differential phase correlation technique as described in [23], which was slightly adjusted using all three input signals thereby resulting in six sharp peaks that define the start of the frames of the three DP-signals. This information was passed on to the 6×6 MIMO data-aided time-domain equalizer (TDE) stage, employing 201 taps with a $T/2$ spacing, with T being the symbol time of 31.25 ps. This stage compensates for transmission impairments like residual chromatic dispersion, polarization-mode dispersion and modal coupling across the FMF-link. Although the spool combination to create the FMF-link was chosen to average out DGD between the LP_{01} and LP_{11} modes, the mode-coupling is distributed along the whole link and therefore requires more memory (i.e. taps) in the receiver than expected from the simple addition of the spool DGDs [8]. The TDE stage used 100,000 symbols for training employing the least-mean squares algorithm (LMS). After training a switch was made to decision directed (DD)-LMS to track the variations over time. A digital phase-locked loop (DPLL) was employed for carrier tracking and removing the phase offset. In the last two stages the recovered constellation was demapped to obtain the bit streams which were compared to the

2^{15} PRBS sequence sent and used for bit-error counting. In total $\sim 500,000$ symbols for each of the three DP-signals were used for error-counting, and for each measurement point three samples collected at different times were taken and the BERs averaged for presentation.

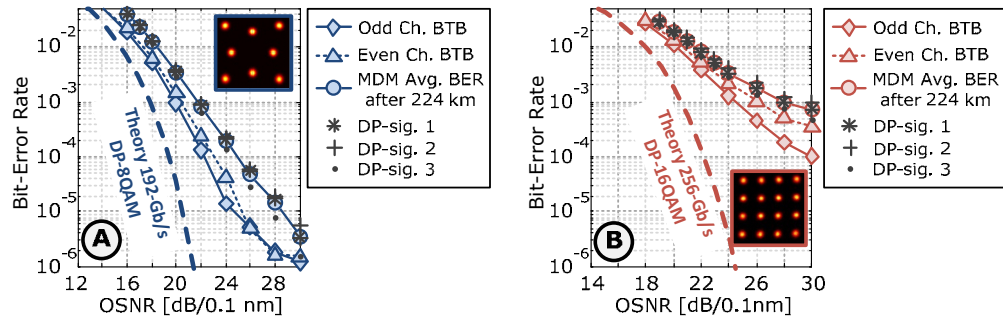


Fig. 8. (Transmitted) OSNR vs. BER curves of odd and even generated channel (Ch.) back-to-back (BTB) and after 224 km transmission of an odd channel, of which 120 km MDM over FMF, for (A) 192-Gb/s DP-8QAM and (B) 256-Gb/s DP-16QAM.

Figure 8(A) and 8(B) show the back-to-back curves measured for a single channel generated by the odd (solid diamond lines) as well as the even (dashed triangle lines) experimental setup. In all cases the noise was loaded and OSNR was measured at the transmitter side. Figure 8(A) and (B) show the results obtained for the generation of 192-Gb/s DP-8QAM and for 256-Gb/s DP-16QAM, respectively, using the worst coherent receiver which limits the MDM performance [7, 8]. In both cases a penalty is observed between the two transmitter setups, which is around 0.5 dB for 192-Gb/s DP-8QAM at a BER of $1 \cdot 10^{-3}$ and grows to 1.5 dB when 256-Gb/s DP-16QAM is employed. Also the performance of a single odd channel after 224 km transmission (solid circle lines), of which 120 km is MDM transmission over FMF, is displayed in the same figures. The OSNR for this curve indicates the transmitted OSNR. With respect to the single-mode BTB performance, transmission penalties of 1.8 dB and 3.4 dB are obtained for 3 · 192-Gb/s DP-8QAM and 3 · 256-Gb/s DP-16QAM transmission, respectively, at a BER of $1 \cdot 10^{-3}$. These penalties are composed of added noise, DGD and mode-coupling occurring during transmission, and additionally mode dependent loss and mode multiplexing by itself [6–8].

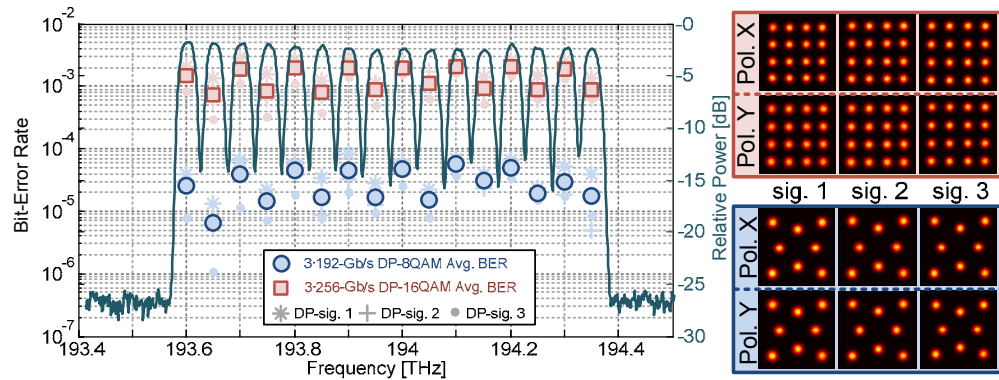


Fig. 9. Transmission results scenario II (BER and received Spectrum). The results show the successful transmission of 16 WDM × 3 MDM × 192-Gb/s DP-8QAM (blue circles) and 256-Gb/s DP-16QAM (red squares), as well as the demodulated constellations for the channel at 193.95 THz.

Figure 9 shows the results obtained after measuring all the 16 transmitted channels for both modulation formats by only changing the LO frequency, as well as the received spectrum for one of the three received signals. Using an optical spectrum analyzer on the same signal, received OSNRs for all channels of between 28.9 dB/0.1 nm and 29.3 dB/0.1 nm were measured. For the transmission of 3·192-Gb/s DP-8QAM and 3·256-Gb/s DP-16QAM average BERs of around $3 \cdot 10^{-5}$ and $1 \cdot 10^{-3}$ for each channel are obtained, respectively.

5. Scenario III: Mode multiplexing and de-multiplexing of multi-rate (different lasers and modulation) and multi-distance (different chromatic dispersion and OSNR) signals

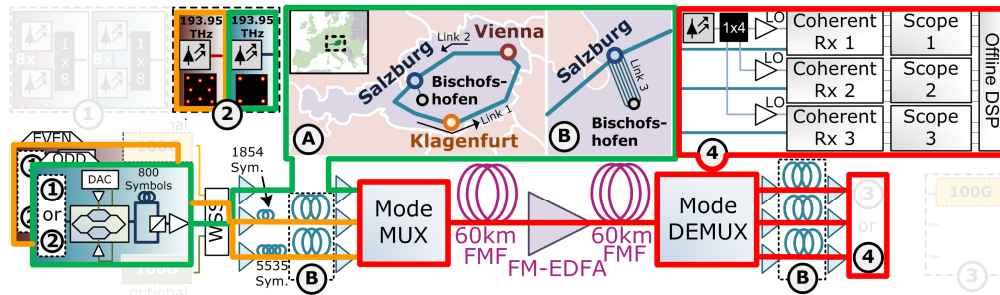


Fig. 10. Scenario III: Multi-rate, multi-distance $3 \times \text{SMF} \rightarrow \text{FMF} \rightarrow 3 \times \text{SMF}$ transmission. The 'odd' transmitter generates 128-Gb/s DP-QPSK with laser source 1, whereas the 'even' transmitter generates 192-Gb/s DP-8QAM at the same wavelength as the 'odd' transmitter, but with a different laser source. The signal of the 'odd' transmitter is sent over link 1, 2 and 3 where it is mode multiplexed with two de-correlated copies of the signal of the 'even' transmitter, which travelled only over link 3. After travelling over the FMF-link the three mode de-multiplexed signals travel via link 3 back to Salzburg to be received.

The third and final upgrade scenario considers the possibility of mode multiplexing differently modulated signals that have travelled different distances over SMF, as is quite possible in a real system due to different transmission impairment tolerances. The signals are at the same wavelength but are generated using different transmitter lasers. This scenario is depicted in Fig. 10.

The 'odd' IQ-modulator was used to create a 128-Gb/s DP-QPSK signal at 193.95 THz. The 'even' IQ-modulator created a 192-Gb/s DP-8QAM signal, also running at 193.95 THz, which was split into two and one component delayed with respect to the other for de-correlation. The 128-Gb/s DP-QPSK signal was first transmitted over the 1,023 km link through the A1 network before being sent to Bhn together with the 192-Gb/s DP-8QAM signals via three separate SMFs. In Bhn the signals were again mode multiplexed using the phase-plate based mode-multiplexer and sent over the 120 km FMF-link with mid-span FM-EDFA. After space-de-multiplexing using the spot-launch de-multiplexer, the signals were transmitted back to Salzburg using three separate SMFs of link 3, where they were received using the setup shown in inset 4 in Fig. 10 and offline 6x6 data-aided MIMO-DSP which was largely the same as for scenario II.

There are several constraints that have to be satisfied to make this scenario work. One of them is a CD constraint. The 128-Gb/s DP-QPSK signal and 192-Gb/s DP-8QAM signal had different accumulated CDs at the receiver, $\sim 16,900$ ps/nm and $\sim 4,100$ ps/nm respectively, since the signals travelled over a different distance and no dispersion compensating modules were used in the transmission link. Both signals will also mix during transmission over the FMF-span and will be mixed on receipt due to the spot-launch spatial de-multiplexer used. Therefore it is of only little use to apply CD-compensation before the TDE stage since the mixed signals have different CD values and any CD compensation of one signal, would not be correct for the other, although it will be partially compensated. One approach to solve this is the use of long filter tap structures in the TDE stage [22], beyond the 201 which we used. But in this case the algorithm used to find the start of the frames described in [23] will not work

since the CD value is too high, making initial convergence challenging. Therefore to mitigate this problem the 128-Gb/s DP-QPSK signal was pre-distorted using the driving DACs by the negative amount of CD accumulated over link 1 and 2 (i.e. 12,800 ps/nm), resulting in the same CD for all signals at the receiver.

Another constraint is that all of the transmitters need to be running at the exact same symbol rate, 32 GSymbols/s in this case, to ensure that the samples are time-aligned using the same receiver structure for all signals.

To assess the quality of the transmitted 128-Gb/s DP-QPSK signal the back-to-back curves and MDM performance over the 224 km link used in scenario II were first measured. The results are depicted in Fig. 11(A). The signals generated by the odd (solid diamond line) and even (dashed triangle line) transmitters both have a penalty of ~ 1.1 dB at a BER of $1 \cdot 10^{-3}$. The solid circle line indicates the performance of a single odd channel (3×128 -Gb/s DP-QPSK) travelling over the 224 km link, of which 120 km is MDM transmission over the FMF-link. An additional penalty of 1 dB is observed for this case at a BER of $1 \cdot 10^{-3}$.

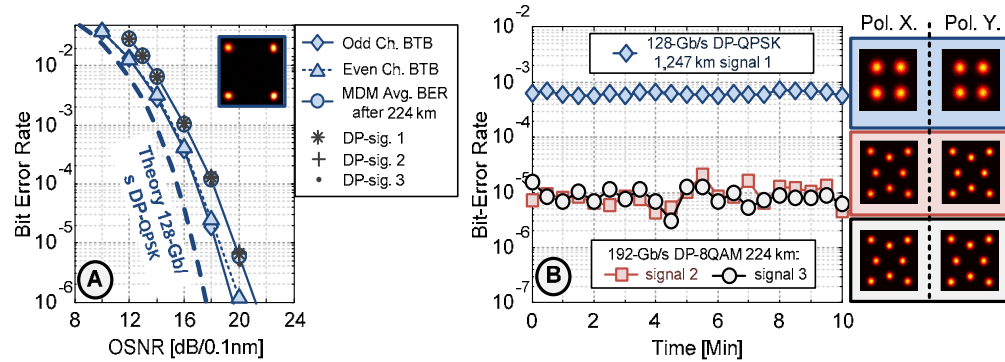


Fig. 11. (A) OSNR vs. BER curves of odd and even generated channel (Ch.) back-to-back (BTB) and after 224 km transmission of an odd channel, of which 120 km MDM over FMF. (B) Bit-Error Rate over time for Scenario III.

Figure 11(B) shows the performance of scenario III over time. The results show stable performance over timescales of multiple minutes, with average BERs of $6 \cdot 10^{-4}$ for the 128-Gb/s DP-QPSK signal, and $1 \cdot 10^{-5}$ for the 192-Gb/s DP-8QAM signals. Both results match well with the results obtained for the two other cases, successfully showcasing the possibility to spatially multiplex, transmit in FMF, and receive together multiple modulation format signals, generated using different transmitter lasers, and transmitted over different distances.

6. Conclusion

We report transmission results from what we believe to be the first ever field experiment to incorporate a component of MDM. Our experiments illustrate three gradual upgrade scenarios that should allow the progressive integration of FMF technology into current single-mode systems. In the first scenario single-mode transmission over a 1,247 km transmission link of which 1,023 km was a live SMF network and 120 km was an FMF-link incorporating a mid-span FM-EDFA, using commercial 100G equipment was successfully tested. In the second scenario three single-mode signals generated from the same laser source and carrying the same modulation format, were sent over three separate SMF spans of the same lengths, being mode multiplexed onto the FMF-link and after mode de-multiplexing sent over three separate SMF spans again (total 224 km transmission distance) before being received using 6×6 MIMO-DSP to demodulate all signals. Successful transmission of $16 \text{ WDM} \times 3 \text{ MDM} \times 192$ -Gb/s DP-8QAM and $16 \text{ WDM} \times 3 \text{ MDM} \times 256$ -Gb/s DP-16QAM was achieved. As the third and last scenario transmission of three differently modulated signals, generated by different lasers running at the same wavelength, and being sent over different distances before being

mode multiplexed onto the FMF-link and received afterwards was tested. The MDM channel under test was built up out of 112-Gb/s DP-QPSK and 2·192-Gb/s DP-8QAM, sent over 1,247 km and 224 km, respectively, and good performance matching with the other cases was obtained. All these scenarios confirm compatibility of current single-mode systems with FMF technology, alleviating the need to deploy a full FMF transmission link at the outset.

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