FONTE EID
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FOCUS on RESEARCH

Fibre-optic communication systems form the backbone of the world's communication infrastructure as they provide for lion fraction (more than 99%) of the global data traffic. The ongoing exponential growth in network traffic, however, is pushing current technology, whose data rates had increased over several decades, towards its limits. It is widely accepted that the nonlinear transmission effects in optical fibre are now a major limiting factor in modern fibre-optic communication systems. Nonlinear properties of the optical fibre medium limit the conventional techniques to increase capacity by simply increasing signal power. Most of the transmission technologies utilized today have been originally developed for linear (wired or wireless) communication channels. Over the past several decades, significant improvements in data rates were obtained by improvements and modifications within the overall linear transmission paradigm. However, there is much evidence that this trend is going to end within the next decade due to fibre nonlinearity. There is a clear need for radically different approaches to the coding, transmission, and processing of information that take the nonlinear properties of the optical fibre into account. This also requires education and training of a new generation of optical communication engineers and specialists with knowledge on nonlinear methods and techniques.

Research in EID FONTE focusses on development of disruptive nonlinear techniques and approaches to fibre-optic communications beyond the limits of current technology. The consortium, which includes the world leading telecom centre Nokia Bell Labs Germany, ***is already making important innovative steps*** in development of the technique of the nonlinear Fourier transform (NFT) and its implementation in the practical communication systems.

This **Newsletter** focusses on the most recent scientific results produced by our ESRs

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WP1: Development of new NFT transmission methods

Lead ESR1:
V. Neskorniuk

What is WP1 about?

WP1, led by Aston University (Prof. S. Turitsyn), is focused on the design of novel NFT-based modulation and demodulation schemes and (with the help of the industry partner, NOKIA BELL LABS) the integration of these schemes into practical optical fibre communication systems.

MOTIVATION

Although several communication methods based on the NFT have been already proposed in the literature, the practical use of the NFT in optical communication systems requires further research. As of today, no commercially viable product based on the NFT exists due to several engineering challenges. FONTE will pioneer the design of new modulation, demodulation and signal processing techniques that take into account the unique advantages of the NFT and real-world constraints. WP1 seeks to improve and optimize existing NFT approaches that are already established by the members of the consortium.

Summary of Progress in WP1

The existing NFT spectrum modulation techniques have been reviewed. We inferred that the following two methods have the potential to render the highest efficiency: b-modulation allowing us to attain the control over the signal's duration, and the periodic NFT, which can bring about benefits in signal processing and signal-noise interference.
Within WP1 we developed a new data-driven approach (neural networks-based, NN) to nonlinearity mitigation in optical fibre links, addressing, specifically, the regime of high nonlinearity. We showed that the NN is able not only to recover the nonlinear impairments caused by optical fiber propagation but also the imperfections resulting from the usage of low-cost legacy transceiver components, such as digital-to-analog converter and Mach-Zehnder modulator.

WP2: Impact of practical impairments on the NFT

Lead ESR2:
V. Bajaj

What is WP2 about?

WP2 led by TUD (Dr. S. Wahls), deals with the analysis of realistic impairments on the NFT and aims at using this knowledge to aid the development of robust numerical NFT algorithms, modulation formats, and equalization methods.

MOTIVATION

Any real fibre-optic transceiver suffers from a multitude of impairments such as, for example, various forms of noise, non-ideal amplification, quantization effects, aliasing, or also cross-talk. The impact of such impairments on the NFT is currently not well-understood. The classical analyses of these effects apply only in the weakly non-linear regime. For the highly-nonlinear regime FONTE aims at, only very little is known. The goal of this work package is to analyse the impact of real-world impairments on the NFT and to exploit this knowledge for the development of robust numerical NFT algorithms, modulation formats and equalization techniques that are as insensitive as possible against such impairments.

Summary of Progress in WP2

Nonlinear distortions limit the transmission capacities of current fiber-optic communication systems. Non-conventional transmission techniques based on nonlinear Fourier transforms (NFTs) are an interesting approach to address these issues. These transmission techniques, however, rely on an ideal lossless fiber model, while in practice fibers are lossy. The impact of the fiber-loss on NFT-based fiber-optic transmission systems has been investigated. A novel approach to incorporating loss into NFT-based systems that uses a modified NFT and operates in specialized dispersion decreasing fibers (DDFs) was investigated. The combined use of DDF along with the modified NFT eliminates the degrading effects due to fiber-loss completely in a mathematical ideal scenario. The numerical assessments showed significant gains achieved using the proposed solution.

WP3: Machine learning techniques for fibre-optic channels

Lead ESR3:
S. M. Ranzini

What is WP3 about?

WP3 led by DTU (Prof. D. Zibar), focuses on the development of the optical performance monitoring schemes and channel estimation algorithms for system that use NFT. Tools from machine learning and data-driven models will be considered for system optimization.

MOTIVATION

Optical performance monitoring is vital to ensure robust and reliable operation of optical communication systems. It provides quality-of-transmission metrics, such as Q-factor, and helps approximate channel parameters. The Q-factor is related to the optical signal-to-noise-ratio and can be computed by looking at the eye-diagrams at the monitoring points along the transmission link. These issues are well-studied in systems that use traditional waveforms. However, if future optical networks are going to employ NFT transmission schemes with unconventional waveforms, it is necessary to develop algorithms for measuring quantities such as Q-factor or OSNR. Currently, there is no known method to estimate the Q-factor from the eye-diagrams in NFT signals. Furthermore, fibre parameters are needed to compute the forward and inverse NFT. This calls for accurate estimation algorithms in the presence of the signal-dependent non-Gaussian noise. Machine learning could help with this task.

Summary of Progress in WP3

ESR3 is developing a new receiver based on optoelectronic machine learning for intensity-modulated and direct detection systems. The optical pre-processing stage slices the received signal spectrum in small sub-bands with passive optical filters and each is detected by a photodetector. The digital post-processing is based on a recent technique in machine learning called reservoir computing. We demonstrated the potential of the receiver for 32-GBd OOK signal transmission, and showed an increase in reach from 10 km to 40 km, corresponding to 400%, compared with digital-only techniques

WP4: Network applications of the NFT technology

Lead ESR4:
A. Shahkarmi

What is WP4 about?

WP4, led by Telecom ParisTech (Prof. M. I. Yousefi), focuses on the development of the NFT based nonlinear frequency-division multiplexed systems for optical fibre networks.

MOTIVATION

Nonlinear frequency-division multiplexed (NFDM) can be applied to single- and multi-user channels. Present simulations and experimental demonstrations are mostly limited to point-to-point transmission. However, the great advantage of NFDM occurs in networks, where there are multiple transmitters and receivers. WP4 is dedicated to network application of the NFT. This is the most relevant case for the industry partner NOKIA BELL LABS and commercial systems.

Summary of Progress in WP4

End-to-end deep learning of the optical fiber channel has recently been proposed to address the limitation that the Kerr nonlinearity sets on the transmission rates of fiber optic communication systems. It is important to understand how this approach compares with the conventional methods. By designing a neural network approximating the channel, we studied this comparison for a small-scale system, which we are currently extending to large-scale systems. In addition, we carried out some research on an approach based on representation learning and feature transfer to help protect the sequence of symbols at the transmitter against errors introduced by the channel.

WP5: Experimental implementation & testing of NFT systems

All ESRs involved

NOKIA
Bell Labs

What is WP5 about?

WP5, led by the FONTE industrial partner NOKIA BELL LABS (Dr. H. Buelow), focuses on the experimental demonstration of the developed algorithms in WP1-WP4, new system designs and techniques, implementation and commercialisation of results.

MOTIVATION

The academic partners at FONTE are world leading experts in the NFT. This extraordinary cluster of experts positions NOKIA BELL LABS very well to identify promising technologies in the very early stage, to develop IP licensing, and to decide on commercialization and product development

Summary of Progress in WP5

The performance of coherent optical high-speed transceivers are limited by their physical limitation and impairments. To operate with their maximum capacity, we should mitigate undesired distortions of these devices. A cost-effective way to overcome this challenge is using digital pre-distortion (DPD) techniques. ESR2 investigated a neural network DPD technique and showed in lab experiments an improvement of 3 dB compared to traditional methods. The ESR3 is investigating a new transceiver based on sharing the complexity between the optical and digital domain with machine learning techniques. Experimental analyses were carried out at NBL and showed a transmission reach gain of 800%, compared to digital-only techniques.

FONTE Publications

WP1:

- D1.1 Review and optimization results for the NIS NFT-based systems
- D1.2 New modulation techniques for NFT systems
- D1.3 Numerical verification advanced modulation techniques

WP2:

- D2.1 Report on major impairments in NFT-based transmission
- D2.2 Software implementations of the developed robust NFT algorithms
- D2.3 Numerical and experimental validation of the robust modulation format
- V. Bajaj, S. Chimmalgi, V. Aref and S. Wahls, "*Exact NFDM Transmission in the Presence of Fiber-Loss*," in Journal of Lightwave Technology, vol. 38, no. 11, pp. 3051-3058, 1 *June 1, 2020, doi: 10.1109/JLT.2020.2984041*

WP3:

- D3.1 Survey of machine learning algorithms for optical performance monitoring
- D3.2 System identification and parameter estimation
- D3.3 Performance analysis of monitoring techniques based on machine learning
- Francesco Da Ros, Stenio M. Ranzini, Henning Bülow, & Darko Zibar. (2020). *"Reservoir-computing based equalization with optical pre-processing for short-reach optical transmission."* http://doi.org/10.1109/JSTQE.2020.2975607
- Ranzini, S.M.; Da Ros, F.; Bülow, H.; Zibar, D. *"Tunable Optoelectronic Chromatic Dispersion Compensation Based on Machine Learning for Short-Reach Transmission."* Appl. Sci. 2019, 9, 4332

WP4:

- D4.1 Principles of linear and nonlinear frequency-division multiplexing
- D4.2 Multi-user communication and information theory

WP5

- D5.1 Transmission regime definition and plan of experiments
- D5.2 Experimental transmissions of NFT-based systems, including (1) the NFDM systems and (2) the nonlinear inverse synthesis systems