Abstract

This thesis investigates advanced signal processing techniques for optical performance monitoring (OPM) in long-haul and metropolitan fiber-optic networks. It demonstrates how the digital signal processing (DSP) already embedded in standard coherent transceivers can be leveraged to enable smarter, cost-effective, and flexible OPM solutions, meeting the evolving needs of modern high-capacity optical networks. The research is organized around two key areas of DSP-based OPM: digital longitudinal monitoring and optical fiber sensing.

Chapter 1 introduces the foundations of DSP in coherent transceivers and gives an overview of the historical development of OPM. It also presents the key concepts of digital longitudinal monitoring, focusing on longitudinal power monitoring algorithms, and explores the use of optical fiber for environmental sensing applications.

Chapter 2 presents novel applications of longitudinal power monitoring (LPM), including polarization-dependent loss (PDL) estimation and localization, as well as its extension to digital subcarrier-multiplexing (DSCM) and ultra-wideband (UWB) systems. A new PDL estimation algorithm based on least-linear squares (LLS) LPM is introduced and shown to provide accurate localization and magnitude estimates across a wide range of PDL configurations. Comparisons with a CM-based alternative highlight trade-offs between sensitivity and complexity. Further, LPM is applied to DSCM systems, demonstrating comparable accuracy despite increased profile noise. Experimental validation over a C+L band UWB link with Raman amplification confirms LPM's accuracy in tracking power evolution, underscoring its practical value in more complex transmission scenarios.

Chapter 3 proposes a new method for estimating Kerr-induced nonlinear interference (NLI) using only receiver-side DSP data. Integrated within the LLS-based LPM algorithm, the method is validated through simulations and experiments over 300-km and 1100-km links. It reliably estimates NLI power and predicts optimal launch conditions. Limitations related to estimating only the self-channel interference (SCI) component are addressed via analytical correction factors. Additionally, the chapter discusses implementation aspects, including

power offsets from using hard-decision symbols, and proposes a BER-based correction that maintains estimation accuracy within 0.3 dB.

Chapter 4 explores DSP-based fiber sensing using coherent receivers, comparing two length-integrated approaches: state-of-polarization (SOP) and optical phase-based sensing. SOP estimation is first analyzed for accuracy, with post-processing via moving averages shown to reduce angular deviation below 2° across different OSNR levels. Experimental and simulation results demonstrate strong consistency, confirming the method's robustness and hardware-independence. A comparative study over a 32-km urban link reveals superior performance of SOP-based sensing in noisy environments. While phase-based sensing suffers from environmental noise and demands narrow-linewidth lasers, SOP extraction can be implemented with minimal DSP modifications and no hardware upgrades, making it more suitable for real-world deployment.

Overall, this thesis establishes DSP-based OPM as a key enabler for next-generation optical networks and fiber sensing. By reusing existing DSP infrastructure, this approach reduces complexity and cost while supporting flexible, multi-impairment monitoring. The proposed methods provide practical insights and validated solutions for deploying adaptive, intelligent monitoring strategies, paving the way toward elastic optical networks and integrated sensing platforms.