Implementation of Eigenvalue Multiplex Transmission with a lossy 75 km Fiber Link

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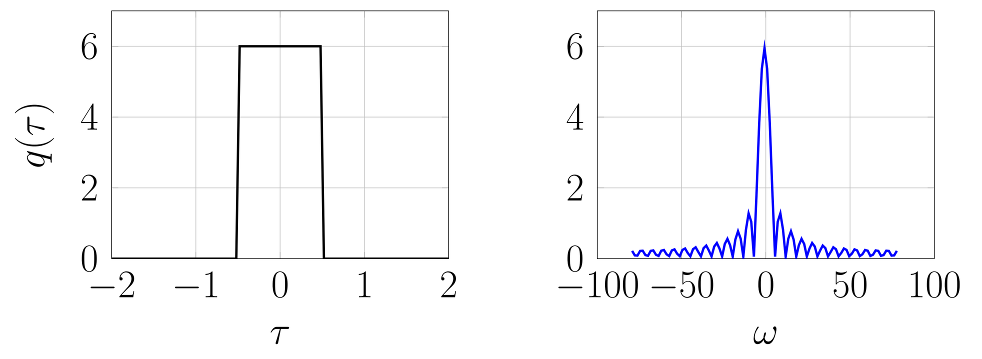
Abstract

To overcome the fiber nonlinearity limit imposed for classical linear transmission schemes in fiber optical communication and based on the broad availability of coherent optical transmission equipment the communication with eigenvalues attracted research interest recently [1]-[6]. This novel type of communication is based on the application of the (Inverse) Nonlinear Fourier Transform. A prerequisite of the theory is a lossless fiber channel. Using a real world lossy link a basic transmission scheme using the eigenvalue's related discrete spectrum phase information was implemented. The transmission of 3 GBit/s over a 75 km fiber link without amplification was realized.

NFT / Inverse NFT

Fourier Transform / Inverse Fourier Transform

⇒ Transformation between time and frequency (ω) domain



(a) (b)

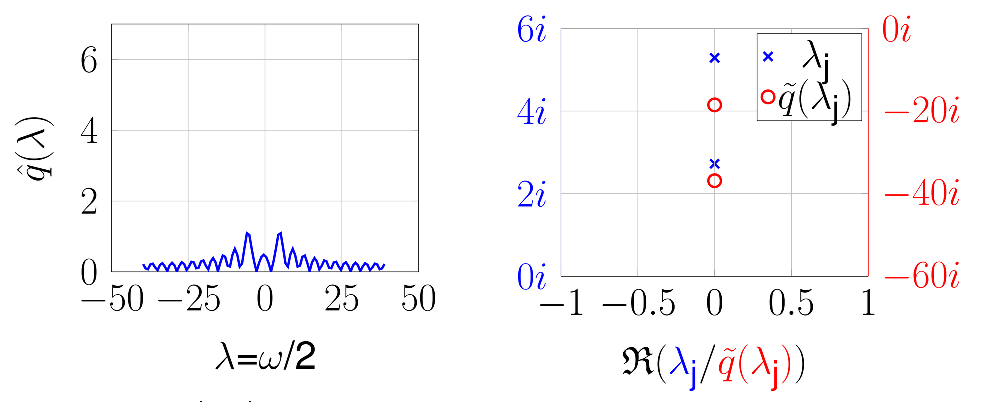
Figure 1: *Rectangular input signal (in "soliton units") and linear Fourier spectrum [1]*

Nonlinear Fourier Transform

⇒ Transformation from time domain to continuous (λ) and discrete frequency (λ_j) domain

⇒ Discrete frequency domain consists of eigenvalues (λ_j, $\Im(\lambda_j) \geq 0$) and discrete spectral amplitudes ($\tilde{q}(\lambda_j)$)

⇒ NFT spectrum converges to linear FT spectrum for small amplitudes ($2\lambda = \omega$)



(a) (b)

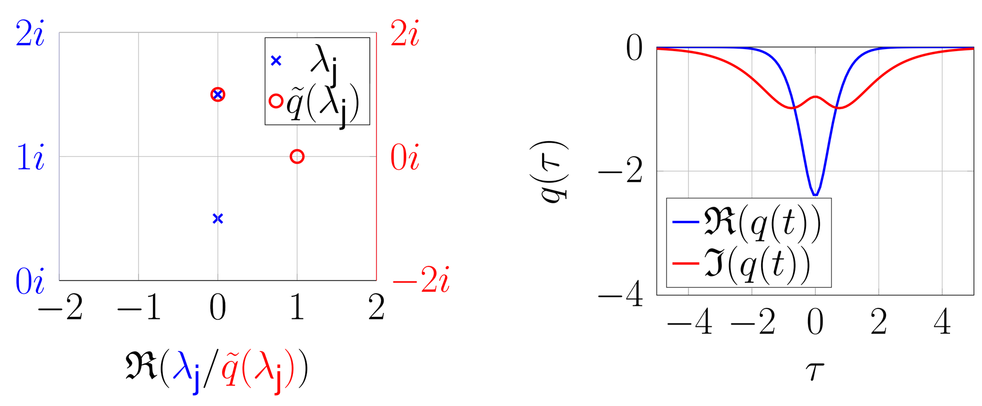
Figure 2: *Continuous ($\tilde{q}(\lambda)$) and discrete ($\tilde{q}(\lambda_j)$) NFT spectrum of input signal in Fig. 1(a), [1]*

Inverse Nonlinear Fourier Transform

⇒ Transformation from continuous and/or discrete frequency domain to time domain

⇒ Significant computational effort for inverse transform considering continuous and discrete spectral components

⇒ **Darboux Transform induces time domain signal from eigenvalues and their related discrete spectral amplitudes**



(a) (b)

Figure 3: *Darboux Transform from λ_j and normalized $\tilde{q}(\lambda_j)$ to time domain signal in "soliton units"*

Normalization

⇒ Normalization constants between "real world" and "soliton units"

$$q = \frac{A}{\sqrt{P_0}}, \quad z = \frac{l}{L}, \quad \tau = \frac{t}{T_0}, \quad N^2 = \frac{L_D}{L_{NL}} = \frac{\gamma P_0 T_0^2}{|\beta_2|}$$

Lossless Fiber Channel

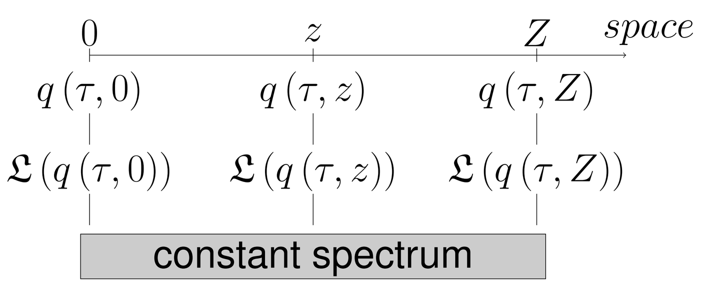


Figure 4: *Spatial evolution along fiber [1]*

⇒ Linear channel for signals in Nonlinear Fourier Domain

$$\widehat{q(\tau,z)}(\lambda) = e^{-4j\lambda^2 z}\widehat{q(\tau,0)}(\lambda)$$
$$\widetilde{q(\tau,z)}(\lambda_j) = e^{-4j\lambda^2 z}\widetilde{q(\tau,0)}(\lambda_j)$$
$$\lambda_j(z) = \lambda_j(0)$$

Modulation Format

⇒ $|\tilde{q}(\lambda_j)|$ is more sensitive to perturbations

⇒ Modulation of $|\tilde{q}(\lambda_j)|$ results in time delays between pulse components

⇒ Pulses with fast phase changes are more sensitive to phase errors of $\tilde{q}(\lambda_j)$

⇒ **Usage of 2 λ_j and different phases of $\tilde{q}(\lambda_j)$ to increase data rate**

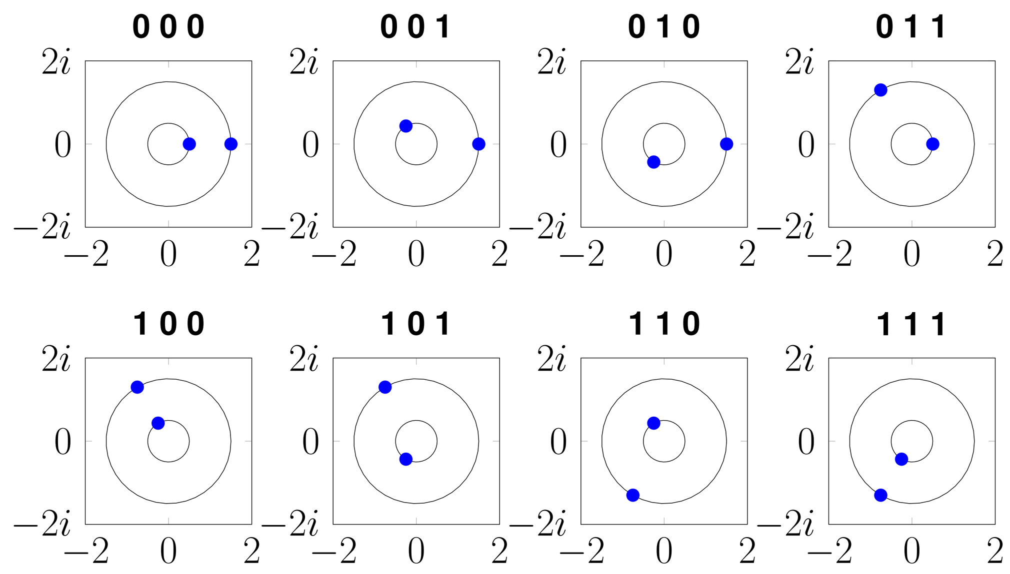


Figure 5: *Mapping of $arg\,\tilde{q}(\lambda_j)$: $|\tilde{q}(\lambda_j)|$ normalized to $\Im(\lambda_j)$*

⇒ Gray mapping not feasible for 2 λ_j and 3 phases

Experimental Setup

Eigenvalue multiplex transmission

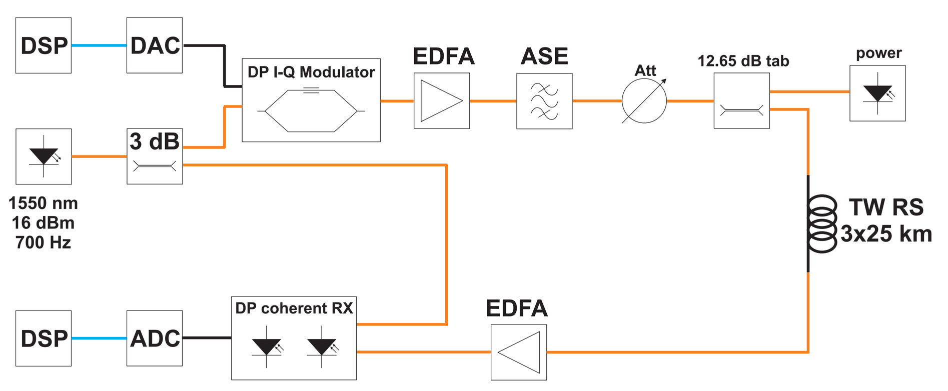


Figure 6: *Coherent setup using self homodyne detection*

⇒ Self homodyne detection using narrow linewidth laser avoids extensive phase noise and frequency deviations

⇒ Digital to analog and analog digital conversion is performed at 80 GSa/s resulting in 1 GBd/s signal

⇒ Phase correction is "data driven", based on knowledge of transmitted signal

Pulse shape: Simulation / Experiment

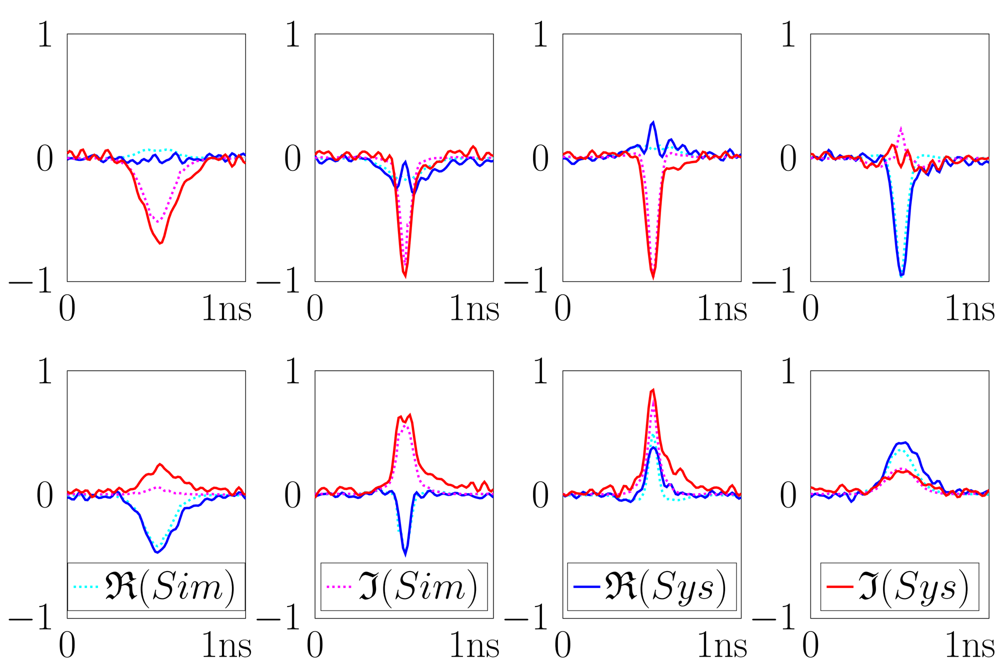


Figure 7: *VPI simulation vs. measurement: normalized intensities*

⇒ Simulation with -6.13 dBm mean launch power and no loss (OSNR: 45.2 dB)

⇒ Measurement with 0.67 dBm (OSNR:36.2 dB)

Experimental Results

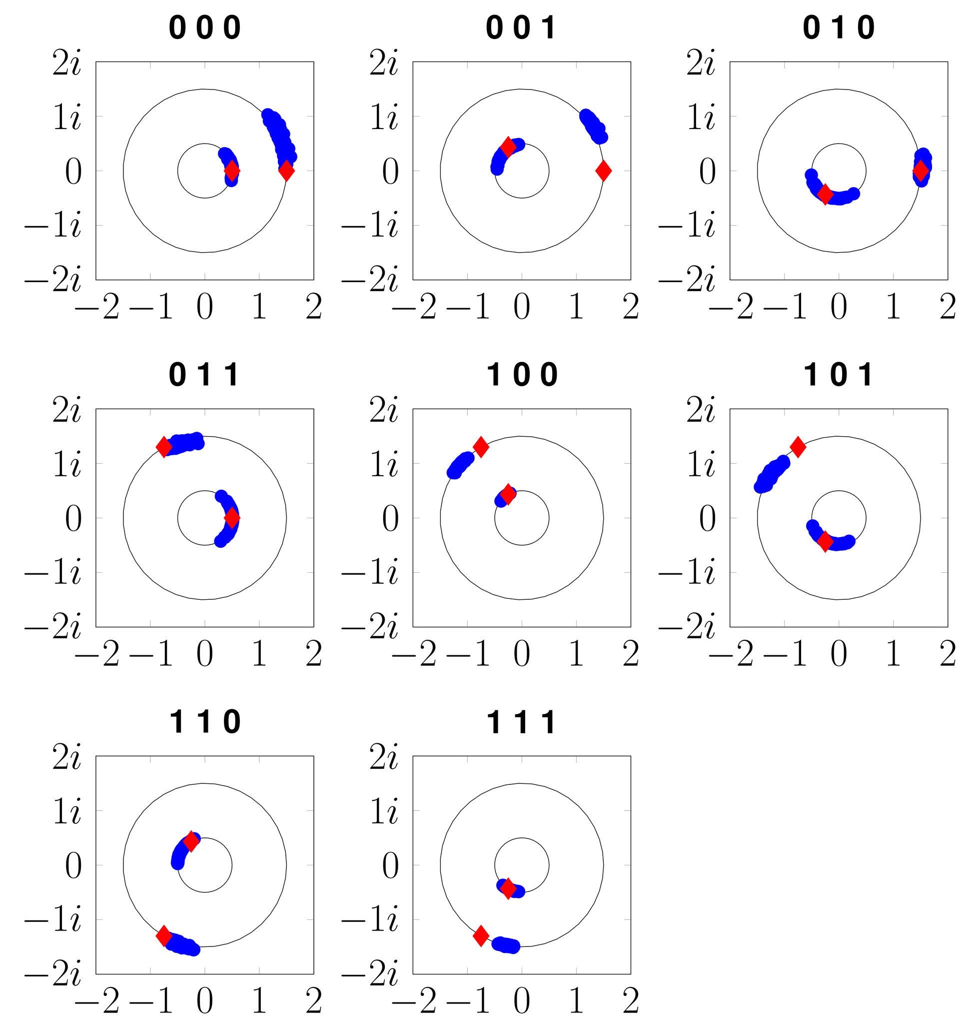


Figure 8: *Discrete spectral amplitude: normalized to λ_j with reference*

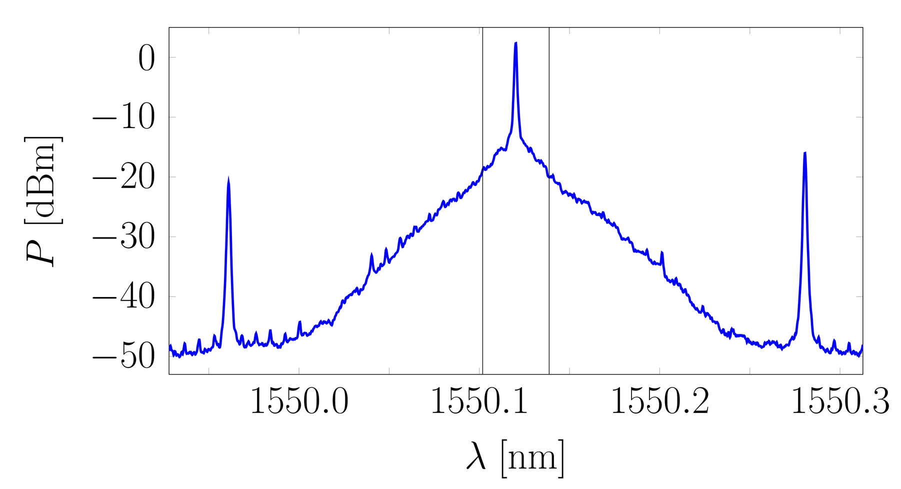


Figure 9: *Measured signal spectrum and 90% bandwidth*

⇒ Evaluation of 2^{10} bit de-Bruijn sequence with Fast Nonlinear Fourier Transform using Ablowitz-Ladik approximation [2] and 80 samples per symbol, 4.6 GHz bandwidth containing 90% of the signal power

⇒ Transmission over 75.46 km at 3 GBit/s with $3.6 \cdot 10^{-3}$ BER

⇒ Improved mapping (exchange of "011" and "100") would result in $2.9 \cdot 10^{-3}$ BER

⇒ Link attenuation is ~17.1 dB (~ 2 dB due to connectors and bending) requiring increased launch power compared to lossless theory

⇒ Best transmission at 0.67 dBm mean lauch power (offset of 6.8 dB to theoretical value without losses, 5.7dB reported in [5])

Summary and Outlook

⇒ **Successful transmission over 75.46 km TW RS fiber with 3 GBit/s**

⇒ **Investigation of influence of distributed raman amplification**

⇒ **Test of applicability of phase estimation schemes**

⇒ **Transmission over larger fiber distance with periodical amplification**

References

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[2] S. Wahls; V. Poor, "Fast Numerical Fourier Transforms", arXiv:1402.1605v2, 10/2014

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