Experimental Demonstration of Capacity Increase and Rate-Adaptation by Probabilistically Shaped 64-QAM

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Abstract We implemented a flexible transmission system operating at adjustable data rate and fixed bandwidth, baudrate, constellation and overhead using probabilistic shaping. We demonstrated in a transmission experiment up to 15% capacity and 43% reach increase versus 200 Gbit/s 16-QAM.

Introduction

Future optical metro and long-haul networks require transceivers that maximize spectral efficiency and throughput and that optimally exploit all available resources. For example, a transceiver that operates on a short network segment with high signal-to-noise ratio (SNR) should achieve a high spectral efficiency to maximize the net data rate over this segment. Similarly, a transceiver operating on a long network segment (e.g., an intercontinental route) with low OSNR should use either a lower order modulation format or a forward error correction (FEC) code with high overhead to ensure reliability.

Today’s coherent optical transceivers typically use a handful of coding and modulation modes for flexibility, e.g., different modulation formats and one or two FEC engines with different overheads. The flexibility of such systems is limited because they are only coarsely adaptable. The different operating modes often require changes in the baudrate or the FEC overhead, which poses implementation problems. Furthermore, conventional coded modulation schemes show a gap to Shannon capacity that can be overcome only by using modulation formats that have a Gaussian-like shape\(^{4,5}\). Such shaping is known to improve the non-linear tolerance as well\(^{6}\).

In this paper, we propose a system that uses probabilistic constellation shaping (PS) to close the gap to capacity. The system design has an unprecedented flexibility in terms of transmission rate without increasing the system and implementation complexity. For the first time, we experimentally verify a coded modulation scheme with rate adaptation\(^{1}\) that substantially increases the transmission distance and that is flexible even though it uses fixed FEC overhead, fixed modulation format and fixed baudrate and bandwidth. The key step is to introduce a distribution matcher\(^{2}\) (DM) that generates a non-uniform modulation symbol sequence (see Fig. 1) from the data sequence. We find that the gains predicted by theory and simulations can be achieved with a practical, low-complexity system.

Rate-Adaptive Constellation Shaping

State-of-the-art systems assume that all symbols are used with equal probability. We use the rate adaptive coding and modulation scheme proposed in\(^{1}\) which deliberately assigns different probabilities to each modulation symbol. Figure 2 shows the high-level model. The key device is...
the DM\textsuperscript{2,3} that transforms the sequence of data bits into a sequence of non-uniformly distributed (shaped) symbols. The shaped symbols are represented by binary labels and encoded by a binary FEC encoder, which is systematic to preserve the distribution of the shaped symbols. The FEC encoder output is mapped to a sequence of complex quadrature amplitude modulation (QAM) symbols. This sequence is fed to the optical transmission system, which outputs a noisy sequence of complex QAM symbols. The demodulator uses the noisy sequence to calculate bitwise log-likelihood ratios (LLRs) that are fed to the FEC decoder. The decoded symbols are transformed back to the data bits by an inverse DM.

As our binary FEC code, we use a spatially coupled rate 5/6 LDPC (SC-LDPC) code\textsuperscript{4}. In principle, we could use any FEC scheme, but we opt for SC-LDPC codes because of their excellent performance. The SC-LDPC code has no error floor and allows for soft decision decoding. SC-LDPC codes are robust and show the same error performance in different scenarios. In particular, our code has the same error performance when operated with different constellation distributions.

Let $P$ denote the constellation distribution after modulation imposed by the DM, let $c$ denote the code rate of the FEC code, and let $m = 6$ be the number of bit-levels of 64-QAM. The transmission rate is given by

$$R = H(P) - (1 - c) \cdot m \left( \frac{\text{bits}}{\text{QAM symbol}} \right) \quad (1)$$

where $H(P)$ is the entropy of $P$ in bits\textsuperscript{1}. By (1), we can transmit at different rates $R$ by changing the distribution $P$ and using the same FEC code. Following\textsuperscript{7}, we choose $P$ from the family of Maxwell-Boltzmann distributions, see Fig. 1 for an illustration of the four distributions $P_1, P_2, P_3, P_4$ and the resulting probabilistically shaped PS-64-QAM constellations that we use in our experiment. The corresponding entropies $H(P_i)$ are listed in the captions of Fig. 1.

**Experimental Setup**

Optical transmission experiments have been conducted using the standard coherent transmission loop setup shown in Fig. 3. The transmitter is based on an 88 GSamples/s quad-digital-to-analog converter (DAC) and a linear amplifier driving the dual polarization IQ-modulator. The channel under test was operated at 32 Gbaud. In the transmitter (Tx) DSP we incorporated Nyquist filtering with 0.15 roll-off factor and a pre-emphasis to compensate for the bandwidth limitations of the DAC and driver amplifier. The precalculated sequences are loaded into the memory of the DAC and transmitted periodically. In addition to the channel under test, we used 2 $\times$ 4 load channels operated at 32 Gbaud DP-QPSK with 4 nm guard bands. The loop consists of three 80 km SMF spans. The signals are amplified in single stage EDFA with a noise figure of 5 dB. The launch power was optimized individually for all experiments. A standard dual-polarization coherent receiver was used with high bandwidth differential photodiodes and 33 GHz bandwidth AD conversion at 80 Gsamples/s. We stored sequences with 500 000 samples and processed the data offline. We applied two receiver digital signal processors (DSPs) for data processing: The regular QAM modes and the PS-64-QAM mode with distribution $P_1$ were processed using a standard DSP with blind adaptation whereas the $P_2, P_3$ and $P_4$ PS-64-QAM modes were processed using a data aided approach. The blind adaptation DSP includes re-sampling to 2 sample/symbol, chromatic dispersion (CD) compensation, polarization de-multiplexing using a butterfly equalizer with a simple constant modulus algorithm (CMA) for adaptation, frequency offset compensation and 4th-power phase estimation. After DSP, we include demodulation and soft-decision decoding as detailed in\textsuperscript{1}. Note that using the data-aided DSP for regular QAM and PS-64-QAM ($P_1$) modes does not lead to noteworthy performance improvements.

**Results**

Fig. 4 shows the results of the transmission experiment. We display the measured mutual information (MI), which give the maximum achievable rate assuming ideal FEC(s)\textsuperscript{9}. For practical FECs, we must add a penalty that depends on the actual FEC realization.

We fix the FEC code with overhead 20% ($c = 5/6$) and use the four distributions in Fig. 1. The data rates are given by (1) and the respective entropies are shown in the captions of Fig. 1.
The reach is determined by the maximum distance where we observe error-free decoding. The rates and achievable distances are summarized in Tab. 1. Note that all systems we compare use the same channel bandwidth and we trade off reach against net data rate. As a reference system, we consider 64-QAM and 16-QAM with uniformly distributed symbols and varying FEC overheads. The points OP_i show how one can trade off reach against net data rate solely by adapting the distribution via the DM. At 300 Gbit/s we found 25% reach increase rising up to 43% at 200 Gbit/s (inset of Fig. 4). The reach increase is inline with the theoretically expected gains \cite{1,4}. Probabilistic shaping increases reach for a fixed net data rate and yields a higher net data rate for a fixed distance as compared to conventional systems.

**Fig. 4:** Experimentally measured mutual information for the regular uniform distribution and PS-64-QAM with the four shaped distributions P_1, P_2, P_3, and P_4. A shaping gain of 4.3 loops, i.e., 1032 km, can be observed at a mutual information of 4 bits per QAM symbol. From Table 1, we display the reference operating points Ref_i and the operating points OP_i.

**Conclusions**

We demonstrated the first optical transmission experiment of probabilistically shaped higher order constellation schemes. The results show a 15% capacity increase and 43% reach increase versus 200 Gbit/s 16-QAM. It realizes simple rate adaptation by adjustable shaping that allows to select arbitrary operating points without changing FEC overhead, constellation, and symbol rate.

**References**

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