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Executive Summary

D2.3 Numerical and experimental validation of the robust modulation formats

Nonlinear Fourier transform (NFT) based transmission techniques are seen as a way to mitigate the nonlinearity of the optical fiber. These transmission techniques are very different from the conventional linear transmission techniques. Thus, the modulation techniques used in the conventional linear transmission techniques may not be optimal for NFT based systems and a proper investigation is needed.

There are many aspects that need to be considered in order to find suitable modulation for NFT systems such as spectral efficiency (time-bandwidth product), control of pulse-duration, noise sensitivity. Furthermore, attention is needed on the challenges related to practical impairments such as bandwidth limitations and fiber-loss. In a previous report, a modified NFT for the modulation of data in dispersion-decreasing fibers was described that can take fiber loss into account and therefore neutralizes one of the major impairments in standard NFDM systems. In this report, we evaluate this new data modulation technique numerically and quantify the improvements over standard NFDM systems.

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LIST OF ACRONYMS

CDF	Constant Dispersion Fiber
DDF	Dispersion Decreasing Fiber
EVM	Error Vector Magnitude
NFT	Nonlinear Fourier Transform
NFDM	Nonlinear Frequency Division Multiplexing
NLSE	Non-Linear Schrodinger Equation
NZDSF	Non-Zero Dispersion Shifted Fiber
PA	Path Average
PAPR	Peak to Average Power Ratio
QPSK	Quadrature Phase Shift Keying

1 INTRODUCTION

The nonlinear Fourier transform parallelises the nonlinear Schrödinger equation (NLSE), the governing model for the nonlinear fiber optic channel. The NFT maps the complicated time-domain evolution of a signal propagating through fiber channel into simple rotations in nonlinear Fourier domain [1-3]. In an ideal fiber, the interference among the nonlinear spectral components obtained by NFT of a signal is absent [4]. This property encourages the idea of using these nonlinear spectral components as data carriers. This approach of modulating nonlinear spectrum is called nonlinear frequency division multiplexing (NFDM) [4]. The nonlinear spectrum of a signal can be very different from the conventional linear Fourier spectrum and the well-known understanding of the time and frequency domains does not apply directly to the case of NFT. The modulation and demodulation of information on nonlinear spectra therefore requires new concepts beyond what is known from conventional transceivers. The nonlinear spectrum of a signal consists of a continuous and/or a discrete spectrum, where the continuous spectrum captures the radiative components of the signal while the discrete spectrum describes the solitonic (non-radiative) components [2]. The continuous spectrum has a continuous range of real nonlinear frequencies. At each nonlinear frequency, corresponding spectral components (reflection or b coefficients) can be modulated in amplitude and phase. The discrete spectrum consists of complex eigenvalues which remain unaltered during propagation and corresponding spectral values. The discrete spectrum can be modulated by the presence/absence or positioning of the eigenvalues and, in addition by modulating the amplitude and phase of the corresponding spectral values. Clearly, the available degrees of freedom for modulation using NFTs is wider in the case of nonlinear Fourier spectrum.

Classical single soliton systems can be seen as a simple special case of nonlinear spectrum modulation. In such systems, information is encoded in the presence/absence of a single soliton (eigenvalue) [5-7]. However, efficient utilization of nonlinear spectrum requires the modulation of the remaining parts of the spectrum as well. The continuous part of the nonlinear spectrum is similar to the linear Fourier spectrum. Thus, a technique was proposed in [8-9] called nonlinear inverse synthesis to modulate the reflection coefficient representation of the continuous spectrum. Modulation of the b-coefficient representation of the continuous spectrum was proposed in [10]. In b-modulation the time-duration of the signal can be controlled. Another advantage is that b-coefficients are more robust against noise in comparison to the reflection coefficients [11]. The modulated signal has to be designed and analysed considering the transmission channel in order to prevent the interference between neighbouring bursts for the case of NFT with vanishing boundaries. Many experimental demonstrations of NFT based transmission system are published in literature which include modulation of continuous spectrum using NIS [12] and b-modulation [13], modulation of discrete spectrum [14-17], and for modulation of both spectrum [18].

There are challenges in realizing NFT based transmission systems in experiments. These challenges are highlighted in [16] where in order to keep high spectral efficiency multi-soliton pulses were designed under explicit consideration of various factors such as peak to average power ratio (PAPR), limited bandwidth of the transmitter and evolution of the pulse during propagation. In experiments with real systems another challenge comes from the non-ideal optical fiber channel. As the fiber channel causes signal attenuation the NFT based model is not applicable directly and an approximation model know as path average model is used [17]. However, the advantageous properties of NFT such as the invariance of eigenvalues during propagation is weakened when path average models are used. In the next sections, we study this effect numerically and investigate the performance improvements when data is modulated as proposed using a specialized NFT for dispersion-decreasing fibers.

2 Modulation of a Two-Soliton Pulse

In this numerical study, the system was designed as proposed in [18]. A two-soliton pulse consisting of purely imaginary eigenvalues ($\lambda_1 = 0.3j$ and $\lambda_2 = 0.6j$), with each of these eigenvalues modulated with quadrature phase shift keying (QPSK) modulation format was transmitted over a noiseless fiber channel. The channel was designed using spans of 80 km of non-zero dispersion shifted fiber (NZDSF) followed by optical amplifier. The pulse was transmitted over multiple spans and its eigenvalues were computed after each span. Figure 1 shows the trajectories of the eigenvalues for the two-soliton pulse propagation setup. Due the presence of the loss in the fiber the eigenvalues do not remain constant even in the case of noiseless transmission. Further, it is also observed that the eigenvalues follow different trajectories depending on the modulation of symbol from QPSK modulation format. These trajectories are represented by different colours where modulation $S_{m,n}$ (in legend) represents the symbol modulated from the QPSK format for eigenvalues $\lambda_1$and λ_2 respectively. Thus, in order to avoid the interaction between the eigenvalues (to avoid the crossing between the trajectories followed by $\lambda_1 = 0.3j$ and $\lambda_2 = 0.6j$), the eigenvalues must be chosen such that they stay well separated considering the fluctuations due to the fiber loss and noise.

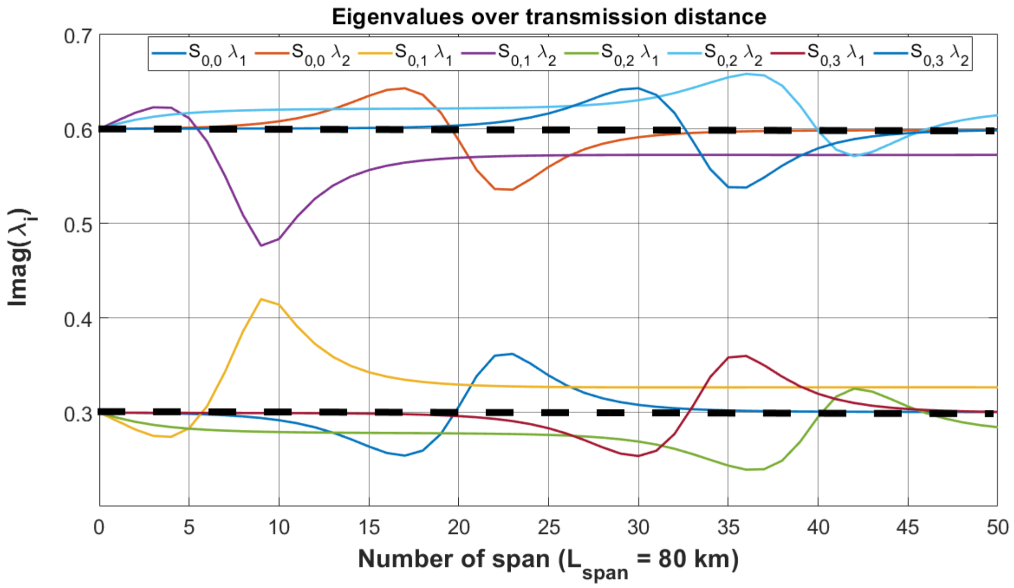

Figure 1: [Propagation of two-soliton pulse in a fiber link. The coloured lines represent the trajectories of eigenvalues for propagation over NZDSF and black dashed line represent the trajectory of eigenvalues for propagation over DDF.]

Earlier we proposed a solution to this problem by designing NFT based transmission system using dispersion decreasing fiber (DDF) [19,20]. By modulating data using a specialized NFT for DDF, the fluctuations of the eigenvalues due to loss can be suppressed. The parameter of the DDF considered are shown in Figure 2. In Figure 1, the black dashed lines represent the trajectory followed by eigenvalues ($\lambda_1 = 0.3j$ and $\lambda_2 = 0.6j$) for the case of noiseless transmission over DDF. **As it is visible from the eigenvalues remain constant even in presence of loss in noiseless scenario.**

In the next sections, we compare the performance of NFDM systems designed using DDF with constant dispersion fiber (CDF) further for the case of modulation of discrete and continuous part of the nonlinear spectrum.

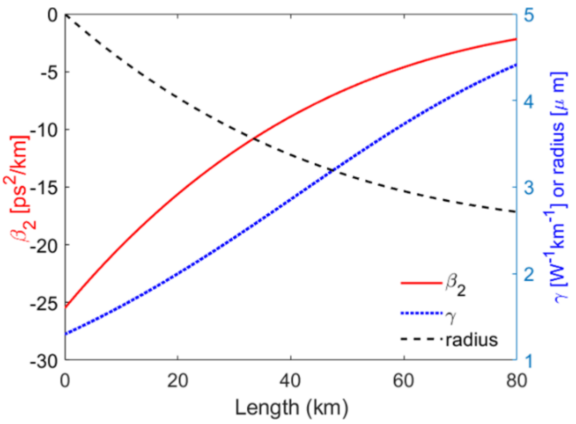

Figure 2: [Parameters of an 80 km dispersion decreasing fiber (β_2 is dispersion parameter and γ is nonlinear parameter).]

3 NFDM System With Modulation of Discrete Spectrum

We considered the multi-soliton transceiver presented in [16] for our numerical study. The simulation setup is shown in Figure 3. At the transmitter, randomly generated QPSK symbols were modulated on the discrete spectral amplitudes of the corresponding seven eigenvalues given in [16]. Then, the inverse NFT (INFT) operation was performed to obtain the time-domain multi-soliton pulse. In order to avoid truncation effects and pulse-overlap during propagation, the duration of the normalized multi-soliton pulse was set to 18π. The normalized multi-soliton pulse is then scaled using the link parameters and the time-scale parameter T_0. The parameter T_0 controls the duration of de-normalized pulse and hence was used to vary the transmit power. The parameters used for CDF are listed in Table 1. For CDF, two types of link configurations were considered. Figure 3(b) shows the transmission link for the first configuration (referred as CDF--PA). In this transmission link, each span in the link consists of 80 km fiber followed by an Erbium-doped fiber amplifier (EDFA) to compensate the span-loss of 16 dB. The same link configuration was used for the NFDM system designed with DDF. The second configuration of link, shown in Figure 3(c), is same as the first one except for the first and the last spans which have different lengths (referred as CDF--PA+Amp-shift). The lengths of the first and the last span were optimized according to the analysis in [20]. It was shown in [20] that the approximation error of path-average model is minimized at those optimal lengths. The transmit power in the second configuration refers to the power at the amplifier outputs.

Fiber Type	CDF	DDF
αdB/km)	0.2	0.2
$\beta_2$ps^2/km)	-6.75	-25 to -2.17
γ (1/W/km)	1.3	1.3 to 4.4

Table 1: [Parameters of constant dispersion fiber.]

The noise figure of the EDFAs was set to 6 dB in both link configurations. The fiber propagation was simulated using a split-step Fourier method. At the receiver (shown in Figure 3(d)), the signal was filtered, and after normalization, the signal was then equalized in the nonlinear Fourier domain. The QPSK symbols were demodulated from the spectral values of the eigenvalues. Finally, performance is measured in terms of the error vector magnitudes (EVMs) of received symbols.

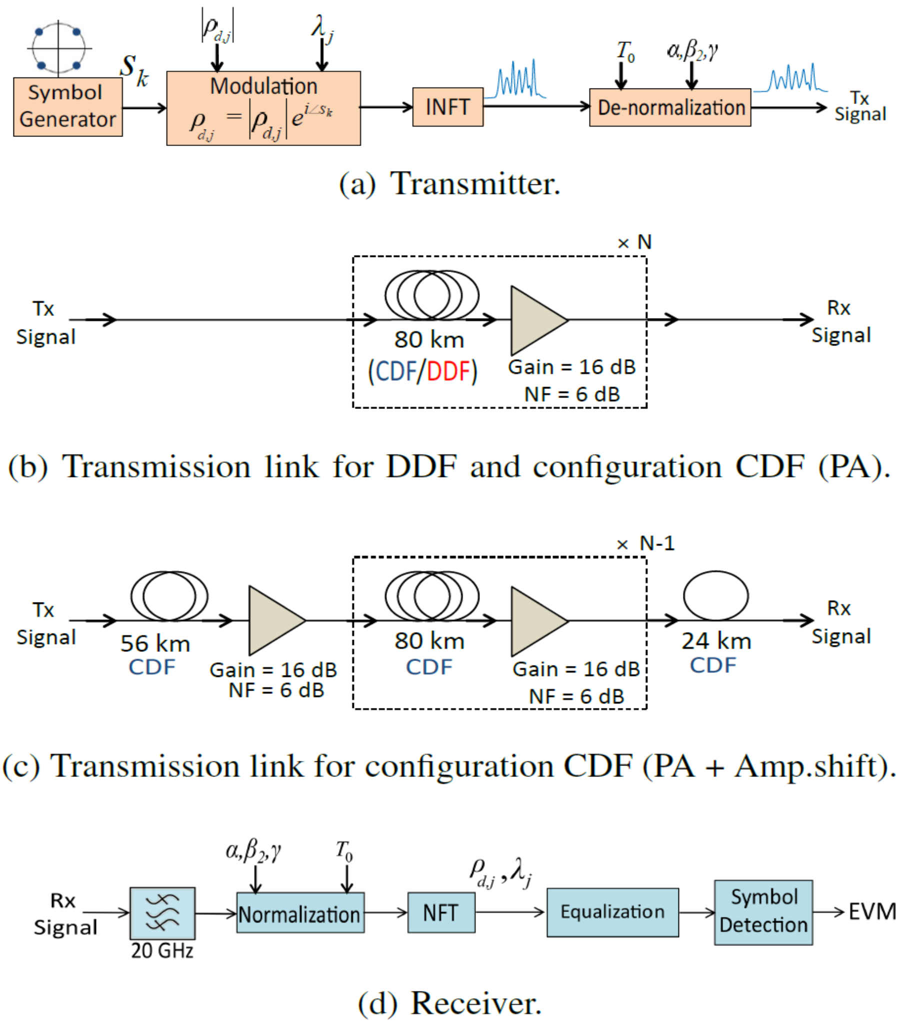

Figure 3: [Simulation setup for NFDM system with discrete spectrum modulation.]

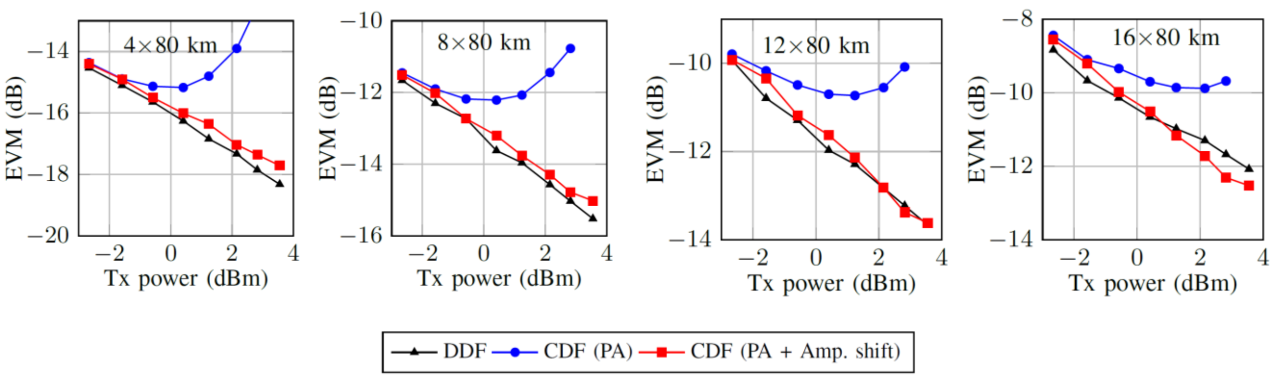

Figure 4: [Transmission performance of considered NFDM system with discrete spectrum modulation.]

The EVM is calculated at different transmit powers for different transmission distances and polotted in Figure 4. For the NFDM system designed using CDF with CDF—PA configuration, the EVM initially decreases with transmit power due to increase in effective signal to noise power ratio (SNR). However, the approximation error due to the path-average model dominates after a threshold transmit power, hence, the EVM starts rising.

For the NFDM system with CDF--PA+Amp-shift configuration, we did not observe any rise in the EVM in the simulated power range. The NFDM scheme that uses DDF performs slightly better than the NFDM scheme that uses CDF--PA+Amp-shift configuration except for the 16 × 80 km transmission. At transmission 16 × 80 km in DDF case, the pulses start overlapping at higher powers causing degradation in EVMs. However, this can be avoided by considering different system design parameters.

We observe a large gain of up to around 3 dB in the EVM for 640 km transmission over DDF in comparison to the NFDM system designed with a conventional CDF configuration. We also observe that the NFDM system designed with CDF--PA+Amp-shift configuration performs as good as the system designed with DDF in this example, which however has been designed specifically to keep the path-average approximation error small. In the next section, we study the continuous spectrum modulation case.

4 NFDM SYSTEM WITH MODULATION OF CONTINUOUS SPECTRUM

An NFDM system with b-modulation presented in [13] was considered to modulate continuous spectrum. The transmitter and receiver of the b-modulation NFDM system is shown in Figure 5. The link configuration used were the same as explained earlier and shown in Figure 4(b), (c). The nonlinear spectrum to be modulated consists of nine flat-top shaped b-carriers with carrier spacing of 15 (in the normalized NFT domain). The average energy of each carrier is controlled by an energy per carrier parameter E_d, which in turn controls the transmit power. At the transmitter, each carrier is modulated with randomly generated QPSK symbols. Then, the INFT operation is performed to obtain time-domain signal with a normalized duration of 4.5. The time-domain pulse is then de-normalized using the fiber parameters and a time scale parameter T_0 of 1.25 ns. A train of 127 pulses is then transmitted through the link. The net data rate and signal bandwidth were 3.2 Gb/s and approximately 40 GHz respectively.

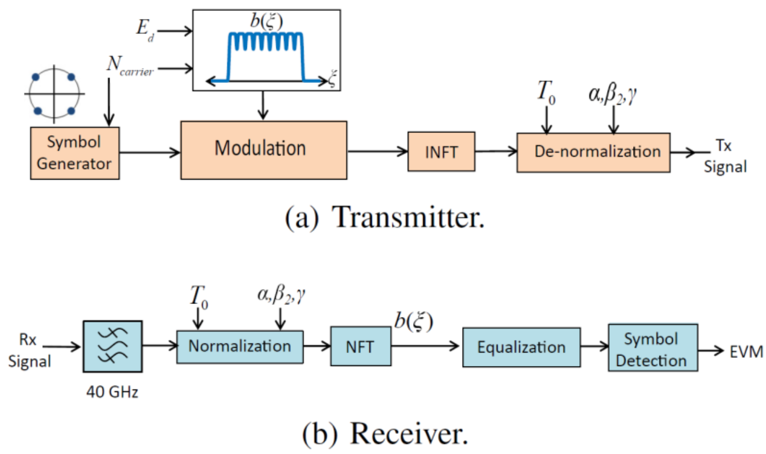

Figure 5: [Simulation setup considered NFDM system with continuous spectrum modulation.]

At the receiver, the signal is filtered and normalized. After the NFT operation the b-coefficients are obtained, which are then equalized in nonlinear Fourier domain. Finally, the symbols are detected from the b-carriers and EVMs were computed.

It must be noted that as the magnitude of b-coefficient cannot be greater than one, we have an upper limit on the carrier energy E_d [13], and thus on the transmit power [22]. It was shown theoretically in [22] that the system in [13] cannot exceed a finite power limit. Figure 6 shows the EVM over transmit power for different transmission length in the presence of noise. The additive noise increases signal power slightly during transmission. Close to the power bound, this increase in signal power due to the noise is enough to push the received signal outside the range of the b-modulator (in this case the energy gets transferred into discrete spectrum that are not accounted for in the receiver). Thus, the impact of noise becomes severe in the higher power region when the signal approaches the aforementioned finite power limit. This results in the rise of the EVMs of all the considered NFDM systems in the high-power region.

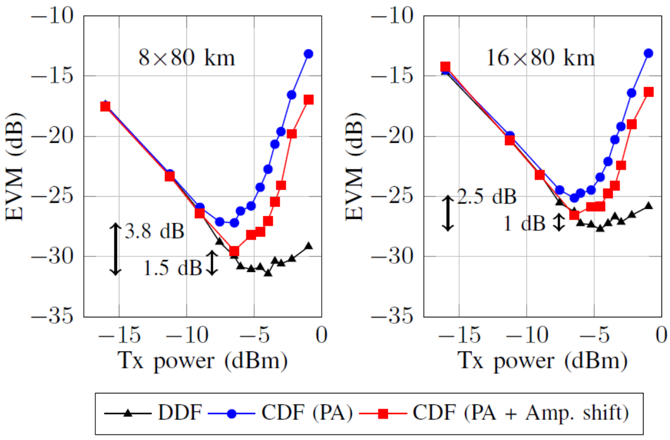

Figure 6: [EVM vs transmit power for NFDM system with continuous spectrum modulation.]

In Figure 6, the errors due to the path-average approximation are clearly visible. We can see that for 8 × 80 km transmission, EVM improves with increasing transmit power but after a threshold the EVM for CDF starts degrading, as the path-average error increases at higher power. Furthermore, we see that the approximation error in the path-average model is reduced by the amplifier-shift as the NFDM system that uses the CDF--PA+Amp-shift configuration has better performance than CDF--PA. The performance of DDF improves with transmit power till -5 dBm, thereafter EVM degrades which is a result of the power limitations due to the b-saturation effect mentioned earlier. A similar trend is observed for the case of 16 × 80 km transmission. We obtained EVM gains of approx. 3.8 dB and 1.5 dB at 640 km with respect to path-average without amplifier-shift and path-average with amplifier-shift, respectively, when data is modulated using the specialized DDF-NFT. At 1280 km, these gains reduce to 2.5 dB and 1 dB respectively.

5 Conclusion

In this report, various modulation schemes for NFT-based system were surveyed. We highlighted some of the difficulties in the experimental realization of NFT-based systems. The previously proposed DDF-NFT approach that mitigates impairments due to fiber loss by modulating data using an adapted NFT in dispersion-decreasing fiber was compared with conventional approaches in numerical simulations. We first showed in a noise-free scenario that modulation-dependent fluctuations in two-eigenvalue signals due to the fiber-loss in conventional NFDM systems are avoided when dispersion decreasing fiber with adapted NFTs is used. Afterwards, we compared the impairment due to fiber-loss in simulations in terms of error vector magnitude for NFT systems using either discrete or continuous spectrum. We observed gains with dispersion decreasing fiber in both cases.

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