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DOI
10.1364/OFC.2019.M3Z.13

Publication date
2019

Document Version
Accepted author manuscript

Published in
Proceedings of the 2019 Optical Fiber Communications Conference and Exhibition (OFC 2019)

Citation (APA)
Brehler, M., Mahnke, C., Chimmalgi, S., & Wahls, S. (2019). NFDMLab: Simulating nonlinear frequency division multiplexing in Python. In *Proceedings of the 2019 Optical Fiber Communications Conference and Exhibition (OFC 2019)* [M3Z.13] OSA - The Optical Society. https://doi.org/10.1364/OFC.2019.M3Z.13

NFDMLab: Simulating Nonlinear Frequency Division Multiplexing in Python

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Abstract: Fiber-optic transmission based on nonlinear frequency division multiplexing (NFDM) has received much attention in recent years. We introduce NFDMLab, an open source software package for simulating NFDM transmissions written in the Python language.

OCIS codes: 060.2330, 060.1660.

1. Overview

Nonlinear frequency division multiplexing (NFDM) is a novel approach to fiber-optic communication [1, 2] that significantly extends an idea by Hasegawa [3]. It rests on the observation that the ideal (loss- and noise-free) nonlinear Schrödinger equation (NSE) can be solved analytically using a so-called nonlinear Fourier transform (NFT) [4]. Their proposal is analogous to the conventional orthogonal frequency division multiplexing (OFDM) method for linear channels: *i)* data is modulated in a nonlinear Fourier spectrum; *ii)* an inverse NFT is used to generate the fiber input; *iii)* the receiver computes the NFT of the fiber output; *iv)* the nonlinear Fourier spectrum of the fiber input is recovered from that of the fiber output through simple division by the nonlinear channel frequency response. In an ideal fiber-optic channel described by the NSE, which does not account for losses or noises, but includes the Kerr effect, NFDM recovers the data *exactly*, without interference. This unique feature has attracted much attention in recent years [5].

The key dimensions engineers need to take into account when designing a conventional communication system are duration and bandwidth, which are related to each other through the uncertainty principle. NFDM is built on a nonlinear transform, the NFT. The loss of linearity in NFDM introduces a third dimension that is connected to the other two – power. This requires engineers to rethink many of the building blocks of a typical communication system such as, e.g., power control, carrier design, or equalization. The fact that the NFT is also richer than the conventional Fourier transform (there can be an additional "discrete spectrum" indicating solitonic components that has no linear analogue), and has several mathematically equivalent representations, also contributes to this issue. Consequently, a myriad of different NFDM system designs has been proposed during the last few years. Since NFDM is a young technology, it is not yet clear what the best design choices are; they might even not have been invented yet.

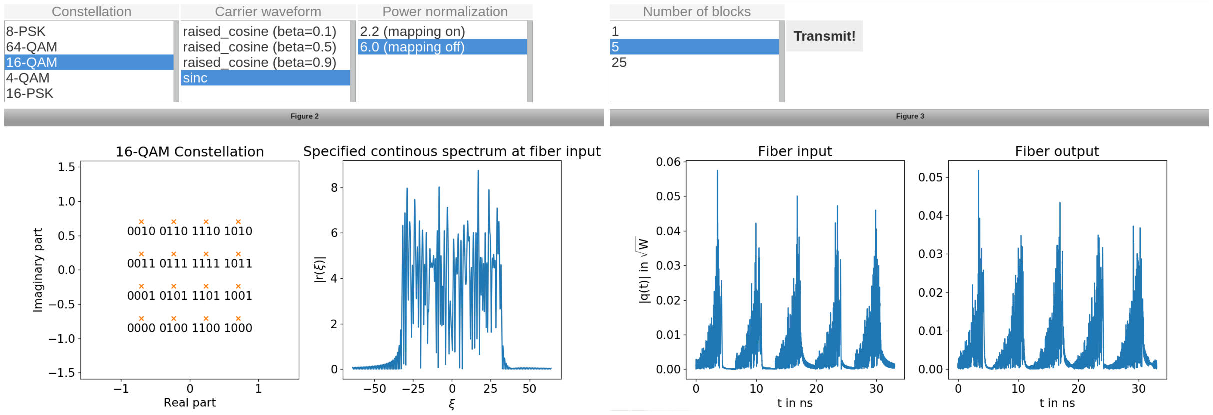
The demonstration will introduce a highly reconfigurable open source simulation environment for NFDM systems called *NFDMLab* that can be controlled using a simple and intuitive graphical environment built on the celebrated *Jupyter notebook* technology [6, 7]. The simulation lets users choose different constellation formats, modulation techniques, carrier shapes, and fiber and amplifier models in an interactive way. It provides visualizations for the whole transceiver chain and provides standard quality measures such as the uncoded bit error ratio.

2. Innovation

Starting to work in the area of NFDM currently requires a significant investment of time. Even though a software library for numerical computation of (inverse) NFTs has recently been published [8], setting up a complete NFDM transceiver requires a lot more work. Moreover, as explained above, there is a myriad of different variants of NFDM.

The demonstration addresses these issues. Our open source software environment NFDMLab allows to investigate many different variants of NFDM in a simple and intuitive way, even if there is no prior experience with NFDM; since NFDMLab is open source, engineers can use it as a starting point for their own investigations. As there seems to be no publicly available implementations of NFDM, neither open- nor closed-source, we believe that NFDMLab fills a gap that currently keeps many researchers from engaging the field. Furthermore, as researchers are welcome to contribute improvements to NFDMLab, it has the potential to develop into a well-tested reference implementation.

This project has received funding from the European Research Council (ERC) under the European Unions Horizon 2020 research and innovation programme (grant agreement No 716669).



Constellation

8-PSK
64-QAM
[✓ 16-QAM]
4-QAM
16-PSK

Carrier waveform

raised_cosine (beta=0.1)
raised_cosine (beta=0.5)
raised_cosine (beta=0.9)
[✓ sinc]

Power normalization

2.2 (mapping on)
[✓ 6.0 (mapping off)]

Number of blocks

1
[✓ 5]
25

(a) Constellation and modulation settings

(b) Fiber-optic transmission

Fig. 1: Screenshots taken from a NFDMLab Jupyter notebook (work in progress).

3. Relevance to OFC

Fiber-optic transmission using NFDM is a timely and innovative topic that is of high interest at OFC, as is demonstrated by many invited presentations in the upcoming as well as previous OFCs [9–13]. The 2018 IEEE Information Theory Society Paper Award was awarded to [1], while the recent survey paper [5] is already highly cited according to Web of Science[1]. Being a young and unconventional field, NFDM offers many opportunities for interesting research.

4. Demonstration

Objective and Contents The objective of the demo is to introduce the open source simulation package NFDMLab to the public. Attendants will be able to interact with the user interface built on the Jupyter Notebook technology [6, 7]. Jupyter notebooks allow to mix static content (text, pictures, ...) with source code that the user can manipulate (directly and through widgets) and run interactively. We provide three notebooks that loosely recreate the three NFDM experiments reported in [14–16]. These experiments were chosen as they represent three quite different types of NFDM systems. The system in [14] is a multi-soliton transceiver that utilizes only the discrete part of the NFT. On the other hand, only the continuous part of the NFT was utilized in [15]. In [16], a different representation of the continuous part is used. Fig. 1 depicts parts of one of the provided Jupyter notebooks, where we remark that they are still work in progress. The final version might look different. The source code of NFDMLab will be released after the demo at `https://github.com/FastNFT` under the terms of the GNU General Public License, version 2.

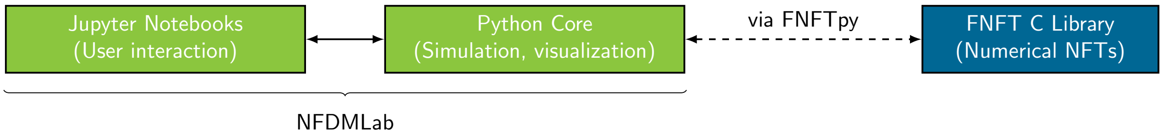


Fig. 2: Overview of components in NFDMLab.

Configuration and Main Elements The structure of NFDMLab is illustrated in Fig. 2. The core of NFDMLab is written in Python, a highly popular and simple to learn programming language. The core realizes all of the simulation and visualization tasks, using standard libraries that can be installed with Python's package manager pip (numpy, scipy, matplotlib). It is organized in modules, each of which provides a typical functionality of a fiber-optic transmission system. A typical simulation workflow is depicted in Fig. 3, where the cyan-colored boxes indicate individual modules. The novelty lies in the NFDM (de-)modulator modules, which map blocks of symbols drawn from a constellation to finite-duration waveforms $q(t)$ using NFDM techniques, and vice versa. NFDMLab is, to the best of our knowledge, the first publicly available software package that provides such functionality. The NFDM (de-)modulator modules utilize the C software library FNFT [8] to compute (inverse) NFTs, which is interfaced using the Python wrapper

[1] Received via `https://apps.webofknowledge.com` on 10/30/19: "As of May/June 2018, this highly cited paper received enough citations to place it in the top 1% of the academic field of Physics based on a highly cited threshold for the field and publication year."

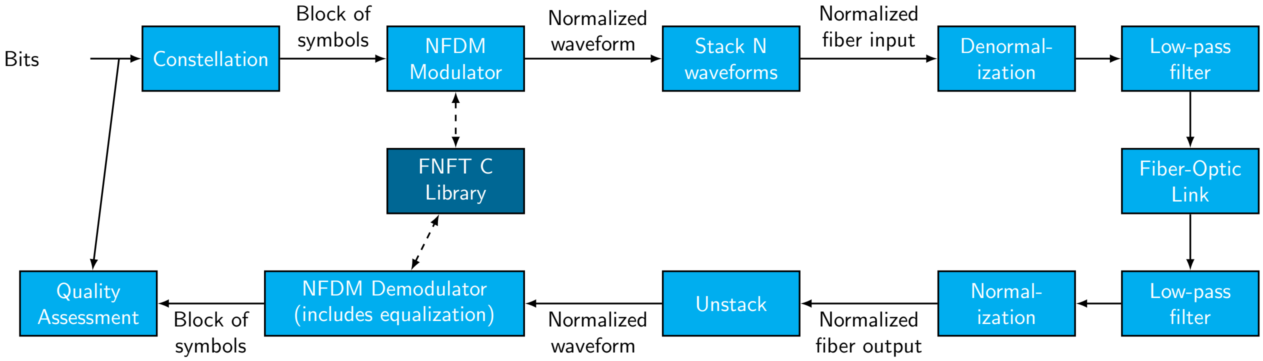


Fig. 3: Schematic representation of the Python core. The arrows indicate a typical workflow.

FNFTpy [17]. The fiber-optic link is able to simulate EDFA amplification (with flat gain and optionally with noise) and Raman amplification (without noise) in multi-span single-mode fiber links. The nonlinear propagation within the link is simulated with a pythonized and a slightly modified port of SSPROP [18]. Raman amplification is simulated in a simplistic way by using a predefined z-dependent gain. More advanced approaches like [19] are not part of NFDMLab, but can be integrated due to NFDMLabs modular structure. The (de-)normalization modules support path-averaging techniques that have been shown to improve the performance of NFDM-based transmission schemes in [20, 21]. The quality assessment module provides standard quality measures such as constellation diagrams or (uncoded) bit error ratios.

The components of the core are assembled in different configurations using Jupyter notebooks that were already described earlier. These notebooks let the user interact with the Python core in a simple and intuitive way.

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