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Tolerance of Continuous NFT Spectrum to Optical Fiber Channel Impairments

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Abstract: The impact of launch power, additive white Gaussian noise and fiber loss on the nonlinear Fourier transform (NFT) continuous spectrum is investigated. NFT is shown to undergo lower spectral distortion than the discrete Fourier transform.

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1. Introduction

Optical communication systems employ transmission techniques originally developed for linear channels. These may not be optimal for the fiber optic communication channel, which is inherently nonlinear due to the Kerr effect. Therefore, by using the currently available linear techniques the achievable transmission rates and distances are limited by fiber nonlinearity. Several techniques have been proposed to tackle this problem. Among them, a significant research effort has been directed towards digital backpropagation (DBP) [1]. However, to achieve sufficient accuracy the nonlinear Schrödinger equation (NLSE) needs to be iteratively solved in multiple steps, making DBP particulary computationally expensive. A potentially more effective technique to cope with fiber nonlinearities is the nonlinear Fourier transform (NFT) [2, 3]. The NFT is a technique that solves the NLSE in a domain where nonlinear effects can be treated simply as linear phase shifts. Recently optical communication systems relying either on the continuous [4] or the discrete spectrum [5] of the NFT have been demonstrated. However, the NFT has been derived for a lossless, noiseless channel, therefore, many challenges of applying the NFT to practical systems still need to be addressed.

In this paper we numerically analyze in more details the effect of some system parameters (launch power, fiber attenuation, and additive white Gaussian (AWG) noise) on the NFT continuous spectrum. This is done by considering a simple scenario of a single isolated Gaussian pulse propagating in a standard single mode fiber (SMF) and measuring the difference between its continuous nonlinear spectrum before and after transmission in terms of normalized mean squared error (NMSE). We show the stronger potential of the nonlinear spectrum for preserving itself along the transmission link when compared to the linear spectrum (discrete Fourier transform (DFT)) regardless of the presence of non-idealities such as fiber loss and noise. The NFT is thus a promising technique in scenarios where the spectrum preservation is desirable, such as multi channel systems using frequency-orthogonal channels.

2. Simulation setup

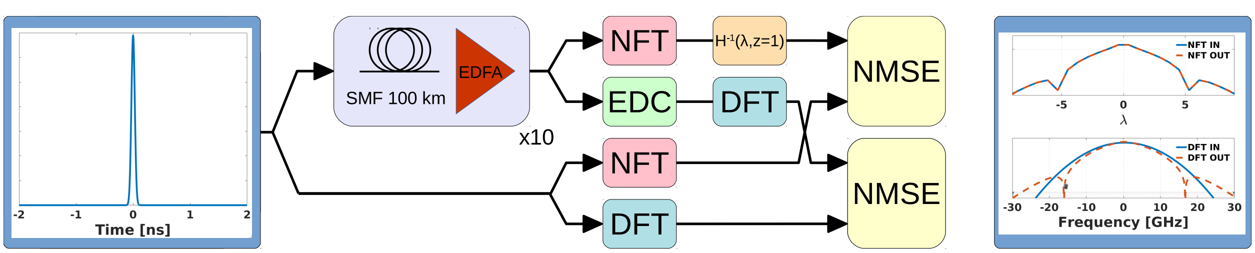

Fig. 1: Simulation setup implemented in Matlab™ and VPI Transmission Maker™. Inset: NFT and DFT spectra at input and output of the fiber lossless channel.

The numerical simulation setup is depicted in Fig. 1 and has been performed in Matlab™ and VPI Transmission Maker™. The transmitter generates a single Gaussian pulse with 50 ps full width at half maximum (FWHM). The simulation time window is 8 ns and the bandwidth 2.56 THz. This choice guarantees that the pulse is well isolated, condition required to properly compute the NFT. An ideal laser with a carrier frequency of 192.4 THz is used. The input waveform $E_i(t)$ is transmitted over 1000 km (10×100 km) of dispersion uncompensated SMF. The fiber is assumed to have a dispersion $D = 17\ ps/nm{\cdot}km$ and a nonlinear coefficient $\gamma = 1.27\ W^{-1}{\cdot}km^{-1}$. The fiber attenuation coefficient is either set to $\alpha = 0$ (lossless, ideal case) or $\alpha = 0.2\ dB/km$ (typical value for SMF). For a lossy channel, perfect attenuation compensation has been achieved by using Erbium-doped fiber amplifiers (EDFAs) after each span. EDFAs with no noise and with a noise figure of 3 dB are considered in two different scenarios. In the simulations where noise is present, the results have been averaged over 30 realizations and the standard error is shown with error bars. The propagation in the fiber is simulated using the split step Fourier method (SSFM) with an adaptive step size allowing a maximum phase rotation of 0.01 deg. At the fiber output, an ideal coherent receiver is assumed to give access to the full signal field $E_o(t)$.

The NFT continuous spectra $\hat{q}_i(\lambda)$ and $\hat{q}_o(\lambda)$ with $\lambda \in C^+$, of $E_i(t)$ and $E_o(t)$ respectively, are computed using the Ablowitz-Ladik method to solve the NFT eigenvalue problem as described in [6]. When the channel is lossy and EDFA amplification is employed, the NFT is computed using the loss path average (LPA) method described in [7]. To compare input and output spectra, the channel inverse transfer function $H^{-1}(\lambda, z=1)$ is used to compensate for the channel propagation, $\hat{q}_{i,est}(\lambda) = e^{4j\lambda^2}\hat{q}_o(\lambda)$. The two spectra $\hat{q}_i(\lambda)$ and $\hat{q}_{i,est}(\lambda)$ are then compared using the NMSE as a metric:

$$NMSE = \frac{\int_\lambda |\hat{q}_i(\lambda) - \hat{q}_{i,est}(\lambda)|^2}{\int_\lambda |\hat{q}_i(\lambda)|^2} \tag{1}$$

In order to benchmark the results, linear spectra are also calculated using standard DFT and the same NMSE metric is applied. In this case, electrical dispersion compensation (EDC) is applied to $E_o(t)$ as shown in Fig. 1.

3. Results

To investigate the impact of noise on the NFT spectrum, an ideal Gaussian pulse has been loaded with AWG noise corresponding to different levels of OSNR defined in a 0.1 nm bandwidth. The NFT and DFT spectra have then been compared to their noiseless counterparts for three different power levels. The dependency of DFT NMSE and NFT NMSE on the OSNR is depicted in Fig. 2. For low powers the DFT and NFT spectra have similar shapes and it can be seen that they are similarly affected by noise. As the power increases to -12 dBm, the NFT is more affected by noise leading to NMSE values greater than those of the DFT. In Fig. 3 (a) the NMSE as a function of launch power

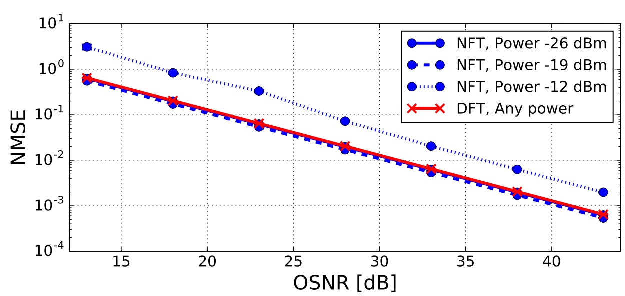

Fig. 2: NMSE between ideal and noise-loaded input spectra for NFT and DFT as a function of the OSNR.

is shown. In the lossless case, the DFT NMSE increases exponentially with the power due to the impact of self phase modulation (SPM). For power levels above -18 dBm, the relative error is higher than 10% making the output spectrum diverge significantly from the input one. Note that SPM impairments are already so strong at this power, because the large guard time intervals used to account for dispersive effects significantly decrease the average power, however, nonlinear effects depend on the pulse peak power which is 22 dB higher than the average. Above -9 dBm the error flattens out to NMSE $= 4$, i.e. the maximum NMSE between two spectra carrying the same energy. On the other hand, the NFT NMSE remains practically constant and below a value of 2×10^{-6} for powers up to -10 dBm, while for powers above this value it slightly increases, possibly due to the numerical precision required for the computation, as above -10 dBm most of the energy is transferred from the NFT continuous spectrum to the discrete one (Fig. 3 (b)). Nevertheless the NMSE stays below a value of 10^{-4}, proving the theoretically expected higher tolerance of the NFT to nonlinear impairments. When fiber loss is taken into account and compensated for by noiseless amplification, the DFT matching improves compared to the lossless case as the effective nonlinearity is lowered by the presence of the losses. Such an improvement is not visible for the NFT, which performs worse with respect to the lossless case due to the approximate equation used to compute the NFT when the channel is lossy and therefore non-integrable. The NMSE exponential increase with power is consistent with [7]. Nonetheless, the spectral mismatch between the NFT spectra is still lower than that of the linear spectrum even in this non-ideal case.

In the last scenario considered, the impact of power variations and noise are combined: the pulse has been transmitted over a lossy channel and EDFAs with a noise figure of 3 dB have been used to compensate for the power loss. In Fig. 3 (a) the dependency of the NMSE as a function of the launch power, and the corresponding OSNR at the receiver , is shown. In the linear regime, the spectral matching increases with the power (NMSE decreases) for both DFT and NFT. Once the power is increased beyond the linear transmission regime, the DFT NMSE worsens as nonlinearity impacts the spectral matching. The behavior of the NFT is similar, but in this case the tolerance to nonlinearity is higher with the optimum launch power increased by 3 dB . For even higher power also the NFT NMSE starts worsening. This is believed to be caused by the use of the LPA approximation . Note that the peak for -6 dBm launch power corresponds to the point where the first discrete eigenvalue appears, i.e., the point where the NFT continuous spectrum energy is slightly different from the NFT total energy (Fig. 3 (d)). Overall, the NFT provides an NMSE decrease of a factor 2.85 compared to the DFT at the respective optimum launch powers, proving its potential for nonlinear transmission.

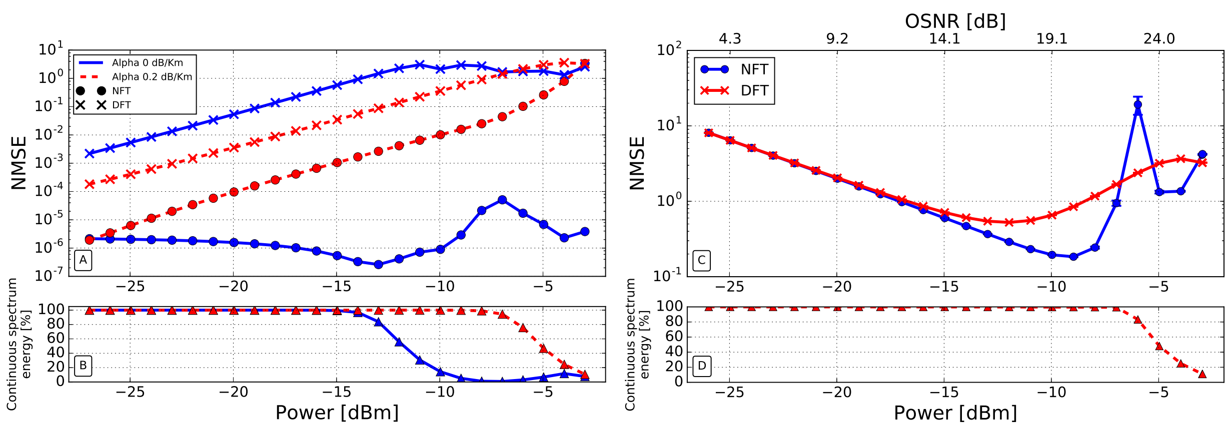

Fig. 3: NMSE between input and output (1000 km) spectrum for NFT and DFT (a),(c) and percentage of energy in the continuous NFT spectrum (b),(d) as a function of the launch power for noiseless (a),(b) and noisy (c),(d) amplification.

4. Conclusion

The impact of AWG noise on the NMSE of the NFT and DFT shows a worsening of performance for the NFT when high launch powers are used. However, a higher tolerance to nonlinearities, in terms of NMSE between input and output spectrum, is reported for the NFT. Lower values are shown compared to the DFT. Finally when lossy and noisy transmission is considered, an improved spectral matching can be achieved by the NFT. A decrease of the NMSE of almost three times as well as an increase in launch power by 3 dB compared to the DFT is demonstrated.

Acknowledgments

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