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Executive Summary

D2.1 Major impairments in NFT-based transmission

The rapidly increasing demand of high data rates is pushing the transmission capacity of optical fiber communication system towards its limit. Modern optical fiber communication systems uses coherent receiver along with digital signal processing to compensate the linear impairments. It is widely accepted that the capacity of current systems is mainly limited by the nonlinear effects [1]. Over the past decade, different techniques have been proposed to mitigate the nonlinear impairments in optical [2,3] and digital domain [4-6]. In Wavelength Division Multiplexing (WDM) systems, where carriers are multiplexed in linear frequency domain, nonlinear interference among the carriers due to fiber nonlinearity limits the transmission capacity.

Recently, Nonlinear Fourier Transform (NFT) based transmission techniques have been proposed as promising approach to overcome the nonlinear behaviour of optical fiber [7]. These transmission methods are consider nonlinear behaviour of optical fiber as essential element in designing communication system as the optical fiber is inherently nonlinear channel. NFT is a mathematical tool that linearizes nonlinear fiber optic channel into set of parallel linear channel [7]. As like, in the ordinary Fourier domain the effect of dispersion is translated into simple phase rotations, the NFT converts the combined effect of nonlinearity and dispersion into trivial phase rotations in nonlinear Fourier domain. Many research groups have demonstrated proof-of-concept experiments using NFT.

While NFT based techniques offer attractive solution, originally these techniques are applicable to ideal lossless optical fiber system. In practical systems it face challenges due to loss and amplification noise. In addition to this, there are implementation challenges at transceiver due to component imperfection, quantization noise and algorithmic limitations. In order to make NFT based techniques realizable, signal processing techniques to compensate such impairments and modulation formats which are more robust to such impairments are needed. Here, in this report, major impairments in NFT are surveyed as first step towards this goal.

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LIST OF ACRONYMS

ADC	Analog to Digital Converter
AiPT	Aston Institute Of Photonic Technologies
ASE	Amplified Stimulated Emission
AWGN	Additive White Gaussian Noise
DAC	Digital to Analog Converter
DBP	Digital Back Propagation
EC	European Commission
EID	European Industrial Doctorates
ESR	Early Stage Researcher
FONTE	Fibre Optic Nonlinear Technologies
LPA	Lossless Path Average
NFT	Nonlinear Fourier Transform
NFDM	Nonlinear Frequency Division Multiplexing
NIS	Nonlinear Inverse Synthesis
NLSE	Non-Linear Schrodinger Equation
OFDM	Orthogonal Frequency Division Multiplexing
PMD	Polarization Mode dispersion
WDM	Wavelength Division Multiplexing

1 INTRODUCTION

The propagation of signal in an ideal optical fiber is governed by Non-Linear Schrodinger Equation (NLSE), which is a nonlinear partial differential equation, given as [8]

$$\frac{\partial E(l,\tau)}{\partial l}+\frac{j\beta_2\partial^2E(l,\tau)}{\partial\tau^2}-j\gamma\,|E|^2E\;=\;0 \tag{1}$$

Where, l is propagation distance, τ is retarded time, and $E(l,\tau)$ is the complex envelope of the signal propagating in the fiber. The coefficients β_2 and γ are dispersion and nonlinear coefficient of the fiber respectively. The second and third term in the above equation accounts for dispersive and nonlinear effects respectively, which affect the shape and spectrum of an optical pulse propagating inside an optical fiber. It was shown by Zakharov and Shabat [9] that the above equation belongs to certain class of integrable nonlinear system , and can be solved by Nonlinear Fourier Transform (NFT). The NFT of a signal is composed of two components, the continuous and the discrete nonlinear spectrum. The continuous nonlinear spectrum is dispersive while, the discrete nonlinear spectrum is non-dispersive and consists of discrete eigenvalues and corresponding spectral amplitudes. The NFT based fiber-optic communication systems are broadly categorized based on their design as shown in Figure 1, 2[10].

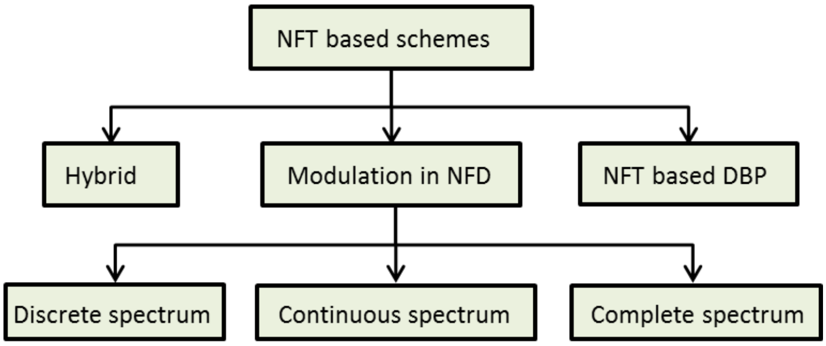

Figure 1: NFT based transmission schemes

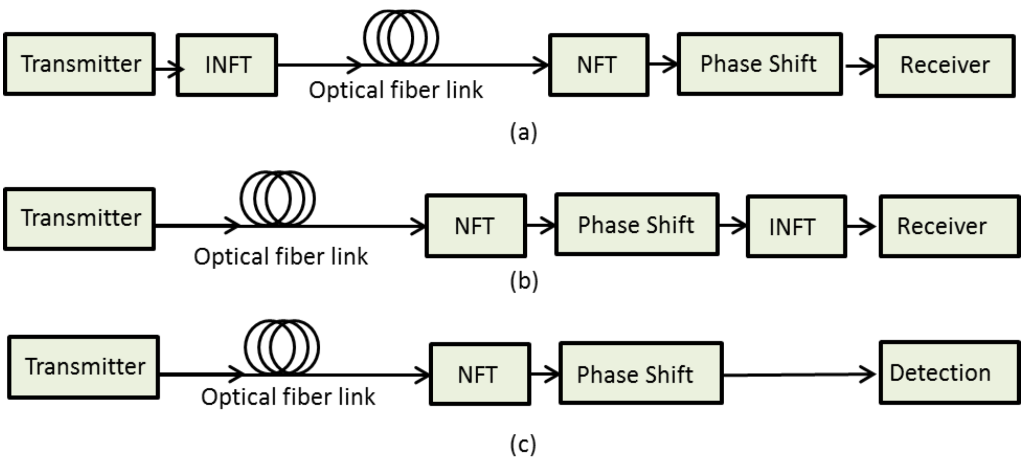

Figure 2: Schematic of NFT based systems (a) NFT based DBP, (b) Modulation in NFD, (c) Hybrid method

In the hybrid scheme, information is encoded in time domain and detected in Nonlinear Fourier Domain (NFD). The discrete and continuous spectrum or both can be used to encode information, which are sub-categorized under modulation in NFD. In NFT based DBP, the signal is digitally back propagated in the NFD at the receiver. Soliton based transmission technique can be seen as the simplest case of a NFT based transmission system, where discrete eigenvalues are used for communication.

2 IMPAIRMENTS IN NFT

The performance of NFT based transmission system is lagging behind the conventional systems because of the impairments from practical limitations. The two main causes for imperfections are the non-ideal transmission medium and imperfect transceivers, which are both discussed in detail in this section.

2.1 FIBER LOSS

The power of an optical signal reduces as it propagates along the optical fiber due to fiber loss. This loss is compensated either by using lumped amplification or distributed amplification. Even though the loss is compensated by the amplification, because of the variation of power throughout the fiber span the integrability property of NLSE is lost.

In distributed amplification, the loss is compensated by amplifying the signal along the fiber length while In lumped amplification, the launch power of signal into every span is maintained constant by amplifying the signal at the end of each fiber span. In a fundamental-soliton based system, the challenge of power variation in periodically amplified links can be addressed by increasing the transmission power provided the amplifier spacing is much less than the dispersion length. In an alternative approach, the use of dispersion decreasing fiber is proposed to balance the reduced nonlinearity by having a fiber with tailored dispersion profile $\beta_2(z) = \beta_2(0)e^{-\alpha z}$ [8]. It was shown in [13], that NLSE can still be integrable for the case of non-ideal amplification. However, it requires to have an optical fiber with variable dispersion and nonlinear parameter. Furthermore, the use a Lossless Path Average model (LPA) of NLSE is proposed to approximate the field propagation in a lossy fiber link [11,12]. In a LPA model, the distance dependent nonlinear parameter in the NLSE is replaced by its average value over the span. However, the LPA model is an approximation and assumes the signal to be narrow band. The accuracy of this model depends on signal power and bandwidth. The inaccuracy can deteriorate performance of NFT based transmission systems.

2.2 AMPLIFICATION NOISE

As just discussed, power loss in optical fiber is compensated using lumped or distributed amplification using optical amplifiers, which in turn introduces noise into the signal due to Amplified Stimulated Emission (ASE) [8]. In a classic single-soliton based communication link, the ASE causes random variation in the soliton's amplitude, center frequency, mean time and phase, out of which the fluctuation in amplitude and frequency affects mostly the quality of transmission[14]. The randomness in the amplitude is almost similar to the linear system. On the other hand, the variation in center frequency is converted into fluctuation in arrival time of pulses by the dispersion, which is known as Gorden-Haus effect. The study in [15] shows that the this timing jitter due to ASE grows with cube of propagation distance in lumped amplification case. The timing jitter and other noise effects can be suppressed in the optical domain by applying appropriate optical filtration [14].

When the noise power is small compared to the signal power, perturbation theory can be applied to understand evolution of NFT data in presence of Additive White Gaussian Noise (AWGN). It was shown in [16] using first order perturbation approach that the fluctuation in the eigenvalue is signal dependent. For single soliton case, the noise variance increases for the higher eigenvalues. A model of noise in discrete spectral amplitudes is proposed in [17] for distributed amplification case. It was shown that for extremely large distance L (i.e. in long-haul communication) noise statistics is no longer Gaussian and variance of noise in spectral amplitude is of order L^6. The nonlinear spectral noise is correlated and depends on the initial spectrum [18,19]. Numerical methods are proposed to compute the statistics of nonlinear spectral coefficients, when the signal is perturbed by AWGN [20,21]. As the noise breaks the integrablity property of NLSE, in case of multi-user system the signal degrees-of-freedom are not independent. The correlation between the nonlinear carriers was investigated in [22,23]. It has turned out that the noise in NFDM can be reduced if the b-coefficient is used for encoding data instead of the reflection coefficient [24].

2.3 Components Imperfection

As like the conventional transmission techniques, NFT based techniques face challenges due to non-ideal response of the components. The transfer function of an optical modulator is non-linear, thus it need to be operated in limited linear region. The response of driving amplifier and digital to analog converter (DAC) attenuate at higher frequencies, which can cause significant distortions to the signal waveform. Further, the Digital to Analog Converter (DAC) and Analog to Digital Converter (ADC) have finite bit resolution. The waveform is hence represented with a finite number of quantization levels, which introduces quantization noise. The peak to average power ratio of the signal should be kept small to avoid performance degradation due to limited resolution of transmitter DAC and nonlinear response of modulator. There are various methods to pre-distort waveform in order to suppress the undesired response of the overall transmitter [25-27]. In the recent demonstrations on NFT based transmission [28,29], the imperfection due to transmitter components is compensated by equalization.

2.4 Higher Order Effects

NFT based techniques are well studied for scalar NLSE. but the effect of polarization mode dispersion, higher order dispersive and nonlinear effects were mostly not accounted for. The Manakov equation is extension of the NLSE which accounts for the polarization dynamics of light in optical fiber. It was shown that the Manakov equation is integrable, hence NFT techniques are applicable [30]. NFT based systems have been demonstrated with polarization division multiplexing using Manakov equation [31-33]. The effect of polarization mode dispersion is negligible for the case of NFT based systems. The typical value of the PMD coefficient is 0.1 ps/√(km), hence the differential group delay is much smaller than the burst duration of currently demonstrated NFT systems [8]. In addition, as like the modern coherent optical receivers, NFT receivers also detects both amplitude and phase of the signal, so similar post-processing methods can be applied to suppress the polarization impairments in NFT systems. In classic single-soliton based systems, third order dispersion (TOD) mainly shifts the peak of soliton. For the typical value of 0.1 ps^3/km, so TOD induces a negligible delay for the soliton pulses of pico-seconds order [8]. The higher order effects are only significant for the case of the ultra-short pulses of femto-seconds order.

2.5 Truncation Error

The signal generated by NFDM are often of infinite duration and need to be truncated before transmission. This introduces two sources of error: one is the truncation error, the other is that the inteference with bursts increases. The truncation error can now be controlled with b-modulation [34] or (at least in theory) periodic signals. The classic way to overcome the interference is to create long signals such that the channel memory becomes short in comparison. However, it has been found that the performance of NFDM systems deteriorates with the signal duration [19], the reason for this phenomena is not yet clear.

3 CONCLUSION

In this report impairments in NFT based transmission systems is discussed. The major challenges are from the impairments due to fiber loss with noisy amplification. The integrability property the NLSE breaks due to these impairments. The challenges from the impairments discussed in the report, need to be addressed to gain the actual advantage of the novel transmission scheme based on NFT.

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