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Executive Summary

In this deliverable we review the most up-to-date nonlinear frequency division multiplexed (NFDM) based systems: the system based on the utilisation of periodic nonlinear solutions and end-to-end learnt system. The numerical simulations of the performance of the first system demonstrate that periodic nonlinear Fourier transform can be used to mitigate the drawbacks of the "ordinary" NFDM. The numerical simulations of the second NFDM system demonstrate that the application of the advanced concepts of the machine learning, particularly end-to-end learning realised via neural networks, can be applied to effectively mitigate the drawbacks of the NFDM concept related to the non-realistic case of the integrable channel.

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LIST OF ACRONYMS

AWGN	Additive white Gaussian noise
AiPT	Aston Institute Of Photonic Technologies
B2B	Back-to-back
DBP	Digital back-propagation
DP	Dual-polarisation
EC	European Commission
EID	European Industrial Doctorates
ESR	Early Stage Researcher
FONTE	Fibre Optic Nonlinear Technologies
GLM	Gelfand-Levitan-Marchenko
I/Q	In-phase/quadrature
INFT	Inverse nonlinear Fourier transform
ML	Machine learning
NF	Nonlinear Fourier
NFD	Nonlinear Fourier domain
NFDM	Nonlinear frequency-division multiplexing
NFT	Nonlinear Fourier transform
NIS	Nonlinear inverse synthesis
NLS	Nonlinear Schrödinger equation
NS	Nonlinear spectrum
OA	Optical amplifier
OFDM	Optical frequency-division multiplexing
PNFT	Periodic nonlinear Fourier transform
Rx	Receiver
Tx	Transmitter

1 Periodic nonlinear Fourier transform-based systems

Together with ordinary nonlinear frequency-division multiplexing (NFDM), where the vanishing signals and the respective nonlinear Fourier transform (NFT) signal processing operations are used, one can use the periodically-extended signals as an information carrier in fiber-optic communication lines — the approach similar to linear optical channels [1]. In this paradigm, the signal are appended with a cyclic prefix, as it is done in the coherent optical frequency-division multiplexing (OFDM) format [2], while still using the NFDM approach for encoding, restoring and demodulating the data [3–5]. Such an approach was introduced in [6] and studied theoretically in [7]. Relatively simple system based on the modulation of periodic nonlinear modes' parameters was recently demonstrated experimentally [8]. Aside from a row of other advantages listed in the previous works [3,9], the periodic NFT (PNFT) not only provides an explicit control over the signal duration, but can also reduce noticeably the required processing window at the receiver, as we do not have to process the dispersion-induced memory [3, 4, 9–11]. The latter fact can make a substantial difference for long-haul transmission, insofar as using the PNFT we are to process only one period of the signal [3, 10].

Comparing to the "conventional" nonlinear spectrum (NS) for the nonlinear Schrödinger equation (NLSE) periodic expressed in time domain, consists of zeros of certain functions, which are static, and called main spectrum. These functions are expressed in terms of the entries of the so-called monodromy matrix, which is given by the solution of the Zakharov-Shabat problem (ZSP), where the potential (our signal) is periodic in t-variable. Another part of the NS, the dynamical part, is called auxiliary spectrum and is also determined by the monodromy matrix. However, such an NS parametrisation suffers from the fact that, while the main spectrum is invariant under the evolution along z, the dynamical part – the auxiliary spectrum – evolves with z in a complicated, nonlinear manner. This property undermines the very reason of using the NFT in optical communications.

One can now compose a wide class of signals by adjusting the particular NS structure by parametring the periodic solutions of NLSE. Furthermore, because of its simple linear evolution with z, as opposed to the complicated, nonlinear evolution of the signal in space-time domain, the NS emerges as a convenient data-bearer in a nonlinear optical fibre system, such that nonlinear frequency division multiplexing concept [12] can be built up.

In a communication system, the goal is to transfer information carried by a signal from a transmitter, through a medium, to a receiver. The information is mapped on some parameters of signal at the transmitter, and then we have to recover it from the received distorted signal. Within the NFDM we use the NS to carry the information, such that either whole NS or some of its parts are modulated with a random stream of symbols. As it is usually the case, there are some characteristics of the signal which are predefined based on the requirements of the link such as signal bandwidth, power, etc. Since the NS uniquely determines the signal, fixing these characteristics will lead to a loss of some degrees of freedom available for modulation. As will be shown later, in our case most of the communication-related characteristics of signals are related to the main spectrum. Therefore, in this work we specifically design the main spectrum of our signals to adjust its characteristics, and modulate the remaining phases to transfer our data. This means that for the signal containing $\mathcal{N}+1$ nonlinear modes (an $\mathcal{N}+1$-band solution), out of $3\times(\mathcal{N}+1)$ total degrees of freedom participating in the NS, we employ $2\times(\mathcal{N}+1)$ parameters to control signal's periodicity, duration and power, and only modulate the remaining $\mathcal{N}+1$ phases.

The communication system considered in [13], is not principally different from other typical NFT-based setups. In this work, the specially structured main spectrum to manipulate signal power, bandwidth and period, is used as well as the periodicity property itself (see Fig. 1). This main spectrum is known by the receiver and is constructed through a procedure which will be explained later. Then, the random bit stream is mapped to the MPSK symbols, the values of which are taken as the values of the phases attributed to each nonlinear mode. Along the main spectrum, this set of phases makes up the full NS. A signal with the chosen modulated NS is then generated through the inverse transformation using the Riemann-Hilbert problem (RHP), and sent to the fibre. Undergone linear and nonlinear distortion in addition to the amplifier spontaneous emission (ASE) noise, the signal is received at the Rx. The NS of the signal is then calculated via the direct transformation using the Zakharov-Shabat problem. The first (invariant) part of the NS, i.e. the main spectrum, is already known by the receiver, but its calculated values can be used to further equalise the signal. The dynamical NS part contains the transmitted random data in the form of phases. These phases are then recovered from the monodromy matrix, and the encoded data are eventually retrieved. The results obtain in work [13] are given in figures 2-4.

2 End-to-end learning of NFDM system

Authors of [14] suggest the full optimization of a convetional NFDM system by joint training an NFT-based transmitter and an NN-based receiver to maximize the overall NFDM transmission performance. Such end-to-end (E2E) optimization [15] is numerically applied to the full NFDM system including a transmission channel

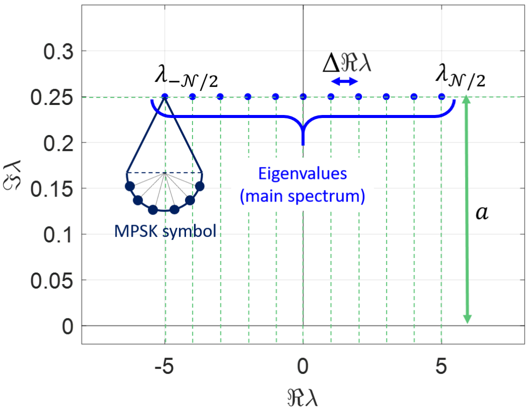

Figure 1: The schematic structure of the NS for a periodic finite-gap signal. In order to ensure the periodicity, the points of the main spectrum (shown as equidistant points) are to be slightly readjusted. The global signal parameters are mainly influenced by the main spectrum ($\Delta \operatorname{Re} \lambda$ influences period while $\operatorname{Im} \lambda \equiv a$ determines power and bandwidth). Since at the receiver we retrieve the phases modulo π, they are depicted as half-circles associated with each point of the main spectrum. The figure is taken from [13].

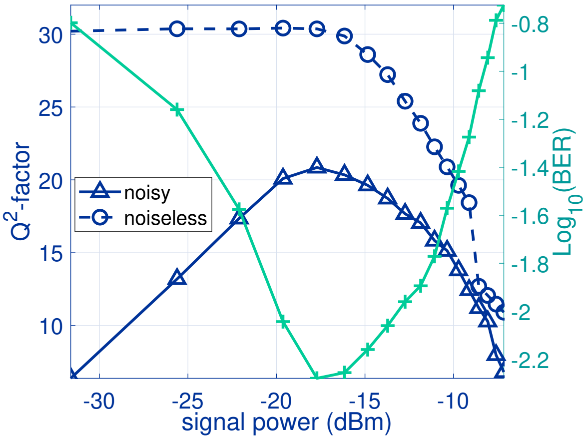

Figure 2: The Q^2-factor (defined from EVM) and BER versus the signal power after 1040 km transmission. The optimum is achieved at $P = -17$ dBm. The dashed line represents the Q^2-factor for a noiseless transmission which indicates the numerical error as the main contributing factor in performance degradation for higher powers. The figure is taken from [13].

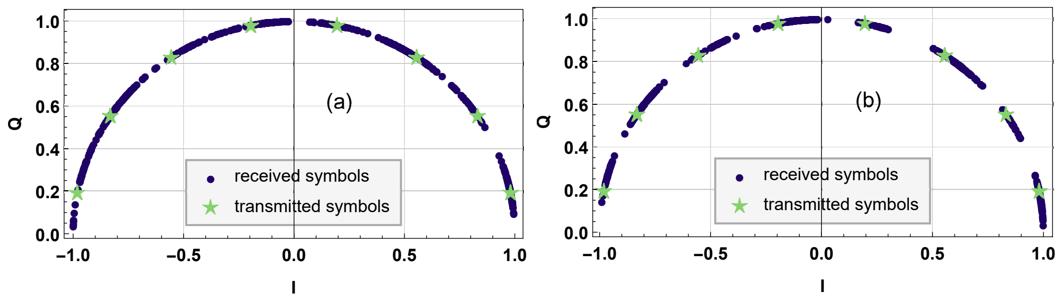

Figure 3: The received phase constellation after 1000 km transmission of an 8PSK auxiliary spectrum modulated signal at signal power a) $P = -6$ dBm, and b) $P = -17$ dBm. The figure is taken from [13].

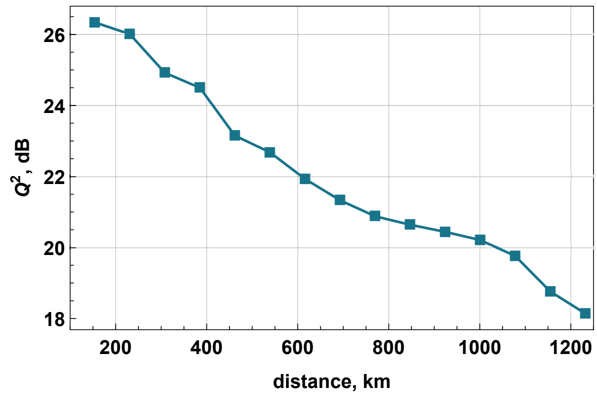

Figure 4: The Q^2-factor versus transmission distance at optimum signal power $P = -17$ dBm. The figure is taken from [13].

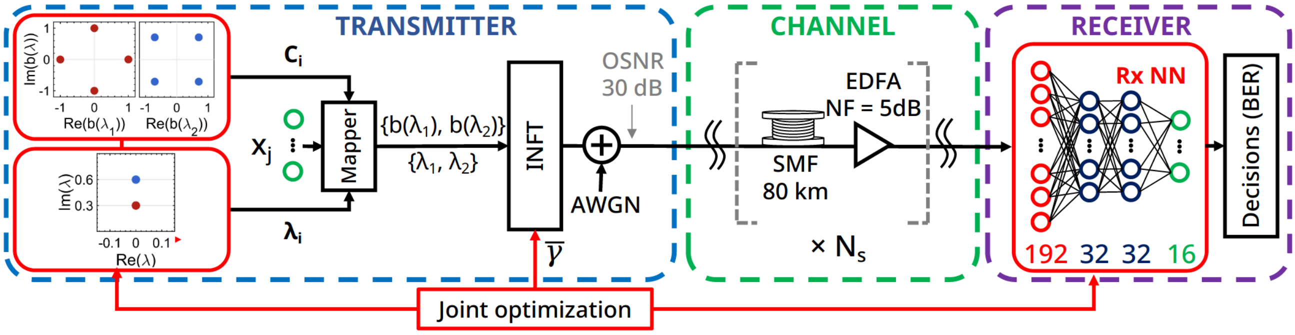

Figure 5: Simulation setup used in [14] for the system E2E optimization and the BER performance evaluation. The figure is taken from [14].

modelled via the split-step Fourier method (SSFM). The parameters of transmitter, nonlinear spectrum and power scaling, are jointly optimized together with the receiver NN. The authors achieved that more two orders of magnitude bit-error ratio improvement for 5600 km (70×80km spans) through E2E optimization, when compared to a system with the standard NFT receiver and to an optimized NN receiver with unoptimized transmitter, respectively. It is shown that the improvement is preserved for at least up to±10 spans from the optimized distance of 70 spans. The full simulation setup used for both the optimization and the performance evaluation of the system is shown in Fig. 5.

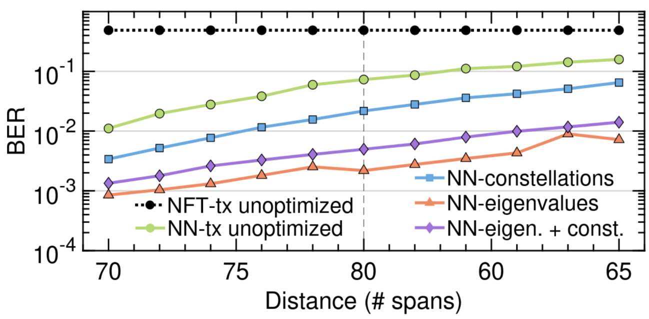

Figure 6: BER as a function of the transmission distance for the NFT receiver and for the NN receiver. The vertical dashed line marks the optimization distance. The figure is taken from [14].

Fig. 6 shows the BER performance obtained in [14] as a function of the transmission distance. In the reference case with an unoptimized constellation with an NFT receiver ('NFT-tx unoptimized') is considered, authors were not able to demodulate the data. A demodulation became possible if the NFT receiver was replaced with the NN receiver and the factor controlling the transmitter power is set to the value found by the E2E optimization. The curves obtained also show that the performance gain is preserved for transmission distances between 60 and 80×80km, even though the optimization was performed at 70 spans, showing the robustness of the optimization to the transmission distance.

To sum up, the considered E2E system outperformed both a system using an NFT receiver and one using an NN receiver with unoptimized transmitter providing an improvement of more than one and two orders of magnitude in terms of BER against them respectively. This demonstrates that the joint optimization of the transmitter with the receiver is critical to improve the system performance.

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