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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.

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References

[1] T. Tanimura, K. Tajima, S. Yoshida, S. Oda, and T. Hoshida, "Experimental demonstration of a coherent receiver that visualizes longitudinal signal power profile over multiple spans out of its incoming signal", in *45th European Conference on Optical Communication (ECOC 2019)*, 2019, pp. 1–4. DOI: 10.1049/cp.2019.1031.

[2] T. Sasai et al., "First coherent DSP and pluggable transceiver capable of distance-resolved, longitudinal power monitoring", in *Optical Fiber Communication Conference (OFC) Postdeadline Papers 2026*, Optica Publishing Group, 2026, Th4B.4.

[3] T. Sasai, M. Nakamura, E. Yamazaki, S. Yamamoto, H. Nishizawa, and Y. Kisaka, "Digital longitudinal monitoring of optical fiber communication link", *Journal of Lightwave Technology*, vol. 40, no. 8, pp. 2390–2408, 2022. DOI: 10.1109/JLT.2021.3139167.

[4] G. P. Agrawal, *Nonlinear fiber optics; 6th edition*. London: Academic Press, 2019.

[5] D. Pilori, M. Cantono, A. Carena, and V. Curri, "FFSS: The fast fiber simulator software", in *2017 19th International Conference on Transparent Optical Networks (ICTON)*, 2017, pp. 1–4. DOI: 10.1109/ICTON.2017.8025002.

[6] E. Ip and J. M. Kahn, "Compensation of dispersion and nonlinear impairments using digital backpropagation", *Journal of Lightwave Technology*, vol. 26, no. 20, pp. 3416–3425, 2008. DOI: 10.1109/JLT.2008.927791.

[7] T. Tanimura, S. Yoshida, K. Tajima, S. Oda, and T. Hoshida, "Fiber-longitudinal anomaly position identification over multi-span transmission link out of receiver-end signals", *Journal of Lightwave Technology*, vol. 38, no. 9, pp. 2726–2733, 2020. DOI: 10.1109/JLT.2020.2984270.

[8] T. Sasai, M. Takahashi, M. Nakamura, E. Yamazaki, and Y. Kisaka, "Linear least squares estimation of fiber-longitudinal optical power profile", *Journal of Lightwave Technology*, vol. 42, no. 6, pp. 1955–1965, 2024. DOI: 10.1109/JLT.2023.3327760.

[9] A. Vannucci, P. Serena, and A. Bononi, "The rp method: A new tool for the iterative solution of the nonlinear schrodinger equation", *Journal of Lightwave Technology*, vol. 20, no. 7, pp. 1102–1112, 2002. DOI: 10.1109/JLT.2002.800376.

[10] T. Sasai, E. Yamazaki, and Y. Kisaka, "Performance limit of fiber-longitudinal power profile estimation methods", *Journal of Lightwave Technology*, vol. 41, no. 11, pp. 3278–3289, 2023. DOI: 10.1109/JLT.2023.3234534.

[11] T. Sasai, S. Y. Set, and S. Yamashita, "Design of fiber-longitudinal optical power monitor", *Journal of Lightwave Technology*, vol. 43, no. 5, pp. 2192–2202, 2025. DOI: 10.1109/JLT.2024.3487862.

[12] T. Sasai et al., "Optical link tomography: First field trial and 4D extension", *Journal of Lightwave Technology*, vol. 43, no. 24, pp. 10 776–10 787, 2025. DOI: 10.1109/JLT.2025.3620127.

[13] L. Andrenacci, G. Bosco, and D. Pilori, "PDL localization and estimation through linear least squares-based longitudinal power monitoring", *IEEE Photonics Technology Letters*, vol. 35, no. 24, pp. 1431–1434, 2023. DOI: 10.1109/LPT.2023.3331110.

[14] L. Andrenacci et al., "Experimental demonstration of linear least squares-based longitudinal power monitoring over a raman-amplified C+L link", in *ECOC 2024; 50th European Conference on Optical Communication*, 2024, pp. 503–506.

[15] R. Kaneko, T. Sasai, M. Nakamura, F. Hamaoka, and E. Yamazaki, "Visualizing longitudinal evolution of forward- and backward-raman-amplified power and gain", in *Optical Fiber Communication Conference (OFC) 2025*, Optica Publishing Group, 2025, W3E.3. DOI: 10.1364/OFC.2025.W3E.3.

[16] C. Hahn, J. Chang, and Z. Jiang, "Localization of reflection induced multi-path-interference over multi-span transmission link by receiver-side digital signal processing", in *Optical Fiber Communication Conference (OFC) 2022*, Optica Publishing Group, 2022, Th1C.3. DOI: 10.1364/OFC.2022.Th1C.3.

[17] C. Hahn, J. Chang, and Z. Jiang, "Estimation and localization of DGD distributed over multi-span optical link by correlation template method", in *Optical Fiber Communication Conference (OFC) 2024*, Optica Publishing Group, 2024, W1B.2. DOI: 10.1364/OFC.2024.W1B.2.

[18] J. Chang, C. Hahn, Q. Guo, and Z. Jiang, "In-band power ripple detection and localization using longitudinal power monitoring", *Journal of Lightwave Technology*, vol. 43, no. 17, pp. 8108–8115, 2025. DOI: 10.1109/JLT.2025.3582219.

[19] C. Hahn, J. Chang, Q. Guo, and Z. Jiang, "Detection and localization of slow SOP changes via longitudinal DGD monitoring", in *Optical Fiber Communication Conference (OFC) 2026*, Optica Publishing Group, 2026, M4K.2.

[20] A. Pacini et al., "Longitudinal power profile monitoring telemetry enabling self-healing optical networks", *J. Opt. Commun. Netw.*, vol. 17, no. 7, pp. 580–589, Jul. 2025. DOI: 10.1364/JOCN.555840.

[21] M. Sena et al., "Exploring the potential of longitudinal power monitoring for detecting physical-layer attacks [invited]", *J. Opt. Commun. Netw.*, vol. 17, no. 7, pp. C30–C40, Jul. 2025. DOI: 10.1364/JOCN.554766.

[22] J. Chang, C. Hahn, X. Tang, T. Zhao, W. C. Ng, and Z. Jiang, "Demonstration of longitudinal power profile estimation using commercial transceivers and its practical consideration", in *49th European Conference on Optical Communications (ECOC 2023)*, vol. 2023, 2023, pp. 1334–1337. DOI: 10.1049/icp.2023.2539.

[23] D. Pilori, S. Straullu, A. Nespola, S. Piciaccia, and G. Bosco, "LPM-based NLI estimation over heterogeneous links: Analysis and comparison", *Journal of Lightwave Technology*, pp. 1–8, 2026. DOI: 10.1109/JLT.2026.3662004.

[24] K. Sone et al., "Implementation of RX-side DSP-based fiber-longitudinal optical power profile monitoring for optical network tomography", in *2022 27th OptoElectronics and Communications Conference (OECC) and 2022 International Conference on Photonics in Switching and Computing (PSC)*, 2022, pp. 1–4. DOI: 10.23919/OECC/PSC53152.2022.9850139.

[25] L. Andrenacci et al., "Implementation penalties for nonlinear interference estimation with linear least squares longitudinal power monitoring", in *Optical Fiber Communication Conference (OFC) 2025*, Optica Publishing Group, 2025, W3E.5. DOI: 10.1364/OFC.2025.W3E.5.

[26] T. Sasai and E. Yamazaki, “Closed-form expression for spatial correlation function of nonlinear fiber propagation and its applications to longitudinal power monitoring”, in *Optical Fiber Communication Conference (OFC) 2026*, Optica Publishing Group, 2026, Tu3A.5.

[27] P. Poggiolini, G. Bosco, A. Carena, V. Curri, Y. Jiang, and F. Forghieri, “The GN-model of fiber non-linear propagation and its applications”, *Journal of Lightwave Technology*, vol. 32, no. 4, pp. 694–721, 2014. DOI: 10.1109/JLT.2013.2295208.

[28] D. Pilori, L. Andrenacci, and G. Bosco, “Estimating the nonlinear interference at the receiver: Methods and pitfalls”, in *Advanced Photonics Congress (IPR, Networks, NOMA, SOLITH, SPPCom)*, Optica Publishing Group, 2025, SpTh2F.3. DOI: 10.1364/SPPCOM.2025.SpTh2F.3.

[29] I. Kim, K. Sone, O. Vassilieva, S. Oda, P. Palacharla, and T. Hoshida, “Nonlinear SNR estimation based on power profile estimation in hybrid Raman-EDFA link”, in *Optical Fiber Communication Conference (OFC) 2024*, Optica Publishing Group, 2024, Th1F.6. DOI: 10.1364/OFC.2024.Th1F.6.

[30] L. Andrenacci, G. Bosco, Y. Jiang, A. Nespola, S. Piciaccia, and D. Pilori, “Dsp-based nonlinear interference estimation using linear least squares longitudinal power monitoring”, *Journal of Lightwave Technology*, vol. 43, no. 8, pp. 3536–3546, 2025. DOI: 10.1109/JLT.2025.3532100.

[31] V. Curri et al., “Design strategies and merit of system parameters for uniform uncompensated links supporting Nyquist-WDM transmission”, *Journal of Lightwave Technology*, vol. 33, no. 18, pp. 3921–3932, 2015. DOI: 10.1109/JLT.2015.2447151.

[32] P. Poggiolini, Y. Jiang, Y. Gao, and F. Forghieri, “Polynomial closed form model for ultra-wideband transmission systems”, *Journal of Lightwave Technology*, pp. 1–18, 2026. DOI: 10.1109/JLT.2026.3678322.

[33] Y. Jiang et al., “Low-complexity nonlinear interference estimation using WRP1-aided coarse step-size power profile estimation”, *Journal of Lightwave Technology*, vol. 44, no. 4, pp. 1259–1269, 2026. DOI: 10.1109/JLT.2025.3635147.

[34] G. Bosco, A. Carena, R. Cigliutti, V. Curri, P. Poggiolini, and F. Forghieri, “Performance prediction for WDM PM-QPSK transmission over uncompensated links”, in *Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2011*, Optica Publishing Group, 2011, OThO7. DOI: 10.1364/OFC.2011.OThO7.

[35] E. Grellier and A. Bononi, “Quality parameter for coherent transmissions with Gaussian-distributed nonlinear noise”, *Opt. Express*, vol. 19, no. 13, pp. 12 781–12 788, Jun. 2011. DOI: 10.1364/OE.19.012781.

[36] Y. Jiang, F. Forghieri, S. Piciaccia, G. Bosco, and P. Poggiolini, “Optimum launch power in multiband systems”, in *ECOC 2024; 50th European Conference on Optical Communication*, 2024, pp. 930–933.

[37] C. Hahn, J. Chang, and Z. Jiang, “Trace back method of the distributed noise in optical transmission systems”, *IEEE Photonics Technology Letters*, vol. 37, no. 2, pp. 81–84, 2025. DOI: 10.1109/LPT.2024.3512184.

[38] T. Sasai et al., “Optical network tomography over live production network in multi-domain environment”, in *2025 European Conference on Optical Communications (ECOC)*, 2025, pp. 1–4. DOI: 10.1109/ECOC66593.2025.11263088.

[39] D. Pilori, L. Andrenacci, S. Straullu, A. Nespola, and G. Bosco, “Enhancing optical link performance with per-span nonlinear SNR estimation enabled by longitudinal power monitoring”, in *2025 11th International Conference on Computer and Communications (ICCC)*, 2025, pp. 1937–1940. DOI: 10.1109/ICCC68654.2025.11437588.