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Original
Digital Signal Processing for Longitudinal Power Monitoring and Nonlinear Interference Estimation / Pilori, Dario. - ELETTRONICO. - (In corso di stampa), pp. 1-4. (2026 European Conference on Optical Communications (ECOC) Málaga (Spa) 20-24 September 2026).

Publisher:
IEEE

Published
DOI:

Digital Signal Processing for Longitudinal Power Monitoring and Nonlinear Interference Estimation

Dario Pilori$^{(1)}$

$^{(1)}$ Dipartimento di Elettronica e Telecomunicazioni (DET), Politecnico di Torino, Italy, dario.pilori@polito.it

Abstract *Longitudinal Power Monitoring (LPM) enables DSP-based receiver-side reconstruction of the optical power evolution. This paper reviews recent LPM techniques and implementations, and demonstrates its use for nonlinear interference estimation and span-wise power optimization, enabling accurate, model-light, and scalable performance monitoring in real-world optical networks. ©2026 The Author.*

Introduction

Fiber Longitudinal Power Monitoring (LPM) techniques had a remarkable evolution in a (relatively) short timeframe. From the first introduction of the concept at ECOC 2019 [1], to its first real-time demonstration [2], less than 7 years have passed. This was driven both by technological improvements of coherent transceivers and by the strong interest within vendors and network operators in this technology.

Therefore, this invited presentation focuses on the main techniques and recent demonstrations of LPM, with a particular focus on one of its key applications: the estimation of nonlinear interference (NLI) at the receiver.

Longitudinal Power Monitoring

The goal of LPM is the estimation of the optical power evolution (power profile) of a channel, using only information already available at the receiver [3]. This exploits the well-known non-commutativity between fiber's chromatic dispersion and Kerr nonlinear effect [4], which is the same principle underlying the Split-Step Fourier Method (SSFM) [5] and Digital Back-Propagation [6]. In fact, earlier demonstrations of LPM [3, 7] were based on a full time-domain simulation of the transmitted channel (e.g., based on the SSFM), and tried to find the link's power profile that best approximates the received signal. This channel model allowed consideration of not only dispersion and Kerr effect, but also other effects, such as filtering by Wavelength Selective Switches (WSSs). However, the estimation performance of WSS filtering effects was poor, and the overall computational complexity was unsuitable for a real-time implementation in the transceivers.

Then, LPM demonstrations focused on two main techniques, which enable the estimation of a power profile with a closed-form expression, without relying on expensive optimizations: Correlation-based Method (CM) [7] and Linear Least-Squares (LLS) [8]. Both methods are based on a first-order regular perturbation approximation [9] of nonlinear propagation, which is known to be valid for many practical cases in optical communications. It was later shown that the difference between those two methods is rather small, and a LLS solution can be obtained from a CM profile [10]. In practice, LLS is often preferred due to the absence of a deconvolution procedure, and its direct connection to NLI estimation.

Main applications

The most straightforward and immediate application of LPM is the localization of anomalies within a link, achieving similar results to an Optical Time-Domain Reflectometer (OTDR). This has been studied in detail [11], and has been demonstrated in real-world field trials [12]. However, LPM has been successfully adopted to monitor other network parameters, such as Polarization-Dependent Loss (PDL) [13], Raman amplification [14, 15], Multipath Interference [16], Differential-Group Delay [17], power ripple [18] and State of Polarization (SOP) [19]. In general terms, LPM can detect (and localize) events that have an impact on the interplay between NLI and dispersion. The stronger the effect, the easier is to monitor it using LPM. LPM telemetry data can be used either for debugging and (manual) tuning of the link, or for automated network operation, e.g. for self-healing networks [20] or to detect attacks [21]. In fact, the use of LPM telemetry in networking scenarios remains an active topic of research, with several contributions in leading research areas.

Real-time implementation

In the last years, the community's interest gradually shifted from finding new applications for LPM, to its real-time implementation. In fact, even if LLS-LPM can obtain a power profile with a closed-form expression [8], its computational complexity and memory requirements make real-time implementation unfeasible in the DSP. For this reason, most of the demonstrations with commercial transceivers [22, 23] relied on offline post-processing on an external computer.

A first implementation was presented in [24], where CM-LPM was accelerated by a Floating-Point Gate Array (FPGA) board. Then, in [20] the authors presented a distributed architecture that allowed reducing the overall complexity of a CM-LPM profile computation. In general, a key requirement for LPM profile computation is the availability of the transmit sequence. While Forward Error Correction (FEC) codes are able to obtain an error-free estimate of it, the presence of large interleavers make it difficult to temporally align this sequence to the received (noisy) constellation. A remarkable result was the discovery that simple hard-decision on the received samples introduces a static shift in the power profile, which can be estimated and compensated. Recent work has shown this both for CM [22] and LLS [25] LPM. Finally, the most recent real-time demonstration, implemented directly on NTT's DSP chip [2] relies on a closed-form expression of the spatial correlation function [26], which allows a significant reduction of the memory requirements of LLS-LPM.

Nonlinear Interference Estimation

One of the most important telemetry metrics for the network operator is the current NLI power affecting a channel. In fact, the knowledge of this parameter enables straightforward optimization of the channel launch power [27], without relying on additional knowledge of network parameters. Unfortunately, NLI estimation at the receiver is notoriously hard, because it requires distinguishing between amplified spontaneous emission (ASE) and NLI, which have similar statistical properties [28]. However, LPM, to compute the power profile, must estimate the NLI power affecting the receiver. Therefore, LLS-LPM, in principle, can (also) be used for NLI estimation. This application was first theorized in [3], and the first simulation-based demonstration was presented at OFC 2024 [29]. However, this demonstration relied on a (slow) SSFM-based method, and it assumed the simultaneous capture of all WDM channels in the network.

The first step towards a practical use of this method was presented in [30], where we were able to obtain a reliable experimental estimation of NLI power in realistic conditions: only one WDM channel (among many) was received and captured. This approach was then further tested and validated in more scenarios in [23]. The key insight is that LPM-based NLI estimation on a single WDM channel estimates only a portion of NLI, namely the Self-Channel Interference (SCI) [27]. Therefore, the remaining step is evaluating the ratio between the SCI and the rest of NLI, which is mainly Cross-Channel Interference (XCI). In [30] we adopted a very simple analytical expression, derived from the GN-model [31], while in [23] we also used a complete NLI model [32]. This addition, referred to as the ζ scaling factor, accounts for the ratio between SCI and cross-channel contributions. This algorithm has been shown to be reliable across different, realistic, network scenarios [23, 30]. Moreover, a lower-complexity version was published in [33]. Thus, LPM enables receiver-side NLI estimation using only a single observed channel, with limited reliance on prior network knowledge.

Power optimization

The main goal of NLI estimation is the optimization of the channel launch power. Thanks to the "3-dB rule-of-thumb" [27], which states that the launch power is optimized when the Optical Signal-to-Noise-Ratio (OSNR) is approximately 3-dB smaller than the nonlinear SNR, this operation is straightforward. In fact, quite remarkably, even if derived more than 20 years ago in very ideal conditions [34, 35], this rule-of-thumb has also been proved in modern scenarios [36]. However, the key limitation of LPM-based NLI estimation is that the nonlinear SNR is an end-to-end metric, i.e. it gives the total NLI power affecting the channel overall in the link. Therefore, this approach is effective only in the presence of a homogeneous link, i.e. made by identical fiber spans and amplifiers.

Thanks to the nature of LPM, this limitation can be overcome by adopting a "disaggregated" approach. This means obtaining a *per-span* estimate of NLI power. Then, adopting the LOGO [27] approach, the link performance is optimized when the power in each span is (individually) optimized. A first approach to disaggregate the LPM estimates was presented in [37] on CM-LPM. Then, the same idea was applied to the LLS method [38, 39] to achieve a span-wise power optimization. These results are also remarkable since, to the best of the author's knowledge, LPM-based NLI estimation is the only NLI estimation method that achieves disaggregated NLI estimation.

Conclusions

In this paper, we reviewed the main features of LPM, with a special focus on the LLS algorithm. After reviewing the main applications and real-time implementations, we focused on the key application of nonlinear interference estimation. We showed that LPM-based NLI estimation provides accurate estimates across several realistic network scenarios, and it has been extensively validated experimentally. Moreover, for channel launch power optimization, LPM-based NLI estimation can also give a disaggregated metric, allowing a precise span-wise optimization. Overall, these advances indicate that real-time LPM is no longer a theoretical possibility, but a viable feature for next-generation coherent transceivers and autonomous optical networks.

Acknowledgements

This research activity was partially sponsored by CISCO under an SRA contract.

The author would like to thank L. Andrenacci, G. Bosco, Y. Jiang, P. Poggiolini and A. M. Rosa Brusin from DET - Politecnico di Torino; A. Nespola and S. Straullu from LINKS Foundation; L. Della Chiesa, F. Forghieri, R. Pastorelli and S. Piciaccia from CISCO.

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