Design Aspects of Multi-Soliton Pulses for Optical Fiber Transmission

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Abstract—We explain how to optimize the nonlinear spectrum of multi-soliton pulses by considering the practical constraints of transmitter, receiver, and lumped-amplified link. The optimization is applied for the experimental transmission of 2ns soliton pulses with independent on-off keying of 10 eigenvalues over 2000 km of NZ-DSF fiber spans.

I. INTRODUCTION

Nonlinear Frequency Division Multiplexing (NFDM) has recently been proposed to design an optical waveform better matched to the nonlinear propagation in a fiber [1]. In particular, the information bits are modulated in the so-called nonlinear Fourier spectrum which is then mapped to a pulse in time domain [1,2]. The spectrum is partitioned into continuous part and discrete part.

The discrete spectrum consists of a finite set of complex values, called eigenvalues, and the corresponding spectral amplitudes. This part represents the solitonic component of the pulse, in which the effects of Kerr nonlinearity and chromatic dispersion are balanced.

In an ideal lossless fiber, modeled by nonlinear Schrödinger Equation (NLSE), the propagation of soliton pulses follows simple principles in the nonlinear Fourier spectrum: the eigenvalues remain the same, and each spectral amplitude transforms linearly only based on its eigenvalue. This suggests to modulate or detect data over nonlinear spectrum.

The first realization of such a modulation was the on-off keying of first-order soliton which has been well-studied in the last three decades, see [3] and references therein. However, the spectral efficiency can be increased by using soliton pulses with several eigenvalues: On-off keying of up to 4 eigenvalues, located on imaginary axis, was experimentally shown [4] as well as the QPSK-modulation of spectral amplitudes for 2-soliton pulses [5,6]. More recently, two of the authors showed the transmission of soliton pulses with seven eigenvalues and QPSK-modulated spectral amplitudes [7].

In this paper, we briefly explain how to optimize the nonlinear spectrum of a multi-soliton pulse in order to reduce the perturbations caused by the practical constraints of transmitter, link and receiver. Applying the optimization, we demonstrate the experimental transmission of 2ns multi-soliton pulses carrying 10 information bits by on-off keying of 10 eigenvalues over 2033 km of NZ-DSF fiber spans.

II. OPTIMIZATION OF MULTI-SOLITON PULSES

We explain our sub-optimal method for the on-off keying modulation in which the spectral amplitudes can be freely tailored to meet the physical constraints. Consider the on-off keying of up to 10 eigenvalues for a target transmission length of at most 2100 km. Our objective is to optimize the discrete spectrum such that the following conditions are satisfied for all 2^{10} possible soliton pulses:

(i) Pairwise distance between eigenvalues is large enough for reliable detection in the presence of perturbations from lumped amplification [6], ASE noise, and numerical limitation of current NFT algorithms.

(ii) The largest pulse-width (duration) of all pulses must become minimum (highest transmission rate). We truncate the tails of each pulse outside a common interval T. To have a negligible inter-symbol interference (ISI), we choose T such that |s(t)/\sqrt{E_s}| < 0.01 for t \not\in T and for all solitons s(t) with energy E_s.

(iii) The bandwidth of multi-solitons is changing during the transmission. The largest bandwidth (BW) of all pulses must become minimum all over the transmission (highest spectral efficiency). We define bandwidth as the frequency range holding more than 99% of energy.

(iv) A further ISI may occur when Re{\lambda_i} \not= 0. There must be a negligible ISI between adjacent pulses during the transmission.

It is not yet fully understood which distribution of eigenvalues maximizes the spectral efficiency. This is because no analytic expression is yet available for bandwidth and pulse-width of multi-solitons and for perturbations of eigenvalues by noise and the lumped amplification. We consider here the simplest (but not the most efficient) distribution for eigenvalues: \lambda = \omega + j\sigma, with \omega = \{\pm 2, \pm 1, 0\} and \sigma = \{1, 2\}.

Fig. 1. Experimental setup with offline NFT-based detection.
The magnitude of spectral amplitudes, $q_d(\lambda)$, mainly controls the pulse-width and the phase of $q_d(\lambda)$ controls the bandwidth. To avoid ISI (condition (iv)), we set $|q_d(\lambda_i)| = A_d(\lambda_i) |\exp(\pm 2j\lambda_i^2z_L)|$, where $z_L$ is the maximum link length (2000 km) and $A_d(\lambda_i)$ is $|q_d(\lambda)|$ in $z_L/2$. In this case, a pulse will first be contracted and then eventually broadened to the same pulse-width it had at transmitter. To minimize the pulse-width, we optimize $A_d(\lambda_i)$. We numerically observe that the pulse-width becomes minimum if $|B_i| = |A_i| = 1$ in Darboux transformation for computing inverse nonlinear Fourier transform \cite{1,8}. Finally, we computed the pulse-width $T = 12$ (for standard nonlinear Schrödinger equation) which scales down to 2 ns in our transmission setup (5 Gbit/s).

The bandwidth (BW) of each soliton is important not only because of spectral efficiency, but also because of deterministic perturbations of eigenvalues in a lumped amplified link. It is shown in \cite{6} that the eigenvalues of the path-averaged solitons may fluctuate when their instantaneous BW are large. The same effect is shown here in Fig. 2 for two soliton pulse with the same 8 eigenvalues but different initial spectral amplitudes. Split-step Fourier method is used to simulate the pulse propagation in our experimental setup (Fig. 1) with NZ-DSF fiber with $\beta_2 \approx -5.75$ ps$^2$/km and $\gamma \approx 1.6$ W$^{-1}$/km and span length of 24.2 km. We first exclude noise in our simulation. Fig. 2 shows that the eigenvalues fluctuate when the BW gets large. The larger BW is, the larger fluctuations of eigenvalues are. In the presence of noise (assumed 50 GHz filtered noise with NF=5 dB), the soliton with larger eigenvalue fluctuations is more distorted. For each soliton, we should then find the spectral amplitudes which minimize the maximum BW over the link. We quantized the phase of $q_d$ to levels of $\pi/4$ and used the exhaustive search to find the soliton with minimum BW for all spans.

III. EXPERIMENTAL RESULTS AND CONCLUSION

The experimental setup is shown in Fig. 1. Following a 88GSa/s digital-to-analog converter (DAC), a drive signal is provided for a Mach-Zehnder IQ modulator which transmits a single polarization 0.5 Gbd stream into a link of up to 28 loops $(5 \times L_{\text{span}} = 72.6$ km) of NZ-DSF fiber with a mean launch power of about $-2.7$ dBm. We used homodyne detection with a low phase noise fiber laser (1 kHz linewidth). The received signal is coherently detected and sampled by an oscilloscope with 80GSa/s and 33 GHz bandwidth, followed by an offline data-aided phase and carrier offset correction.

A subset of $2^8$ solitons were randomly chosen such that each eigenvalue is “on” in one-half of pulses, and a “fair” number of $k$-soliton pulses are chosen, $1 \leq k \leq 10$. The pulse train is repetitively transmitted. We used Fourier Collocation (FC) method \cite{1} to detect the eigenvalues of each received pulse. The eigenvalues of all received pulses after 28 loops ($\approx 2033$ km) are plotted in Fig. 3. By mapping each pulse to 10 bits, we found the BER $\approx 8 \times 10^{-3}$.

In this paper, we briefly explained how the eigenvalues of a multi-soliton are sensitive to the BW in a periodically lumped amplified link and how to optimize a soliton pulse using the available degrees of freedom in spectral amplitudes.

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