Increased Reach of Long-Haul Transmission using a Constant-Power 4D Format Designed Using Neural Networks

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Abstract *We demonstrate ultra long-haul transmission of a new four-dimensional (4D) modulation format having low generalized mutual information (GMI) gap to Shannon and designed using neural networks. We experimentally demonstrate an improved transmission distance.*

Introduction

Advanced modulation formats are needed to maximize spectral efficiency (SE) of fiber-optic communication systems. Various conventional and high-dimensional 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) or transmission distance[1]. One generally classifies advanced modulation formats into geometric[2] or probabilistic[3] shaping or a combination of the two.

Examples of high-dimensional constellations geared towards performance in 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[6],[7] and 4D constant-power constellations optimized for GMI[8].

In this paper, we implement a constant-power 4D modulation format designed using neural networks. The constellation does not show any obvious geometric structure usually associated with the conventional design of geometrically-shaped advanced formats. Importantly, the design method also largely resolves the bit labeling challenge of large constellations and ease the decoding problem by providing a high performance computationally efficient neural network-based decoder for high-dimensional formats. The constellation exhibits a low gap to Shannon considering even the constant-power geometric shaping. We experimentally demonstrate an improved GMI

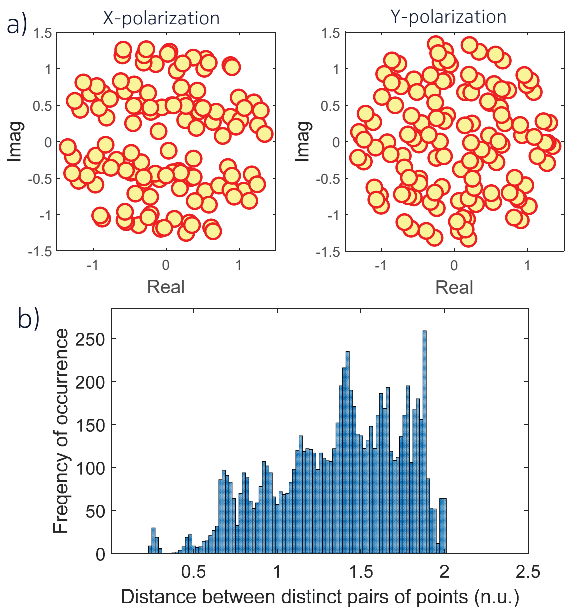

Fig. 1: a) Bidimensional projections in the x and y polarizations of the 4D constant-power 128 pts modulation format CP128; b) Histogram of the distance between pairs of points of the CP128 constellation. The normalized units (n.u.) refers to a constellation of energy of 1.

after transmission compared to formats such as polarization-division multiplexed (PDM) quadrature phase-shift keying (PDM-QPSK) and PDM 16- quadrature amplitude modulation (QAM).

4D Modulation Format and Autoencoder

Figure 1a displays two 2D projections of the 128 points forming the constant-power 4D format labeled *CP128*. The constellation has been designed to maximize the GMI around an SE of 3 bits/symbol using a neural network shown in Fig. 2. The neural network incorporates a power normalization layer, a Gaussian noise layer and

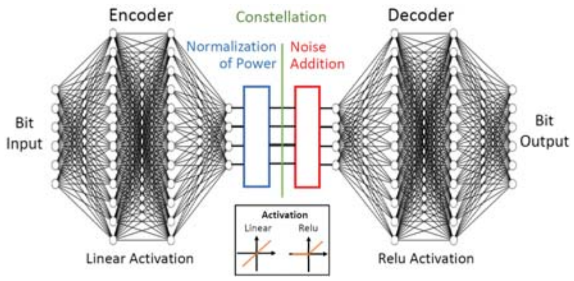

Fig. 2: The neural network structure, known as autoencoder, used to design the constant-power 4D constellation. This structure allows imposing a constant power constraint in 4D while performing bit mapping to each symbol.

a decoder. The encoder comprises four layers of fully connected neurons. The activation functions are a combination of linear and 'relu'. The neural network objective is for the soft output bits to re-create the input as closely as possible by minimizing the binary entropy between the input and output bit sequences. Training is done by generating 100,000 random input binary vectors and using back-propagation to update the weights. The neural network simultaneously designs the 4D constellation points and corresponding bit patterns. The design of a format with 128 points in 4D like CP128 takes a few minutes on a general processing unit (GPU). In contrast to most geometric- or hybrid-shaped formats, the constellation found by the neural network do not seem to possess much of a geometric structure as can be seen from the histogram of distance between pairs of constellation points as shown in Fig. 1b. Despite this lack of structure, the GMI gap to Shannon can be smaller than formats that have regular geometric structures and are Gray-mapped.

Experimental Set-Up

The experimental setup shown in Fig. 3 consists of a transmitter generating 15 wavelength-division multiplexed (WDM) channels spaced at 33.3 GHz and modulated at 30 Gbaud. The channel under test is generated by using an external cavity laser (ECL) with a linewidth of 10 KHz followed by a polarization diverse (PD) double-nested Mach-Zehnder modulator (DN-MZM) driven by a 4 channel digital-to-analog converter (DAC), operating at 60GS/s, capable of generating arbitrary 4D modulation signals. The fourteen dummy WDM signals are generated by using 5 combined distributed feedback lasers (DFBs) spaced at 100 GHz, followed by a Mach-Zehnder modulator driven with a 33.33 GHZ sinusoidal tone, resulting in 15 laser lines spaced at 33.33 GHz. The laser lines are subsequently divided in odd and even channels by a flexgrid wavelength selective switch (WSS), which is additionally programmed to block the central laser line located at a wavelength of 1532.68 nm with an extinction ratio of > 30 dB. Odd and even laser lines are modulated by a pair of DN-MZMs driven by a 4 channel DAC operated at 60GS/s, followed by a polarization multiplexing stage. Dummy channels and channel under test are combined using a 10:90 coupler and injected into the recirculating loop by using a cascade of two solid-state optical switches.

The loop consists of three spans of 120 km of standard single-mode fibers (SSMFs) with an insertion loss of 27.9, 29.2, 28.4 dBm, respectively. A dynamic gain equalizing filter (DGEF) is used to compensate for the spectral gain variation of the loop amplifiers, and a 10:90 coupler is used to extract the signal from the loop. The extracted signal is amplified and filtered, and subsequently detected by a polarization-diverse coherent receiver (PD-CRX), wich uses a second ECL as local oscillator. The four electrical signals generated by the PD-CRX are captured for off-line processing on a digital sampling oscilloscope (DSO) operating at 40GS/s.

The digital signal processing consists of an initial up-sampling to 2 samples/symbol, performing chromatic dispersion and frequency-offset compensation followed by timing identification and a 2x2 MIMO processing based on a frequency domain equalizer with 1000 symbol-spaced taps, followed by a phase recovery for each polarization. The reconstructed fields are subsequently processed as 4D fields using a neural network decoder and SNR, MI and GMI are calculated.

Transmission

The GMI of the four constellations considered are displayed in Fig. 4. One notices that at a SE between 2.8 and 3.6 bits/symbols, the constant-power CP128 4D format displays a better GMI despite being constrained to constant power in 4D, improving even slightly over PDM-16-QAM that does not display the constant power restriction. The GMI gap to Shannon of the CP128 4D format is only $\sim$0.4 dB.

The GMI after transmission of four modulation formats are shown in Fig. 5. At a distance between 7500 and 10500 km, where the spectral efficiency ranges from 2.8 to 3.5 bits/symbols, the CP128 format exhibits better GMI than all three other formats. The set-partitioned (SP) format is PDM SP-16-QAM that achieves the lowest GMI, in part due to its larger GMI gap to Shan-

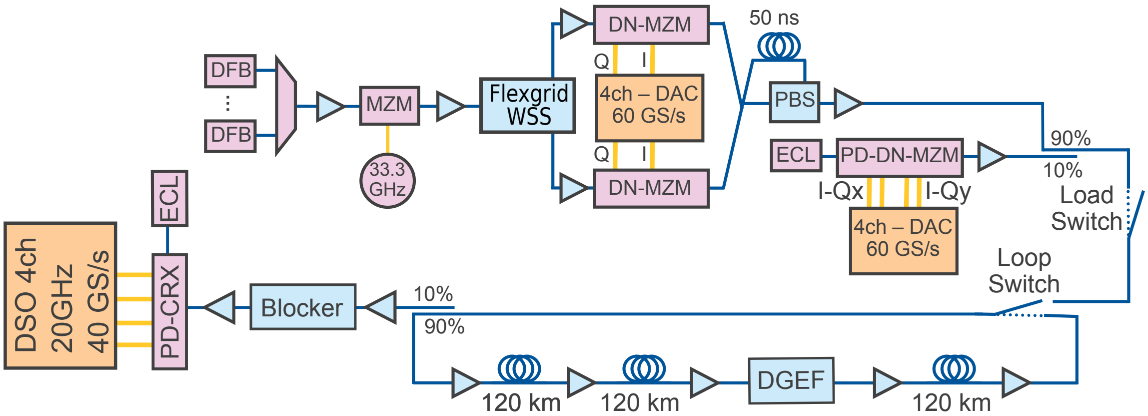

Fig. 3: Experimental transmission set-up.

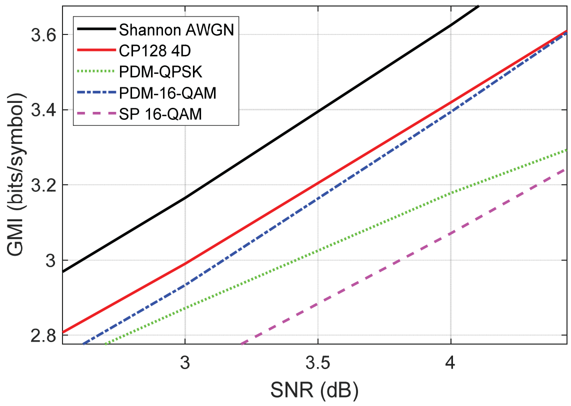

Fig. 4: The GMI of four modulation formats versus SNR and the Shannon AWGN capacity limit.

non for an AWGN channel. The format PDM-QPSK achieves excellent nonlinear performance largely due to its inherent constant power but it not sufficient to compensate the GMI gap difference with CP128. The GMI of PDM-16-QAM is excellent but its performance degrades faster than CP128 and PDM-QPSK partly due to large variations in amplitude exhibited by this format. Note that our transmission system exhibited a large polarization-dependent loss from the gain equalizer that significantly distorted the 4D format, thereby strongly reducing its nonlinear transmission benefit.

Conclusion

We presented constant-power 4D format with low gap to Shannon. The autoencoder structure enabled to simultaneously perform bit labeling and to apply constraints. The technique can be easily applied to generate various formats. We would like to acknowledge A. Ghazisaeidi, D. Fishman, J. Cho, G. Gavioli and C. Constantini for helpful discussions.

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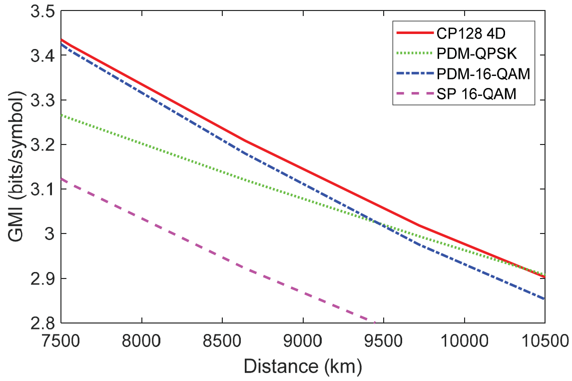

Fig. 5: The experimental measurements of GMI as a function of distance for the CP128 4D constellation in comparison to other modulation formats. The signal power was varied and the maximum GMI value recorded. The optimum power per channel is around 1 dBm, for all distances shown.

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