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Adaptive Rates of High-Spectral-Efficiency WDM/SDM Channels Using PDM-1024-QAM Probabilistic Shaping

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Abstract *We demonstrate adaptive rates and spectral efficiencies in WDM/SDM transmission using probabilistically shaped PDM-1024-QAM signals, achieving up to 7-Tbit/s data rates per spatial-super-channel and up to 297.8-bit/s/Hz aggregate spectral efficiency using a 30-core fiber on 12.5 and 25-GHz WDM grids.*

Introduction

To meet the ever-growing demands for higher bandwidth, the potential of space-division multiplexing (SDM) based on single-mode multi-core fibers (SM-MCFs) or few-mode multi-core fibers (FM-MCFs) has been demonstrated in several impressive results[1-3]. SM-MCF transmission systems have the advantage of being free from mode-dependent loss/modal differential group delay and remove the need for high-complexity multiple-input multiple-output (MIMO) processing, lowering both power consumption and latency. In order to further increase the transmission capacity, dense SDM based on high-count SM-MCFs over 30 cores have been studied recently[4]. To further increase the data capacity in high-count SM-MCF transmission, more advanced modulation formats with higher spectral efficiency (SE) will be needed. While 1024-QAM and 2048-QAM have been used for single channel SM-MCF transmission with a symbol rate of ~3 GBd[5,6], the most advanced modulation format used for WDM/SDM transmission so far is PDM-64-QAM[2,7]. To achieve higher-order QAM (such as 1024-QAM) with higher symbol rates (>10 GBd) over multiple WDM channels, there are several challenges such as hardware-limitations of available transceivers, achievable OSNR after transmission and the cost of narrow-linewidth lasers. Recently, probabilistic shaping (PS) has attracted a lot of attention in optical communications, not only for achieving shaping gain but also for the capability of adapting their rate to the channel conditions[8-10].

In this paper, we demonstrate the first probabilistic shaping (PS) for WDM/SDM transmission. Eight WDM channels either modulated at 12 GBd on a 12.5-GHz grid or at 24.5 GBd on a 25-GHz grid carrying PS PDM-1024-QAM signals are transmitted through a 9.6-km 30-core fiber, reaching the highest modulation format order for WDM/SDM transmission to date. We employ full soft-decision (SD)-FEC decoding with adaptive information rates for the different spectral and spatial channels to obtain error-free performance, and achieve aggregate data rates of 3.7 Tbit/s and 7 Tbit/s per frequency channel for the 12.5-GHz grid and 25-GHz grid cases, respectively. We thus achieve record-high spectral efficiencies of 297.8 bit/s/Hz and 280.3 bit/s/Hz for the 12.5-GHz grid and 25-GHz grid cases, respectively, for SM-MCF transmission

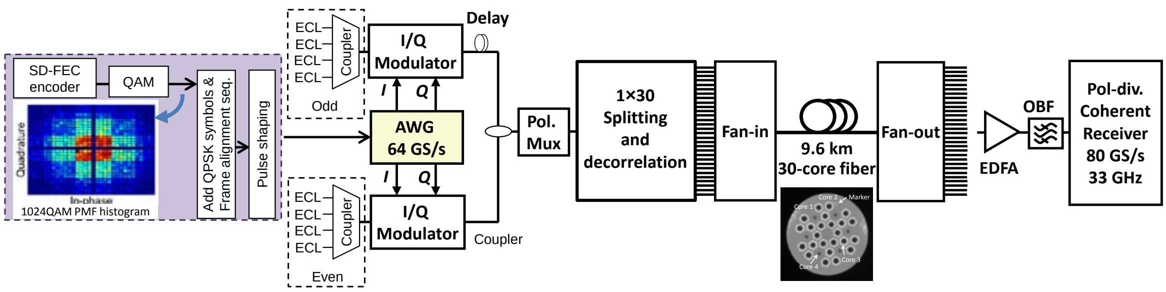

Fig. 1: Schematic of experimental setup for WDM/SDM transmission of probabilistic shaped PDM-1024-QAM channels over a 9.6-km 30-core fiber, including external cavity lasers (ECLs) with a linewidth of 10 kHz, erbium-doped fibre amplifier (EDFA), arbitrary waveform generator (AWG), polarization multiplexer (Pol. Mux), optical bandpass filter (OBF). Inset: cross-sectional view of the 30-core fiber.

systems.

Experimental setup

The experimental setup for the WDM/SDM transmission of PS PDM-1024-QAM channels is shown in Fig. 1. Eight external cavity lasers (ECLs) with a linewidth of 10 kHz and centered around 193.4 THz are divided into odd and even channels, and independently modulated with two I/Q modulators driven by a 4-channel 64 GSa/s arbitrary waveform generator (AWG) to produce a PS 1024-QAM WDM signal. Two symbol rates and frequency grids are used in the experiment, i.e. either 12 GBd on a 12.5-GHz grid or 24.5 GBd on a 25-GHz grid. The modulated signals are combined by a 3-dB coupler, amplified by an EDFA and then passed through a delay-and-add polarization emulator to generate polarization-multiplexed signals. Thirty de-correlated SDM channels are generated using splitters, amplifiers and delays (at least 2.5 ns between SDM channels) and then launched into a 9.6-km heterogeneous single-mode 30-core fiber through a 3D-waveguide based fan-in device. The launched power for each core is between 4 and 8 dBm accounting for loss-variations in the fan-in/fan-out from 5 dB to 8 dB.

The single-mode 30-core fiber has four different types of cores to realize a high-density core arrangement with a low cross-talk of < -50 dB after 9.6 km[11], which can support such a large constellation QAM signal transmission without MIMO processing. The 30 cores are arranged within the limited cladding diameter of 228 μm, with A_{eff} of ~80 μm^2. At the output of the 30-core fiber, the 30 spatial channels are demultiplexed using another 3D-waveguide based fan-out device. The demultiplexed spatial channels are then amplified; one WDM channel at a time is filtered out and detected with a polarization-diversity coherent receiver followed by a digital sampling oscilloscope (DSO, 80 GS/s, 33 GHz) and offline digital signal processing.

Probabilistic shaping, FEC and DSP

The user data is encoded by a convolutional turbo code, and then many-to-one bit-to-symbol mapping is performed in order to achieve an optimized probability mass function (PMF) of the QAM symbols[8]. With many-to-one labeling, in contrast to standard QAM with unique Gray mapping, multiple bit strings are mapped to the same constellation symbol, making it appear more often on average (see histogram on Fig. 1). The resulting ambiguities are resolved by the decoder. The net data rate of this scheme is controlled by properly puncturing the turbo code to the desired SD-FEC overhead. Data rates of 5, 5.5 and 6 information bits/QAM symbol are used (see Table 1). The PS QAM symbols are then uniformly interleaved with 10% QPSK symbols, which carry 2 bits per symbol, resulting in a hybrid modulation. Finally, a frame alignment sequence (FAS) is added to the beginning of the sequence, pulse shaping is performed (square root raised cosine, roll-off 0.01), and the waveform is sent to the AWG.

At the receiver, actual soft decision demapping and turbo decoding is performed. More than 300 blocks of 6600 (6000 QAM + 600 QPSK) symbols are transmitted and decoded in each case, making the number of decoded information bits $>10^7$ in all cases and thereby BER values above 10^{-5} reliable. Consequently, when no errors are measured, the BER is reliably below 10^{-5}. An outer HD-FEC[12] is then assumed with overhead 0.8% and decoding threshold of 5×10^{-5}, which can correct the remaining errors and bring the BER below 10^{-15}.

Experimental results

Fig. 2 shows the achieved mutual information (MI, bits/QAM symbol)[8] and achieved spectral efficiency (SE, bits/s/Hz/polarization/core) after the 30-core fiber transmission of all the WDM and SDM channels for the cases of 12-GBd PS PDM-1024-QAM signal on a 12.5-GHz grid and 24.5-GBd PS PDM-1024-QAM signal on a 25-GHz grid. The MI gives an upper bound on the achievable SE using ideal SD-FEC decoding.

Tab. 1: Summary of the main results.

	HD-FEC overhead	QPSK hybrid	Tested **input** data rate (shaping) [bits/QAM symbol] / Tested **input** net SE [bit/s/Hz/pol/core]			**Achieved** average SE [bit/s/Hz/pol/core]	**Achieved** average MI (hybrid) [bits/symbol]	**Achieved** aggregated SE [bit/s/Hz]	**Achieved** aggregated data rate per frequency channel [Tbps]
12 Gbaud @ 12.5 GHz	0.8%	10%	5	5.5	6	4.9636	5.3931	297.816	3.722
			4.502	4.935	5.268				
24.5 Gbaud @ 25 GHz			5	5.5	6	4.6712	5.0901	280.272	7.006
			4.596	5.038	5.479				

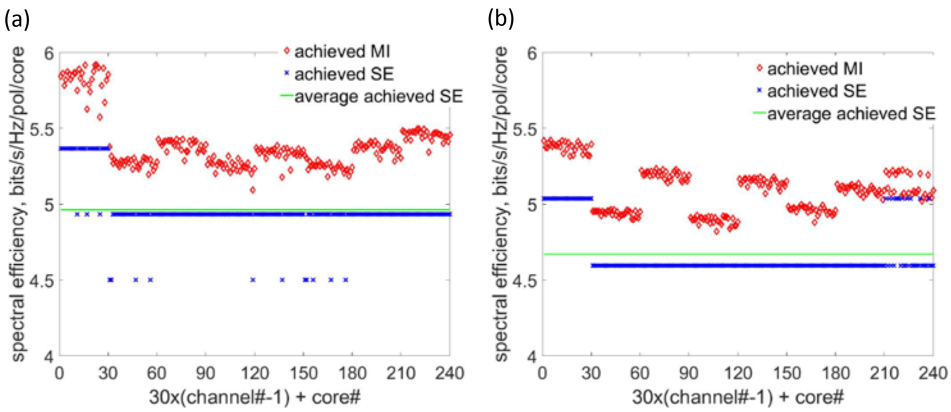

Fig. 2: Achieved mutual information (MI, bits/symbol) and achieved spectral efficiency (SE, bits/s/Hz) using the employed non-ideal SD-FEC decoding after the 30-core transmission of all the WDM and SDM channels for the cases of 12-Gbaud PS PDM-1024-QAM signal on 12.5-GHz grid (a) and 24.5-Gbaud PS PDM-1024-QAM signal on 25-GHz grid (b). Channel# corresponds to the WDM channels (from 1 to 8) and core# corresponds to the cores of the 30-core fiber (from 1 to 30).

We also performed actual SD-FEC decoding, and the experimentally achieved SE based on our non-ideal codes is also shown. Due to the OSNR variations between the WDM channels and loss variations in the different cores of the 30-core fiber, the transmission performances of the WDM/SDM channels are different. Adaptive rates and SEs are used to achieve error-free performance for different WDM/SDM channels without changing the modulation format. For the 12-GBd PS PDM-1024-QAM signal on a 12.5 GHz grid, the achieved average MI is 5.39 bits/QAM symbol and the achieved average SE with employed FEC decoding is 4.96 bit/s/Hz/pol/core, resulting in an aggregated spectral efficiency of 297.8 bit/s/Hz. For the 24.5-GBd PS PDM-1024-QAM signal on a 25 GHz grid, the achieved average MI is 5.09 bits/QAM symbol and the achieved aggregated net data rate per frequency channel is 7.006 Tbit/s, as summarized in Table 1.

Conclusion

We have demonstrated adaptive rates and SEs in WDM/SDM transmission over a 9.6-km 30-core fiber using probabilistically shaped PDM-1024-QAM signals with up to 7 Tbit/s per frequency channel. Actual SD-FEC decoding was employed to obtain error-free performance, and owing to the shaping gain we achieved record-high aggregate spectral efficiencies of up to 297.8 bit/s/Hz for SM-MCF transmission systems.

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References

[1] H. Takara et al., “1.01-Pb/s (12 SDM/222 WDM/456 Gb/s) Crosstalk-managed Transmission with 91.4-b/s/Hz Aggregate Spectral Efficiency,” Proc. ECOC, Th.3.C.1, (2012).

[2] B. J. Puttnam et al., “2.15 Pb/s transmission using a 22 core homogeneous single-mode multi-core fiber and wideband optical comb,” Proc. ECOC, PDP.3.1 (2015).

[3] D. Soma et al., “2.05 Peta-bit/s super-nyquist-WDM SDM transmission using 9.8-km 6-mode 19-core fiber in full C band,” Proc. ECOC, PDP.3.2 (2015).

[4] T. Mizuno et al., “32-core Dense SDM Unidirectional Transmission of PDM-16QAM Signals Over 1600 km Using Crosstalk-managed Single-mode Heterogeneous Multicore Transmission Line,” Proc.OFC, Th5C.3 (2016).

[5] M. Yoshida et al., “1024 QAM, 7-core (60 Gbit/s x 7) fiber transmission over 55 km with an aggregate potential spectral efficiency of 109 bit/s/Hz,” Opt. Express, 23(16), p. 20760 (2015).

[6] D. Qian et al., “698.5-Gb/s PDM-2048QAM transmission over 3km multicore fiber,” Proc. ECOC, Th.1.C.5 (2013).

[7] D. Soma et al., “665 and 947b/s/Hz Ultra-highly Aggregate-Spectral-Efficient SDM/WDM Transmission over 6-Mode 19-Core Fibre Using DP-16QAM/64QAM Signals,” Proc. ECOC, Th.3.C.2 (2016).

[8] M. P. Yankov, et. al. “Constellation shaping for WDM systems using 256QAM/1024QAM with probabilistic optimization”, J. Lightwave Technol., 34(2), 2016.

[9] S. Chandrasekhar et al., “High-spectral-efficiency transmission of PDM 256-QAM with Parallel Probabilistic Shaping at Record Rate-Reach Trade-offs,” Proc. ECOC, Th.3.C.1 (2016).

[10] F. Buchali et al., “Experimental demonstration of capacity increase and rate-adaptation by probabilistically shaped 64-QAM,” Proc. ECOC, PDP.3.4 (2015).

[11] Y. Amma et al., “High-density Multicore Fiber with Heterogeneous Core Arrangement,” Proc. OFC, Th4C.4 (2015).

[12] D. S. Millar, et. al, ” Design of a 1 Tb/s superchannel coherent receiver”, J. Lightwave Technol., 34(6), 2016.