A Novel Detection Strategy for Nonlinear Frequency-Division Multiplexing

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Abstract: A novel decision feedback detection strategy exploiting a causality property of the nonlinear Fourier transform is introduced. The novel strategy achieves a considerable performance improvement compared to previously adopted strategies in terms of Q-factor.

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1. Introduction

In recent years, novel transmission schemes based on the nonlinear Fourier transform (NFT) \(^1\) are attracting attention as a way to tame optical fiber nonlinearity, which limits the capacity of current optical fiber transmission systems. Indeed, nonlinear frequency-division multiplexing (NFDM) uses the NFT to encode information on the nonlinear spectrum, that evolves in a very simple way along the optical channel, free from any deterministic dispersive and nonlinear interference. However, due to their novelty and complexity, NFT-based systems are affected by some drawbacks still to be addressed. For a complete review about NFT and NFT-based transmission schemes we refer to \(^2\).

A specific and promising implementation of NFDM is the nonlinear inverse synthesis (NIS) technique based on vanishing boundary conditions and modulation of the continuous spectrum \(^3\). NIS is a nonlinear analogue of OFDM, from which it is obtained by replacing the inverse and direct FFT operations with a backward NFT (BNFT) and forward NFT (FNFT), respectively. It can be easily combined with spectrally efficient modulation formats, such as quadrature amplitude modulation (QAM), and with a modulation of the discrete spectrum to further increase spectral efficiency \(^4\). A major issue concerning NIS is the need of operating in burst mode by inserting a certain number of guard symbols between bursts of information symbols to emulate the vanishing boundary conditions of the NFT theory. This is an issue because guard symbols reduce the overall spectral efficiency. While the minimum number of guard symbols is set by the memory of the channel (in particular, by the accumulated dispersion), the number of information symbols can, in principle, be increased at will to mitigate the efficiency loss. However, it has been observed that the performance of NIS systems decreases as the burst length increases, such that only short burst lengths can be practically considered, with a significant reduction of spectral efficiency \(^5\). This peculiar effect, not present in conventional systems, is caused by a sort of signal-noise interaction taking place at the receiver (RX) when computing the NFT of the received noisy signal \(^6\). The effect is so detrimental to mask all the potential advantages of NFDM in terms of robustness to nonlinear interference. As a consequence, NFDM can not yet be considered an attractive replacement to conventional systems.

In this work, we propose a novel detection strategy for NFDM that, by exploiting a decision feedback scheme based on the BNFT (DF-BNFT), avoids the detrimental signal-noise interaction at the RX. Through numerical simulations, we show that the considered detection strategy achieves a Q-factor improvement of more than 7 dB compared to the previously proposed strategy based on the FNFT.

2. System description

The transmission scheme considered in this work is sketched in Fig. 1(a). As in the NIS scheme \(^3\), the transmitter (TX) encodes a burst of \(N\) symbols \(\{x_1, \ldots, x_N\}\) drawn from the \(M\)-ary QAM alphabet \(\{X_1, \ldots, X_M\}\) onto a QAM signal \(s(t)\), whose ordinary Fourier transform is then mapped on the continuous part of the nonlinear spectrum \(\rho(\lambda)\). Furthermore, before computing the BNFT to obtain the samples of the corresponding optical signal \(q(0,t)\), deterministic propagation effects (dispersion and nonlinearity) are precompensated by multiplying the nonlinear spectrum by \(\exp(j4\lambda^2L)\), where \(L\) is the link length.

In conventional NIS, the RX recovers a noisy version of the transmitted nonlinear spectrum \(\rho(\lambda)\) by computing the FNFT of the received optical signal \(q(L,t)\), and then makes decisions based on standard matched filtering and symbol-by-symbol detection. The improved detection scheme proposed in this work originates from the idea that, since a
to the inverse Fourier transform of its nonlinear spectrum
Levitan-Marchenko equation (an integral equation used to compute the BNFT [1]) and relates the optical signal

where \eta depends only on the first

that the accumulated optical noise can be modelled as additive white Gaussian noise (AWGN). To avoid an exponential
growth of the detector complexity with the burst length \(N\), a causality property of the NFT (more on this later) and a
decision feedback scheme are finally employed, obtaining the DF-BNFT detection scheme depicted in Fig. 1(a).

The causality property of the NFT, employed to derive the above detection strategy, can be derived from the
Gelfand-Levitan-Marchenko equation (an integral equation used to compute the BNFT [1]) and relates the optical signal \(q(t)\)
to the inverse Fourier transform of its nonlinear spectrum \(s(t)\). The property ensures that \(q(t)\) for \(t > -\tau\) depends
only on \(s(t)\) for \(t < \tau\). Thus, if \(s(t)\) is intersymbol interference (ISI)-free, the optical signal received after \(-t_k\)
depends only on the first \(k\) symbols \(x_1, \ldots, x_k\). Therefore, one can take a decision on the \(k\)-th symbol by using only
the portion of signal received after \(-t_k\) and the previously decided symbols \(\{x_1, \ldots, x_{k-1}\}\), avoiding ISI. Unfortunately,
as the converse property does not hold—the signal received before \(-t_k\) does not depend only on the remaining
symbols \(x_{k+1}, \ldots, x_M\)—the proposed strategy is suboptimum. The application of the property to our scheme is sketched
in Fig. 1(b), where it is shown that the optical signal generated from a sequence of 8 16-QAM symbols, and the signal
generated by only the first 6 symbols of the same sequence, are equal after time \(-t_6\). However, the shorter optical signal
has a non-zero tail before \(-t_6\) even if the corresponding QAM signal vanishes after \(t_6\). As regards the computational
cost, the detection of each burst requires \(M\) BNFT of the whole signal (at each step, trial waveforms are computed
only in a short time window), while the conventional FNFT-based strategy uses only 1 FNFT.

3. System performance

System performance has been evaluated through simulations for a 16-QAM modulation format. A Gaussian pulse
shape with normalized root mean square width 0.2 is chosen, such that the resulting QAM signal \(s(t)\) is practically
ISI-free. The symbol rate is \(R_s = 1/T_s = 50\, \text{GBd}\). The fiber channel, whose length is \(L = 2000\, \text{km}\), is characterized
by group velocity dispersion parameter \(\beta_2 = -20.39\, \text{ps}^2/\text{km}\), attenuation \(\alpha = 0.2\, \text{dB/km}\), and nonlinear coefficient
\(\gamma = 1.22 \, \text{W}^{-1}\text{km}^{-1}\). Polarization effects are neglected and ideal distributed amplification with spontaneous emission
factor \(\eta_{sp} = 4\) is considered along the channel. This idealized scenario ensures that the investigated effect is not masked
by other propagation effects, and that its impact and mitigation can be clearly observed. The bandwidth of both the

Fig. 1. (a) NFDM system with the novel DF-BNFT detection strategy; (b) example of the NFT causality property.
A train of Gaussian pulses, modulated with 16QAM symbols and almost ISI-free, before (on the left) and
after (on the right) the BNFT is shown. The solid red and the dashed blue curves refer to the case in which only
8 or 6 symbols, respectively, are considered to generate the signal.
digital-to-analog converter (DAC) and the analog-to-digital converter (ADC) is 100 GHz. To account for dispersion, 2000 guard symbols separate different bursts. As customary, the performance is expressed in terms of the Q-factor, defined as $Q_2^2 = 20\log_{10}[\sqrt{2}\text{erfc}^{-1}(2P_b)]$, where $P_b$ is the bit error probability measured by direct error counting. All digital operations, in particular both the BNFT and the FNFT, were computed with the accuracy required to avoid any numerical impact on simulation results. The rate efficiency term $\eta = N_b/(2000 + N_b)$ was used to take into account the spectral efficiency loss due to the insertion of 2000 guard symbols, as previously explained.

Fig. 2(a) reports the system performance as a function of the optical power, for the FNFT (dashed lines) and proposed DF-BNFT (solid lines) detection and different burst lengths. Firstly, Fig. 2(a) shows the typical behavior of NIS, confirmed also by theoretical studies [6]: the higher the burst length, i.e., the rate efficiency, the worse the performance. Secondly, the figure highlights a significant performance improvement of DF-BNFT with respect to FNFT detection (4.7 dB for $\eta = 11\%$, 7.4 dB for $\eta = 51\%$). Thirdly, despite the improvements, performance decay remains.

Fig. 2(b) compares, as a function of the rate efficiency, the best performance (at optimum power) obtained by NFDM systems using the two considered detection schemes with those obtained by conventional systems using ideal electronic dispersion compensation (EDC) and digital backpropagation (DBP). As can be seen, the improvement achieved by DF-BNFT detection, though significant with respect to FNFT detection, is still not sufficient to outperform conventional systems, as performance decay continues to worsen, rather than saturate as in conventional systems.

4. Conclusions

This work introduces a novel detection strategy for NFDM based on the backward NFT and a decision feedback scheme. The proposed DF-BNFT technique allows for a considerable advantage (more than 7 dB) with respect to a standard detection based on the forward NFT. The improvement, though not yet sufficient to make NFDM competitive with conventional systems, demonstrates that the critical NFDM limitations due to signal-noise interaction at the RX can be overcome, and paves the way for the advent of transmission paradigms customized for the nonlinear optical channel. Further improvements and complexity reduction of the proposed technique are currently under investigation.

References

[1] M. J. Ablowitz and H. Segur, Solitons and the inverse scattering transform, vol. 4 (SIAM, 1981).
[2] S. K. Turitsyn, J. E. Prilepsky, S. T. Le, S. Wals, L. L. Frumin, M. Kamalian, and S. A. Derevyanko, “Nonlinear fourier transform for optical data processing and transmission: advances and perspectives,” Optica 4, 307–322 (2017).
[3] S. T. Le, J. E. Prilepsky, and S. K. Turitsyn, “Nonlinear inverse synthesis for high spectral efficiency transmission in optical fibers,” Opt. Express 22, 26,720–26,741 (2014).
[4] V. Aref, S. T. Le, and H. Buelow, “Demonstration of fully nonlinear spectrum modulated system in the highly nonlinear optical transmission regime,” in “Proc. Europ. Conf. Optical Communication (ECOC) 2016,” Post-deadline paper.
[5] S. Civelli, E. Forestieri, and M. Secondini, “Why noise and dispersion may seriously hamper nonlinear frequency-division multiplexing,” IEEE Photonics Technology Letters 29, 1332–1335 (2017).
[6] S. A. Derevyanko, J. E. Prilepsky, and S. K. Turitsyn, “Capacity estimates for optical transmission based on the nonlinear fourier transform,” Nature Communications (2016).