# First Transmission of a 12D Format Across Three Coupled Spatial Modes of a 3-Core Coupled-Core Fiber at 4 bits/s/Hz

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**Abstract:** We demonstrate the first transmission of a space-division multiplexed 12D modulation format over a three-core coupled-core multicore fiber. The format occupies a single time slot spread across all three linearly-coupled spatial modes and shows improvements in MI and GMI after transmission compared to PDM-QPSK. © 2020 The Author(s)

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## 1. Introduction

Advanced modulation formats are essential to achieve high spectral efficiencies (SEs). Various bidimensional (2D) modulation formats with different SEs have been considered to minimize bit-error rate (BER), maximize mutual information (MI) or generalized mutual information (GMI) at a given signal-to-noise ratio (SNR) [1]. There are two main techniques to optimize constellations, geometric [2] and probabilistic [3] shapings.

The design of modulation formats in high (above two) dimensions is a promising area to improve system performance. Examples of high-dimensional constellations geared towards additive white Gaussian noise (AWGN) are hybrid formats [4] and Hurwitz constellations [5]. Other high-dimensional formats designed to suppress nonlinear distortions include 4D formats using points symmetrically located on two rings [7, 8], 4D constant-power constellations optimized for GMI [6], 12D [9] and 16D [10], the last two being limited to low SE. So far, these formats have been implemented as time sequences of 4D symbols or across *uncoupled* fiber cores.

In this paper, we implemented a 12D modulation format across all the three linearly *coupled* spatial modes of a multicore fiber. We show improved transmission compared to PDM-QPSK at the same SE. To our knowledge, this is the first experiment of a multidimensional constellation spanning *strongly linearly coupled* spatial modes.

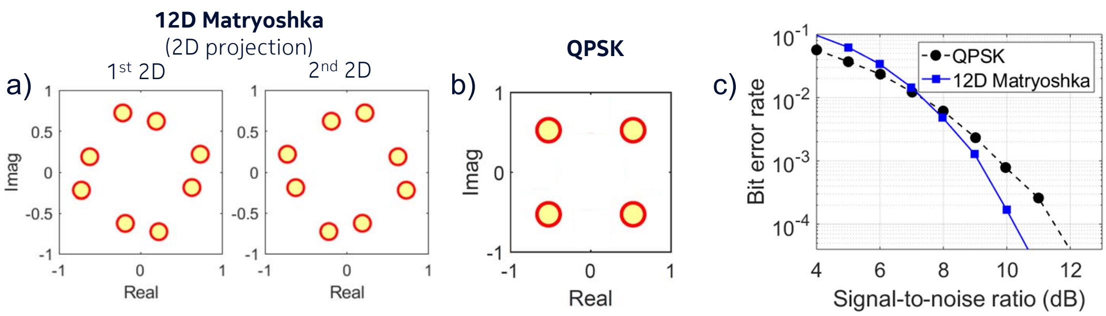


Fig. 1. a) 2D projections of the proposed 12D Matryoshka modulation format. The three pairs of 2D projections of the 12D Matryoshka format are identical to the pair shown; b) the (2D) QPSK format and c) BER curves.

## 2. 12D Matryoshka Modulation Format

Figure 1a displays two 2D projections of the first four dimensions of the proposed 12D modulation format, referred to as *12D Matryoshka*. The other two pairs of two 2D projections that complete the six 2D projections are omitted here as they are identical to the first two shown. All six 2D projections along with selection rules constitute the 12D

Matryoshka format. Selections rules between points across 2D sets reduce the unconstrained $8^6 = 2^{18}$ constellation points to $2^{12}$ points. One notices that each 2D projection of the 12D format has two sets of four points on two (nearly identical) radii offset by an angle of 0.15 radians. We impose a rule of selecting only points on the different radii within the three pairs of 2D sets that form a 12D format. The format is then bit mapped using Gray code for each of the two rings in each 2D sets with a single bit added for ring selection. All 12D constellation points having either even or odd bit parity are then removed (constellation puncturing), leaving 4096 points in 12D. The resulting Matryoshka constellation is then bit mapped again with 12-bit sequences. This results in a SE of 4 bits/s/Hz for each wavelength, identical to the PDM-QPSK format shown in Fig. 1b. The different sizes of the constellation points between the two formats reflect their frequency of use. The 12D Matryoshka format has constant power in 4D and therefore in 12D, as is the case for PDM-QPSK. Figure 1c displays the BER curves for both formats showing better BER for the proposed Matryoshka format at an SNR $> 7.3$ dB, or a BER $< 9 \times 10^{-3}$.

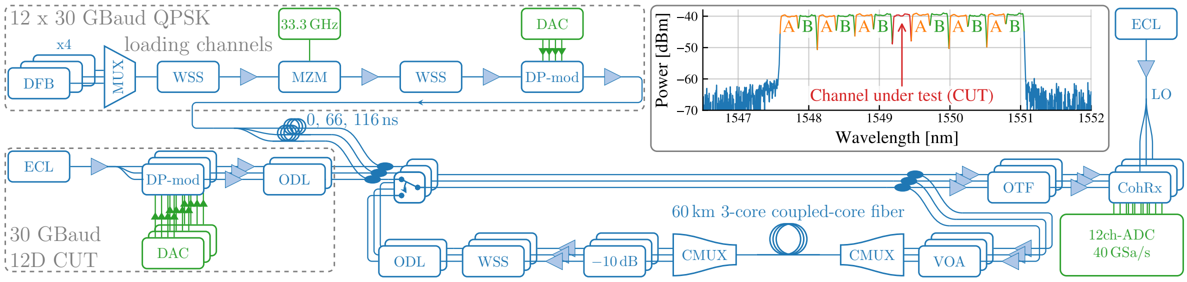


Fig. 2. Experimental transmission set-up.

## 3. Experimental Set-Up

The experimental setup shown in Fig. 2 consists of a transmitter producing 13 wavelength-division multiplexed (WDM) channels spaced at 33.3 GHz and modulated at 30 Gbaud. Three time-synchronized four-channel 60 GSa/s digital-to-analog converters (DACs) were used to create the 30 GBaud 12D Matryoshka modulation format described in Sec. 2 as the channel under test (CUT). It is inserted in the middle of the signal spectrum (see inset in Fig 2). The DACs drive three dual-polarisation modulators (DP-mods), based on dual-polarisation double-nested Mach-Zehnder modulators (MZMs), each modulating a copy of a tone at 1549.3 nm provided by an external cavity laser (ECL). The three tributaries of the 12D signal are time-aligned with an accuracy of $\pm 4$ ps using two optical delay lines (ODLs) placed in the second and third tributary path. The twelve 30 GBaud PDM-QPSK channels are created by modulating six tones of an optical frequency comb. A 120 GSa/s DAC provides the driving signals to a fourth DP-mod, creating two uncorrelated PDM-QPSK channels out of each tone. The 12D CUT and the loading channels are combined and injected into a recirculating loop. The three spatial tributaries are launched into a 60 km spool of three-core coupled-core multicore fibre (CC-MCF) [11] using a core multiplexer (CMUX), consisting in a tapered structure similar to a photonic lantern that couples three input fibers into the three cores of the CC-MCF, resulting in an added insertion loss of $(0.7 \pm 0.2)$ dB. Since the recirculating loop components are single mode, a second CMUX is used to separate the output of the CC-MCF into three tributaries. They are subsequently amplified, filtered, and launched into the CC-MCF again, where variable optical attenuators (VOAs) where used to change the launch power into the fiber cores and wavelength-selective switches (WSSs) were optimized to correct for the launch power dependent spectral tilt. The ODLs insured that the three tributaries experienced identical delays, within the accuracy of $\pm 4$ ps. The three tributaries are extracted from the recirculating loop by using splitters with a splitting ratio of 10:90 followed by optical amplifiers an optical tunable filters (OTF) to select the CUT, followed by three polarisation-diverse intradyne coherent receivers (cohRxs) connected to a single local oscillator (LO) and a 12-channel 40 GSa/s digital storage oscilloscope.

The captured signals are processed offline by first up-sampling the signals to 2 samples/symbol, performing chromatic dispersion and frequency-offset compensation followed by timing identification and a $6 \times 6$ MIMO processing, based on a frequency domain equalizer with 1000 symbol-spaced taps, followed by a phase recovery for each spatial tributary. The reconstructed fields are subsequently processed in 12D to calculate MI and GMI. The 60-km long CC-MCF [11] had an effective area of 120 $\mu$m$^2$, and a loss of 0.18 dB/km. An additional 10 dB attenuation was added at the end of the span to increase the span loss to $(22.8 \pm 0.2)$ dB. This enabled operating at a reduced number of loops, preventing excessive growth of loop artifacts and mode-dependent loss (MDL).

## 4. Transmission and Conclusion

The mutual information (MI) after transmission of the two modulation formats are shown in Fig. 3a. Both modulation formats can carry 12 bits of information after a few spans. After 10 to 20 spans depending on the power, the

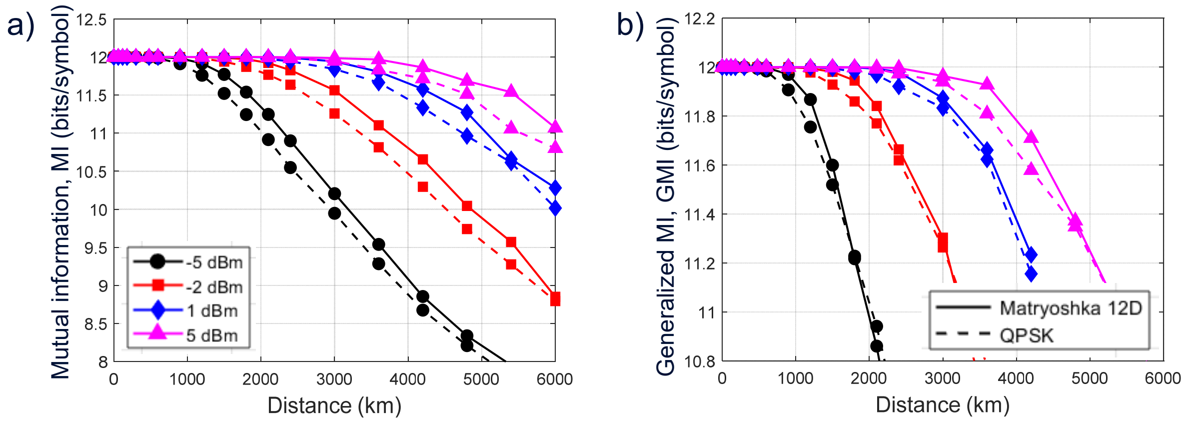


Fig. 3. a) Mutual information (MI) as a function of distance for the 12D Matryoshka and PDM-QPSK for different powers per channel; b) Generalized mutual information (GMI) for the same power levels. The MI and GMI of PDM-QPSK are reported over 12D for a fair comparison

MIs of the two formats start to differ with the 12D Matryoshka outperforming PDM-QPSK at all distances and powers. At an MI = 11 bits/symbol, the 12D Matryoshka format allows an averaged increase of 8 to 15% of the propagation distance. There appears to be a slight increase in the difference of MIs at high powers favoring 12D Matryoshka over PDM-QPSK. Further investigation is needed for a more precise assessment in this regime and in the presence of MDL.

The generalized MI (GMI) for the same conditions of Fig. 3a is reported in Fig. 3b. It shows that most of the benefits of the 12D format for MI are preserved at high values of GMI, including in the high power regime. The bit mapping therefore appears to offer 'resistance' to the types of distortions produced during transmission. We presented the first long-distance transmission of a 12D modulation format implemented across coupled spatial modes in a 3-core coupled-core multicore fiber. The format shows improved performance over PDM-QPSK, both having spectral efficiencies of 4 bits/s/Hz.

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