Experimental Comparison of Probabilistic Shaping Methods for Unrepeated Fiber Transmission

This paper studies the impact of probabilistic shaping on effective signal-to-noise ratios (SNRs) and achievable information rates (AIRs) in a back-to-back configuration and in unrepeated nonlinear fiber transmissions. For back-to-back, various shaped quadrature amplitude modulation (QAM) distributions are found to have the same implementation penalty as uniform input. By demonstrating in transmission experiments that shaped QAM input leads to lower effective SNR than uniform input at a fixed average launch power, we experimentally confirm that shaping enhances the fiber nonlinearities. However, shaping is ultimately found to increase the AIR, which is the most relevant figure of merit as it is directly related to spectral efficiency. In a detailed study of these shaping gains for the nonlinear fiber channel, four strategies for optimizing QAM input distributions are evaluated and experimentally compared in wavelength division multiplexing (WDM) systems. The first shaping scheme generates a Maxwell-Boltzmann (MB) distribution based on a linear additive white Gaussian noise channel. The second strategy uses the Blahut-Arimoto algorithm to optimize an unconstrained QAM distribution for a split-step Fourier method based channel model. In the third and fourth approach, MB-shaped QAM and unconstrained QAM are optimized via the enhanced Gaussian noise (EGN) model. Although the absolute shaping gains are found to be relatively small, the relative improvements by EGN-optimized unconstrained distributions over linear AWGN optimized MB distributions are up to 59%. This general behavior is observed in 9-channel and fully loaded WDM experiments.
Characterization and optimization of a high-efficiency AlGaAs-On-Insulator-based wavelength converter for 64- and 256-QAM signals

In this paper, we demonstrate wavelength conversion of advanced modulation formats such as 10-GBd 64-QAM and 256-QAM with high conversion efficiency over a 29-nm spectral window by using four-wave mixing in an AlGaAs-On-Insulator
(AlGaAsO1) nano-waveguide. A thorough characterization of the wavelength converter is reported, including the optimization of the AlGaAsO1 nano-waveguide in terms of conversion efficiency and associated bandwidth and the analysis of the impact of the converter pump quality and power as well as the signal input power. The optimized converter enables generating idlers with optical signal-to-noise ratio (OSNR) above 30 dB over a 29-nm bandwidth leading to error-free conversion of 64-QAM and 256-QAM with OSNR penalty below 1.0 dB and 2.0 dB respectively. The generated idlers exhibit an OSNR margin to the chosen forward error correction thresholds of >3 dB and >7 dB for 64-QAM and 256-QAM, respectively, that can be used for transmission after conversion.

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Digital signal processing for fiber nonlinearities [Invited]

This paper reviews digital signal processing techniques that compensate, mitigate, and exploit fiber nonlinearities in coherent optical fiber transmission systems.

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Organisations: Department of Photonics Engineering, Coding and Visual Communication, High-Speed Optical Communication, Centre of Excellence for Silicon Photonics for Optical Communications, Queen's University, Politecnico di Torino, University of Toronto, University College London
Authors: Cartledge, J. C. (Ekstern), Guiomar, F. P. (Ekstern), Kschischang, F. R. (Ekstern), Liga, G. (Ekstern), Yankov, M. P. (Intern)
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Experimental analysis of pilot-based equalization for probabilistically shaped WDM systems with 256QAM/1024QAM

Pilot based equalization is studied in a 5x10 Gbaud WDM transmission experiment. The equalization is independent of the modulation format and is demonstrated for 256/1024QAM with uniform and probabilistically optimized distribution using an optimized pilot insertion rate of 2-5%.
Low-complexity Joint Sub-carrier Phase Noise Compensation for Digital Multi-carrier Systems

Joint sub-carrier phase noise processing is proposed which recovers the SNR penalty related to decreased sub-carrier baudrate w.r.t. single carrier systems. The method enables digital sub-banding to be safely employed for nonlinear mitigation for modulation formats of up to 256-QAM.

Nonlinear Phase Noise Compensation in Experimental WDM Systems with 256QAM

Nonlinear phase noise (NLPN) is studied in an experimental wavelength division multiplexed (WDM) system operating at 256QAM. Extremely narrow linewidth lasers (<1 kHz) at the transmitter and the receiver allow for extracting the phase part of the nonlinear noise in a Raman amplified link. Based on the experimental data, the autocorrelation function of the NLPN is estimated and it matches the theoretical predictions. Several algorithms are examined as candidates for tracking and compensating the NLPN. It is shown that algorithms which exploit the distribution of the NLPN achieve higher gains than standard methods, which only exploit the correlation properties. Up to 300 km reach increase is achieved for a 5x10 GBAud WDM system with base distance of up to 1600 km. The gains are comparable to the gains of single channel digital back-propagation, with even further improvements from the combination of both techniques.
Phase Noise Compensation for Nonlinearity-tolerant Digital Sub-carrier Systems with High-order QAM

The fundamental penalty of sub-carrier modulation (SCM) with independent sub-carrier phase noise processing is estimated. It is shown that the fundamental signal-to-noise ratio (SNR) penalty related to poorer phase noise tolerance of decreased baudrate subcarriers increases significantly with modulation format size and can potentially exceed the gains of the nonlinearity tolerance of SCM. A low complexity algorithm is proposed for joint sub-carrier phase noise processing, which is scalable in the number of sub-carriers and recovers almost entirely the fundamental SNR penalty with respect to single carrier systems operating at the same net data-rate. The proposed algorithm enables high-order modulation formats with high count of sub-carriers to be safely employed for nonlinearity mitigation in optical communication systems.

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BFI (2013): BFI-level 1
Scopus rating (2013): SJR 1.374 SNIP 1.338 CiteScore 2.83
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Scopus rating (2012): SJR 1.469 SNIP 1.286 CiteScore 2.69
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Prediction of Second-Order Moments of Inter-Channel Interference with Principal Component Analysis and Neural Networks

A machine learning framework for predicting auto-correlation functions of inter-channel nonlinearities within the uncompensated optical fiber link is proposed. Low generalization error is obtained on the test data.

Temporal probabilistic shaping for mitigation of nonlinearities in optical fiber systems

In this paper, finite state machine sources (FSMSs) are used to shape quadrature amplitude modulation (QAM) for nonlinear transmission in optical fiber communication systems. The previous optimization algorithm for FSMSs is extended to cover an average power constraint, thus enabling temporal optimization with multi-amplitude constellations output, such as QAM. The optimized source results in increased received SNR and, thereby, increased achievable information rates (AIRs) under memoryless assumption. The AIR is increased even further when taking the channel and transmitter memory into account via trellis processing at the receiver. Significant gains are reported in the highly nonlinear region of transmission for an FSMS of up to second order and 16QAM and particularly for unrepeated transmission. At the optimal launch power of WDM transmission, the FSMS order needs to be increased further in order to notably outperform previous probabilistic shaping schemes.
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Web of Science (2017): Indexed yes
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Scopus rating (2014): SJR 1.801 SNIP 2.423 CiteScore 4.23
Web of Science (2014): Indexed yes
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Scopus rating (2013): SJR 1.533 SNIP 2.341 CiteScore 4.03
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BFI (2012): BFI-level 2
Scopus rating (2012): SJR 1.711 SNIP 2.335 CiteScore 3.21
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Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): SJR 1.605 SNIP 2.758 CiteScore 3.2
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 1.802 SNIP 2.411
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 2.312 SNIP 2.761
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 2.371 SNIP 2.423
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Scopus rating (2005): SJR 2.939 SNIP 3.016
Web of Science (2005): Indexed yes
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Web of Science (2004): Indexed yes
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Web of Science (2003): Indexed yes
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Web of Science (2002): Indexed yes
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Web of Science (2000): Indexed yes
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Electronic versions: JLT2671452.pdf
Characterization of a Wavelength Converter for 256-QAM Signals Based on an AlGaAs-On-Insulator Nano-waveguide

High efficiency and broadband wavelength conversion in a 9-mm AlGaAs-On-Insulator waveguide is shown to provide high-quality (OSNR > 30 dB) idler generation over a 28-nm bandwidth enabling error-free conversion of 10-GBd 256-QAM with OSNR penalty below 2.5 dB.

Constellation Shaping for WDM systems using 256QAM/1024QAM with Probabilistic Optimization

In this paper, probabilistic shaping is numerically and experimentally investigated for increasing the transmission reach of wavelength division-multiplexed (WDM) optical communication system employing quadrature amplitude modulation (QAM). An optimized probability mass function (PMF) of the QAM symbols is first found from a modified Blahut-Arimoto algorithm for the optical channel. A turbo coded bit interleaved coded modulation system is then applied, which relies on many-to-one labeling to achieve the desired PMF, thereby achieving shaping gain. Pilot symbols at rate at most 2% are used for synchronization and equalization, making it possible to receive input constellations as large as 1024QAM. The system is evaluated experimentally on a 10 Gbaud, 5 channels WDM setup. The maximum system reach is increased w.r.t. standard 1024QAM by 20% at input data rate of 4.65 bits/symbol and up to 75% at 5.46 bits/symbol. It is shown that rate adaptation does not require changing of the modulation format. The performance of the proposed 1024QAM shaped system is validated on all 5 channels of the WDM signal for selected distances and rates. Finally, it was shown via EXIT charts and BER analysis that iterated demapping, while generally beneficial to the system, is not a requirement for achieving the shaping gain.
WDM, Probabilistic shaping, Experimental demonstrations, 1024QAM, Nonlinear transmission
Experimental Comparison of Gains in Achievable Information Rates from Probabilistic Shaping and Digital Backpropagation for DP-256QAM/1024QAM WDM Systems

Gains in achievable information rates from probabilistic shaping and digital backpropagation are compared for WDM transmission of 5 × 10 Gb/s DP-256QAM/1024QAM up to 1700 km of reach. The combination of both techniques is shown to provide gains of up to ∼0.5 bits/QAM symbol.
Temporal Probabilistic Constellation Shaping for WDM Optical Communication Systems
Finite state machine sources transmitting QPSK are studied as input to WDM optical fiber systems with ideal distributed Raman amplification. The probabilities of successive constellation symbols are shaped for nonlinear transmission and gains of around 500km (5-10%) are demonstrated.

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Achievable Information Rates on Linear Interference Channels with Discrete Input
In this paper lower bound on the capacity of multi-dimensional linear interference channels is derived, when the input is taken from a finite size alphabet. The bounds are based on the QR decomposition of the channel matrix, and hold for any input distribution that is independent across dimensions. Calculation of the bounds can be performed on a per-dimensions basis via look-up tables of the information rates of 1D channels.

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Approximating the constellation constrained capacity of the MIMO channel with discrete input
In this paper the capacity of a Multiple Input Multiple Output (MIMO) channel is considered, subject to average power constraint, for multi-dimensional discrete input, in the case when no channel state information is available at the transmitter. We prove that when the constellation size grows, the QAM constrained capacity converges to Gaussian capacity, directly extending the AWGN result from [1]. Simulations show that for a given constellation size, a rate close to the Gaussian capacity can be achieved up to a certain SNR point, which can be found efficiently by optimizing the constellation for the equivalent orthogonal channel, obtained by the singular value decomposition. Furthermore, lower bounds on the constrained capacity are derived for the cases of square and tall MIMO matrix, by optimizing the constellation for the equivalent channel, obtained by QR decomposition.

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Capacity Estimation and Near-Capacity Achieving Techniques for Digitally Modulated Communication Systems

This thesis studies potential improvements that can be made to the current data rates of digital communication systems. The physical layer of the system will be investigated in band-limited scenarios, where high spectral efficiency is necessary in order to meet the ever-growing data rate demand. Several issues are tackled, both with theoretical and more practical aspects. The theoretical part is mainly concerned with estimating the constellation constrained capacity (CCC) of channels with discrete input, which is an inherent property of digital communication systems. The channels under investigation will include linear interference channels of high dimensionality (such as multiple-input multiple-output), and the non-linear optical fiber channel, which has been gathering more and more attention from the information theory community in recent years. In both cases novel CCC estimates and lower bounds are provided in this thesis. Intuition about the optimal signaling distribution is also provided, which is generally not the standard uniform for high spectral and energy efficiency communications. The practical part deals with tools to approach the CCC with real-life transceivers. The constellation shaping concept is one such tool. More specifically, the probabilistic shaping concept is of interest to this thesis. A rate-adaptive solution is proposed for designing the mapping function of a probabilistic shaped coded modulation system, which allows for approaching the above mentioned optimal distribution in practice. This results in increased energy and/or spectral efficiency for both linear and non-linear channels, but also increased maximum reach of the optical link at fixed spectral efficiency. The specific problem of phase noise in digital systems is also studied in this thesis. Phase noise, and particularly non-linear phase noise is especially detrimental to high-speed, high spectral efficiency optical communications. As part of this work, a low-complexity solution is proposed for tracking, which is able to combat the combined effect of linear and non-linear phase noise in optical fibers, achieving close to the CCC estimate. The main contribution of the PhD project is providing engineers with limits on the data rates that current digital communication systems can achieve, and also with methods and insights for approaching those rates, thus interconnecting theory and practice.

Compensation of XPM Interference by Blind Tracking of the Nonlinear Phase in WDM Systems with QAM Input

Exploiting temporal correlations in the phase, achievable rates are studied and a blind trellis-based receiver is presented. Gains of 0.5 bit per symbol are found in point-to-point links irrespective of the symbol rate. These gains disappear in network configurations.
In this paper, the wavelength division multiplexed (WDM) fiber optic channel is considered. It is shown that for ideal
distributed Raman amplification (IDRA), the Wiener process model is suitable for the non-linear phase noise due to cross
phase modulation from neighboring channels. Based on this model, a phase noise tracking algorithm is presented. We
approximate the distribution of the phase noise at each time instant by a mixture of Tikhonov distributions, and derive a
closed form expression for the posterior probabilities of the input symbols. This reduces the complexity dramatically
compared to previous trellis-based approaches, which require numerical integration. Further, the proposed method
performs very well in low-to-moderate signal-to-noise ratio (SNR), where standard decision directed (DD) methods,
especially for high-order modulation, fail. The proposed algorithm does not rely on averaging, and therefore does not
experience high error floors at high SNR in severe phase noise scenarios. The laser linewidth (LLW) tolerance is thereby
increased for the entire SNR region compared to previous DD methods. In IDRA WDM links, the algorithm is shown to
effectively combat the combined effect of both laser phase noise and non-linear phase noise, which cannot be neglected
in such scenarios. In a more practical lumped amplification scheme, we show near-optimal performance for 16 QAM, 64
QAM, and 256 QAM with LLW up to 100 kHz, and reasonable performance for LLW of 1 MHz for 16 QAM and 64 QAM, at
the moderate received SNR region. The performance in these cases is close to the information rate achieved by the above
mentioned trellis processing.
Constellation Shaping for Fiber-optic Channels with QAM and High Spectral Efficiency

In this letter the fiber-optic communication channel with Quadrature Amplitude Modulation (QAM) input constellation is treated. Using probabilistic shaping, we show that high order QAM constellations can achieve and slightly exceed the lower bound on the channel capacity, set by ring constellations in [1]. We then propose a mapping function for turbo coded bit interleaved coded modulation based on optimization of the mutual information between the channel input and output. Using this mapping, spectral efficiency as high as 6.5 bits/s/Hz/polarization is achieved on a simulated single channel long-haul fiber-optical link excluding the pilot overhead, used for synchronization, and taking into account frequency and phase mismatch impairments, as well as laser phase noise and analog-to-digital conversion quantization impairments. The simulations suggest that major improvements can be expected in the achievable rates of optical networks with high order QAM.

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Scopus rating (2010): SJR 1.474 SNIP 1.623
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 2
In this work we study the properties of the optimal Probability Mass Function (PMF) of a discrete input to a general Multiple Input Multiple Output (MIMO) channel. We prove that when the input constellation is constructed as a Cartesian product of 1-dimensional constellations, the optimal PMF factorizes into the product of the marginal 1D PMFs. This confirms the conjecture made in [1], which allows for optimizing the input PMF efficiently when the rank of the MIMO channel grows. The proof is built upon the iterative Blahut-Arimoto algorithm. We show that if the initial PMF is factorized, the PMF on each successive step is also factorized. Since the algorithm converges to the optimal PMF, it must therefore also be factorized.
Improved Energy Efficiency for Optical Transport Networks by Elastic Forward Error Correction

In this paper we propose a scheme for reducing the energy consumption of optical links by means of adaptive forward error correction (FEC). The scheme works by performing on the fly adjustments to the code rate of the FEC, adding extra parity bits to the data stream whenever extra capacity is available. We show that this additional parity information decreases the number of necessary decoding iterations and thus reduces the power consumption in iterative decoders during periods of low load. The code rate adjustments can be done on a frame-by-frame basis and thus make it possible to manipulate the balance between effective data rate and FEC coding gain without any disruption to the live traffic. As a consequence, these automatic adjustments can be performed very often based on the current traffic demand and bit error rate performance of the links through the network. The FEC scheme itself is designed to work as a transparent add-on to transceivers running the optical transport network (OTN) protocol, adding an extra layer of elastic soft-decision FEC to the built-in hard-decision FEC implemented in OTN, while retaining interoperability with existing OTN equipment. In order to facilitate dynamic code rate adaptation, we propose a programmable encoder and decoder design approach, which can implement various codes depending on the desired code rate using the same basic circuitry. This design ensures optimal coding gain performance with a modest overhead for supporting multiple codes with minimal impact on the area and power requirements of the decoder.
Rate-adaptive Constellation Shaping for Near-capacity Achieving Turbo Coded BICM

In this paper the problem of constellation shaping is considered. Mapping functions are designed for a many-to-one signal shaping strategy, combined with a turbo coded Bit-interleaved Coded Modulation (BICM), based on symmetric Huffman codes with binary reflected Gray-like properties. An algorithm is derived for finding the Huffman code with such properties for a variety of alphabet sizes, and near-capacity performance is achieved for a wide SNR region by dynamically choosing the optimal code rate, constellation size and mapping function based on the operating SNR point and assuming perfect channel quality estimation. Gains of more than 1dB are observed for high SNR compared to conventional turbo coded BICM, and it is shown that the mapping functions designed here significantly outperform current state of the art Turbo-Trellis Coded Modulation and other existing constellation shaping methods.
Projects:

**Information Theory and Coding in Regenerative and Non-linear Fiber Optical Communications**

Department of Photonics Engineering  
Period: 01/06/2016 → 31/05/2019  
Number of participants: 5  
Phd Student:  
Iqbal, Shajeel (Intern)  
Supervisor:  
Oxenløwe, Leif Katsuo (Intern)  
Yankov, Metodi Plamenov (Intern)  
Zibar, Darko (Intern)  
Main Supervisor:  
Forchhammer, Søren (Intern)

**Financing sources**  
Source: Internal funding (public)  
Name of research programme: Samfinansieret - Andet  
Project: PhD

**Machine learning algorithms for emulation of nonlinear optical fibre impairments**

Department of Photonics Engineering  
Period: 01/11/2015 → 31/10/2018  
Number of participants: 3  
Phd Student:  
Jones, Rasmus Thomas (Intern)  
Supervisor:  
Yankov, Metodi Plamenov (Intern)  
Main Supervisor:  
Zibar, Darko (Intern)

**Financing sources**  
Source: Internal funding (public)  
Name of research programme: Samfinansierede - Virksomhed  
Project: PhD

**Design and Optimization of Coded Modulation Systems with Iterative and Non-iterative Processing**

Department of Photonics Engineering  
Period: 01/12/2012 → 20/04/2016  
Number of participants: 6  
Phd Student:  
Yankov, Metodi Plamenov (Intern)  
Supervisor:  
Larsen, Knud J. (Intern)  
Main Supervisor:  
Forchhammer, Søren (Intern)  
Examiner:  
Galili, Michael (Intern)  
Agrell, Erik (Ekstern)  
Rasmussen, Lars Kildehøj (Ekstern)

**Financing sources**  
Source: Internal funding (public)  
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