# High-Spectral-Efficiency Mode-Multiplexed Transmission over Graded-Index Multimode Fiber

Roland Ryf(1), Nicolas K. Fontaine(1), Steffen Wittek(1,2), Karthik Choutagunta(1,3), Mikael Mazur(1,4), Haoshuo Chen(1), Juan Carlos Alvarado-Zacarias(1,2), Rodrigo Amezcua-Correa(2), Mark Capuzzo(5), Rose Kopf(5), Al Tate(5), Hugo Safar(5), Cristian Bolle(5), David T. Neilson(1),Ellsworth Burrows(1), Kwangwoong Kim(1), Marianne Bigot-Astruc(6), Frank Achten(7), Pierre Sillard(6), Adrian Amezcua-Correa(6), Joseph M. Kahn(3), Jochen Schröder(4), Joel Carpenter(8)

(1) Nokia Bell Labs, 791 Holmdel Rd, Holmdel, NJ, 07733, USA
(2) CREOL, The University of Central Florida, Orlando, Florida 32816, USA
(3) E. L. Ginzton Laboratory, Stanford University, Stanford, California 94305 USA
(4) Photonics Laboratory, Chalmers University of Technology, SE-41296 Gothenburg, Sweden
(5) Nokia Bell Labs, 600 Mountain Ave., New Providence, NJ 07974, USA
(6) Prysmian Group, Parc des Industries Artois Flandres, 62092 Haisnes Cedex, France
(7) Prysmian Group, Zwaanstraat 1, 5651 CA Eindhoven, The Netherlands
(8) The University of Queensland, Brisbane, QLD, 4027, Australia

***Abstract***
*We demonstrate mode-multiplexed 90×90 MIMO transmission over all nine mode groups of a 26.5-km graded-index multimode fiber span, achieving a record spectral efficiency of 202 bit/s/Hz.*

**Introduction**

Graded-index multimode fibers (MMFs) are widely used for short-reach interconnects due to the ease of coupling to low-cost VCSEL-based transponders. In this work, we use a similar graded-index multimode fiber (GI-MMF) in which the refractive index profile is optimized to minimize the differential mode-group delay (DGD) at 1550 nm wavelength instead of the commonly used 860 nm. The resulting fiber supports a total of nine mode groups (90 spatial and polarization modes) at 1550 nm wavelength and has a standard cladding diameter of 125 µm. We transmit independent wavelength- and polarization multiplexed signals into each spatial and polarization mode and use 90×90 multiple-input-multiple-output (MIMO) digital signal processing (DSP) to recover the signal after transmission. In our previous work, we demonstrated mode-multiplexed transmission in 36 spatial modes over a 2-km long GI-MMF[1]. Here we significantly increase the number of modes to 45 and the fiber length to 26.5 km, while considerably improving transmission performance. We demonstrate the transmission of five wavelength channels carrying 15-Gbaud dual-carrier polarization-multiplexed 16-QAM signals with a channel spacing of 50 GHz, resulting in a total capacity of 101 Tbit/s over a bandwidth of 500 GHz, assuming 7% overhead for forward error correction (FEC). The resulting spectral efficiency of 202 bit/s/Hz is the highest reported for a single fiber core or any fiber with a 125 µm cladding diameter.

**Graded-Index Multimode Fiber Span**

The MMF span comprises four spools with lengths of 8.878, 4.35, 8.878, and 4.445 km, and DGD values of -0.057, 0.140, 0.172, 0.171 ps/m, respectively, resulting in a total accumulated DGD of 2.4 ns. The MMF used here has a graded-index profile, with 50/125 µm core/cladding diameters and maximum index difference between core center and cladding of $15\times10^{-3}$ at 1550 nm ($\Delta \approx 1\%$). In order to reduce bending sensitivity of the 10 supported mode groups (55 spatial modes) at 1550 nm, a trench is added to the cladding. Even keeping the bend radius $> 100$ mm, however, bend losses in the $10^{th}$ mode group are substantial, so only nine mode groups (45 spatial modes) are usable. The effective index differences between the mode groups are $>1.4\times10^{-3}$, resulting in acceptable coupling between the $9^{th}$ and $10^{th}$ mode groups. The fiber design has been optimized to minimize the DGD at 1550 nm by tuning the alpha parameter of the graded-index core and adjusting the trench position. The attenuation and the effective area $A_{eff}$ of the 1st mode group (fundamental LP01 mode) are measured to be 0.22 dB/km and 170 µm$^2$, respectively, at 1550 nm[2].

The modes are multiplexed in the MMF by using a pair of mode multiplexers (MMUXs) based on the multi-plane light conversion device (MPLC) principle[5]. We use off-axis interferometry to precisely characterize the modal content, crosstalk and, most importantly, the mode-dependent loss (MDL) of the mode multiplexers and fiber spools at various stages. The MMUXs have an insertion loss of  4 dB and a peak-to-peak MDL of 3 dB measured for each multiplexer. The total loss and MDL for the span including the MMUXs is 14 dB and 8 dB, respectively, including all nine mode groups.

In this experiment we use four samples of such MMFs with small positive and negative DMGDs to realize a partially DMDG-compensated link of 26.5-km length with DMGDs $\leq$100 ps/km for the first nine mode groups[3].

**Experimental Setup**

The experimental setup is shown in Fig. 1a and consists of a transmitter producing 10 WDM channels spaced by 50 GHz and modulated with a dual-carrier 15-Gbaud QPSK signal, resulting in 20 logical 15-Gbaud QPSK and 16-QAM wavelength channels. The channel under test uses an external cavity laser (ECL) as light source and is modulated by a polarization-multiplexed double-nested Mach Zehnder modulator (DN-MZM) using four independent high-speed digital-analog converters (DACs) operated at 60 GSamples/s, to produce a dual-carrier 15-Gbaud QPSK signal. The QPSK signals are Nyquist shaped with a spacing between the digital carriers of 15.2 GHz. Similarly, a second set of DFB lasers are modulated, using another single-polarization DN-MZ, with independent DeBruijn sequences of length $2^{15}$. The two transmitters are combined and split three ways and subsequently amplified by three high power erbium-doped amplifiers (EDFAs) with 30 dBm maximum output powers. Finally, each of the the three paths is split 15 ways and delay-decorrelated with a relative delay of 50 µs, producing 45 copies of the signal that are coupled into the first nine mode groups of the 26.5-km MMF span. The 45 polarization-multiplexed transmitted signals are detected using a time multiplexing scheme[4], where an acousto-optic switch operated at 33.3% duty cycle is used as time gate for the channel under test. Note that, in contrast to previous experiments, the acousto-optic switch is placed at the transmitter and only modulates the channel under test. The multimode acousto-optic modulator used in the previous 36-mode experiment[1] causes severe modal distortions because of diffraction and could not be used, whereas we do not have 45 individual fast switches to gate the modes at the receiver, as we used in 10-mode fiber experiments. The multimode signal is then spatially demultiplexed using a second mode multiplexer and connected the delay fibers. We use two sets of 15-fiber spools with lengths of 5 km and 10 km, that are precisely adjusted within $<$ 1 m of length difference. The 15 undelayed modes are then recombined with two sets of delayed modes by using 15 3:1 combiners, where each output is connected to a two-stage EDFA, with a programmable filter placed between the stages of the EDFA to provide the optical filtering necessary for heterodyne detection, and the resulting 15 single-mode fibers are individually detected by 15 polarization-diverse heterodyne receivers (PD-HRx) and detected on 30 electrical channels of a 40 Gsamples/s digital storage oscilloscope (DSO).

The 30 captured electrical signals are processed off-line by first down-sampling the signals to 2 samples-per-symbol (30 Gsample/s), while keeping only the digital sub-band closer to the center of the spectrum (the second sub-band can be accessed by moving the LO to the opposite side of the dual-carrier signal). This transforms the 30 detected real signals into 30 complex-valued amplitudes, as is customary in heterodyne detection. Afterwards, the time record is split into three parts, corresponding to the three delays introduced by the 5 km and 10 km fiber delays, resulting in 90 complex amplitude waveforms representing the detected modes and polarizations of the multimode fibers.

Additionally, we apply a phase correction to the delayed fields to compensate for phase variations of the LO between the time-multiplexed captures. The correction is obtained by measuring a delayed copy of the LO by using an additional 5 km and 10 km fiber delay, which are detected simultaneously with the modal capture by using an additional polarization-diverse coherent receiver (PD-CRx). The experimental arrangement is shown in Fig. 1a on the lower right side, and uses a second acousto-optic switch also driven at 33.3% duty cycle followed by 1:3 splitter connected to the delay fibers and 3:1 combiner followed by an EDFA and the PDCRx. Finally, the 90 complex amplitude signals are processed by a frequency-domain 90$\times$90 MIMO equalizer with 300 symbol-spaced taps. The initial convergence of the equalizer is obtained by using the data-aided least-mean-square (LMS) algorithm, whereas the constant-modulus algorithm (CMA)

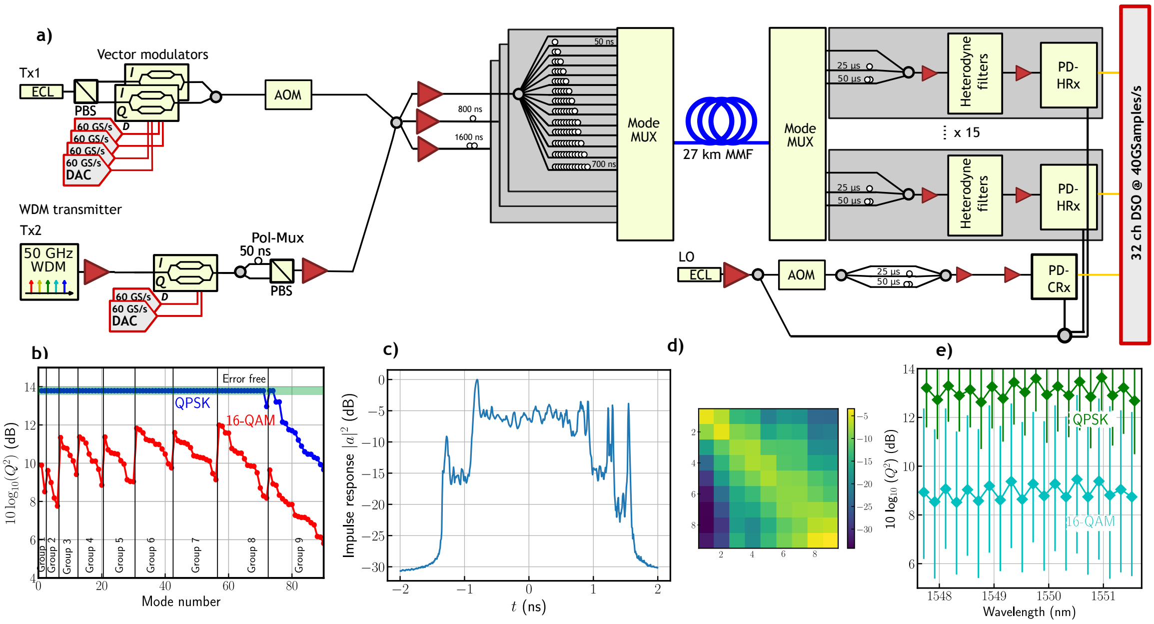


**Fig. 1:** a) Setup for MIMO based 45-mode transmission over a multimode fiber. b) $Q$ factors of the 90 spatial tributaries for QPSK and 16-QAM transmission over 27 km multimode fiber arranged according to the mode groups and sorted by performance within the mode group. c) Intensity averaged impulse response of a 27 km long multimode fiber obtained from a channel estimation. d) Intensity transfer matrix showing the coupling between the nine mode groups. e) Average Q-factor for QPSK and 16-QAM as a function of wavelength, The error bars represent the best and the worst spatial tributaries.

is used afterwards. Finally, carrier-phase recovery and bit-error-rate (BER) counting are performed and $Q$ factors are computed by evaluating an inverse Q function of the BER.

The obtained $Q$ factors are reported for a wavelength of 1549.70 nm in Fig. 1b as function of the mode group and sorted by performance within the mode group. For QPSK signals all modes have $Q > 9.8$ dB for all wavelengths, whereas for 16-QAM, the Q factors vary from 5.8 to 12 dB and are $>$8 dB for almost all of the first eight mode groups. The $Q$ factors calculated from the average BERs are 13.5 dB and 9.2 dB for QPSK and 16-QAM, respectively. This value is representative for a system that uses a simple bit-interleaved encoding scheme[6], and is within the capability of a hard-decision FEC, and results in a spectral efficiency of 202 bit/s/Hz if an FEC overhead of 7% is assumed.

Additionally, we also performed a channel estimation and the resulting intensity-averaged impulse response of all 90×90 impulse responses is shown in Fig. 1c. The impulse response shows the effect of modal group dispersion where some of the peaks corresponding to the mode groups are still visible. The overall width of the impulse response is around 2.5 ns, as expected from the previously measured fiber DGD. The intensity transfer matrix between the input and output 9 groups is shown in Fig. 1d. In Fig. 1e we show the average and best/worst spatial tributaries represented as error bars for all 20 WDM channels under test, confirming a consistent performance as function of the wavelength.

## Conclusion

We experimentally demonstrated 90×90 MIMO based mode-multiplexed transmission over 45 spatial modes and 20 wavelength channel resulting in a total capacity of 101 Tb/s. We used a 50 µm core diameter graded-index multimode fiber with a length of 26.5 km, resulting in a spectral efficiency of 202/bit/s/Hz, which is the largest reported for a single fiber core.

## References


[1] R. Ryf, et al., "Mode-Multiplexed Transmission over 36 Spatial Modes of a Graded-Index Multimode Fiber," ECOC 2018.

[2] P. Sillard, et al., "50 $\mu$m multimode fibers for mode division multiplexing," JLT, 34(8), pp. 1672–1677, 2016.

[3] P. Sillard, et al., "DMGD-compensated links," OFC 2017, p. Tu2J

[4] R. G. Van Uden, et al."Time domain multiplexed spatial division multiplexing receiver," Optics express, vol. 22, no. 10, pp. 12 668–12 677, 2014.

[5] N. K. Fontaine, et al. "Packaged 45-Mode Multiplexers for a 50-µm Graded Index Fiber," ECOC 2018.

[6] J. van Weerdenburg, et al.,"10 spatial mode transmission using low DGD 6-lp fiber using all-fiber photonic lanterns," Optics express, 23(19), no. 19, pp. 24 759–24 769, 2015.