Adaptive Geometric Constellation Shaping in a Transmission System with a Real-time Optimisation Loop

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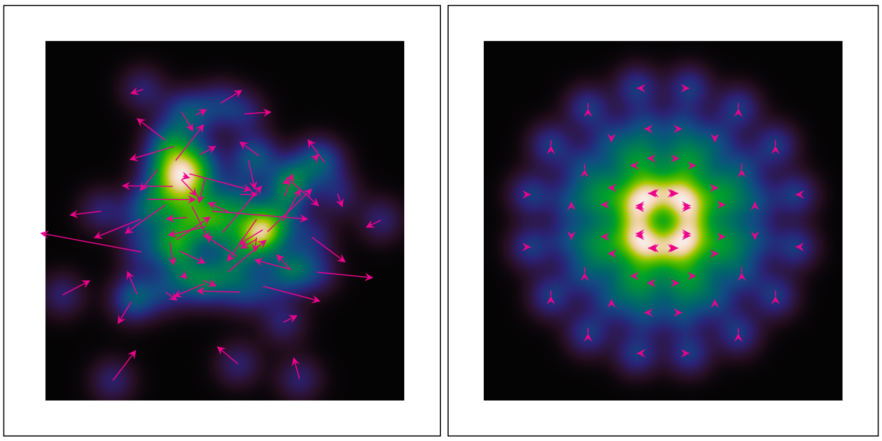
Abstract: We demonstrate the real-time performance of an adaptive intelligent transceiver, tailoring the constellation shape to the transmission system by iteratively maximising the information throughput, quantified by the GMI.

1. Overview

In recent years, constellation shaping has attracted considerable attention in the research community as a way to increase the achievable data rate and close the gap to the Shannon capacity. The constellation shaping allows tailoring of the modulation alphabet to the transmission system, effectively optimising the information throughput with respect to the incurred noise. For short-distance transmission, high-cardinality constellation shaping is optimised for the transceiver noise and distortion, while in long-distance and high-rate scenarios, shaping balances the interplay of the amplifier noise and fibre nonlinearity.

There are two approaches to constellation shaping: geometric and probabilistic, with recent work combining two approaches, known as hybrid shaping. In geometric shaping, the constellation points change their position within the complex plane, effectively moving closer points less affected by distortions, making more room for more distorted points. In probabilistic shaping, the position of the points does not change but points can be picked for the modulation with different probabilities. It has been shown for various realistic scenarios that probabilistic shaping provides a larger gain in terms of achievable data rate, but the mapping and demapping of the probability density function come at a higher computational cost.



(a) Random constellation (b) Optimised constellation

Fig. 1. Constellation diagram with ∇GMI for a random constellation and a constellation optimised for 12 dB SNR.

2. Innovation

To employ constellation shaping in the communication system, one must include modified modulation/demodulation components in the DSP chain at the transmitter (TX) and receiver (RX). To date, the constellation shaping is typically performed offline, when the optimal configuration is identified from simulations, and then the respective waveforms are generated to be reproduced at the transmitter.

In high-rate optical fibre communication systems research, constellation shaping is a widely-used approach experiments. There is active research in designing the constellations for systems affected by phase noise [1] or for 4D constellations accounting for polarization mode dispersion [2]. However, it is not yet commonly implemented in commercial systems. One of the reasons for this is that the approach is not yet mature with virtually no hardware prototypes demonstrating constellation shaping and its performance in realistic transmission systems [3–5]. In addition, the existing literature is focused on the implementation of the DSP chain components related to constellation shaping, such as constellation demappers and distribution matchers. In this way, the ability of the shaping to adapt to the transmission link behaviour is overlooked. In this demo, we focus on constellation shaping which is dynamically updated based on the measured accumulated noise in the system.

By efficiently calculating the gradient of the general mutual information (GMI) (∇GMI) from noisy symbols received from the lab, we can intelligently adapt the constellation to the transmission system behavior. The gradient of the auxiliary channel [6, Eq. (53)] is calculated whilst the Monte-Carlo integration is evaluated on the received noisy symbols from the transmission system. This way, the resulting gradient maximises the information throughput for our system. Fig. 1 represents this progress starting with random constellations with ∇GMI shown as arrows and optimised constellations after multiple iterations.

This demo will showcase the performance of first adaptive geometric shaper which can respond to the received signal and update real-time the constellation used by the transceiver in realtime, maximising the GMI. This reconfigurable geometric shaping will be implemented on a field programmable gate array (FPGA) to demonstrate a proof-of-concept for dynamic constellation reconfiguration implemented in hardware. The configuration of the constellation points is updated based on the received signal after transmitting via 100 km SSMF. We propose to use the received symbols according to [7], to obtain a gradient of the GMI as a function of the constellation points locations, using the stochastic gradient descent methodology (SGD) [8, Sec. 8.3.1]. This gradient can be used to tailor the constellation in real-time to the transmission system, maximising the system throughput.

3. OFC relevance

The demonstration is showing the OFC audience constellations being optimised in front of them. The promise of near real-time optimisation of the constellations tailored to the transmission system is of interest to both researchers wanting to maximise their transmission results as well as equipment manufacturers wanting to add intelligent adaptive constellations to transmission hardware.

At recent OFC conferences, constellation shaping was covered within the S2 subsystems track. A multitude of contributed papers was related to constellation shaping, including [9, 10] at OFC 2021 and [11, 12] at OFC 2022. There also were a number of invited papers [13, 14] and a tutorial [15] discussing the recent achievements in this area and current challenges.

4. Demo content & implementation

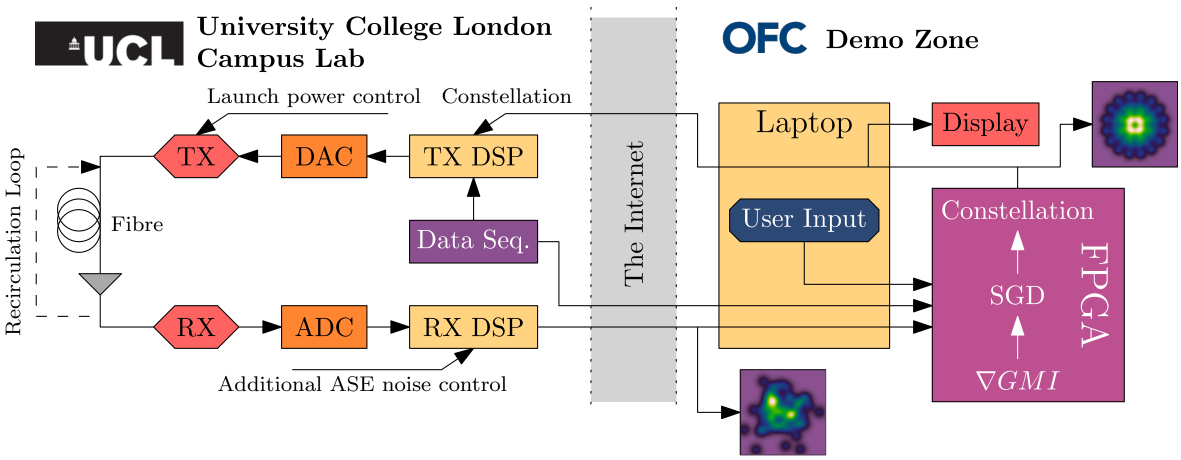


Fig. 2. Simplified overall system diagram.

In the demonstration, FPGA board will be used to implement the constellation optimisation in hardware. We find it important to show the hardware carrying out the optimisation on-site, therefore we will show the FPGA at the demo zone. The FPGA board will be connected to a laptop and an external display. Laptop will be used to take user input and as a Ethernet bridge to enable communication to the UCL campus and the transmission equipment. UCL campus includes a high-bandwidth remotely-reconfigurable fibre-optic transceiver which will transmit sequences over a reconfigurable recirculating loop with approx 100km fibre span. Improved constellations will be sent over the Internet to the optical transmitter (TX DSP) and transmitted through the rest of the optical system. Digital signal processing (DSP) is done offline [16, 17]. Transmitted random symbols and received noisy symbols are sent back to the FPGA in order to compute GMI. The attendees will see real-time updates of constellation diagrams shown on a display. We will invite attendees to draw initial constellation points and change experimental transmission parameters (launch power, ASE and phase noise load, number of recirculations etc.) to see in real-time how these parameters change the optimal constellation diagram. A video link will enable the attendees to simultaneously watch the transmission equipment in the lab at UCL. The recirculating loop test-bed can be configured to include the UK National Dark Fibre Infrastructure Facility [18] (subject to availability) to demonstrate distance-dependent adaptive constellation shapring over an installed fibre link up to 4000km. The National Dark Fibre Facility (NDFF) is an Engineering and Physical Sciences Research Council National Research Facility, established in 2014 to enable researchers to develop the underpinning communications technologies for the future internet.

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