Advanced Digital Signal Processing and Artificial Neural Networks in Modern Optical Communications

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The main focus of this thesis is to investigate the combination of advanced digital signal processing (DSP) and artificial neural network (ANN) algorithms to enhance the capabilities of modern optical communication systems.

The first part of the thesis focuses on short-reach optical data center intra-connects up to 100 meters. These links, which utilize multi-mode fiber (MMF) and vertical-cavity surface-emitting lasers (VCSELs), require nonlinear digital pre-distortion (DPD) to efficiently compensate for the nonlinear effects that impair the transmitted signals. The thesis proposes an ANN-based optimization algorithm for nonlinear DPD, leveraging the end-to-end (E2E) learning concept. The developed methodology has been experimentally shown to enhance the performance of VCSEL-MMF optical links at data rates exceeding 100 Gbps per wavelength (λ). In particular, this thesis presents an E2E learning architecture based on the transmitter and dispersion eye closure quaternary (TDECQ), a key quality metric for optical links employing the PAM4 modulation format. Experimental results show that the TDECQ-based E2E learning architecture enables VCSEL-based optical transmitters to meet the IEEE Std 802.3db$^{\text{TM}}$-2022 TDECQ specifications for net 100 Gbps/λ. Furthermore, the proposed E2E learning scheme significantly outperforms conventional ANN-based algorithms for nonlinear DPD optimization, such as direct learning, with a consistent performance gain of more than 1 dB in several VCSEL nonlinear driving conditions.

In the second part, the thesis focuses on developing an ANN-based DSP scheme for monitoring inter-channel interference (ICI) in optical transport networks (OTNs) leveraging elastic wavelength division multiplexing (WDM). The efficiency of flexible OTNs can be increased by maximizing the throughput of each individual channel, provided that the positions of neighboring channels are known. Firstly, the thesis investigates the use of an ANN-based algorithm that leverages the histograms of the in-phase and quadrature components of the equalized digital samples from a coherent receiver (RX) to estimate ICI. Subsequently, it proposes estimating the distance to neighboring WDM channels by directly processing the RX raw digital samples through the analysis of their power spectral density (PSD) using an ANN. Moreover, an efficient dataset design approach based on latin hypercube sampling is presented to effectively optimize and test the ANN-based DSP scheme for estimating ICI under realistic assumptions in a flexible WDM scenario. The proposed methodology has been validated through both simulation and experimental analysis using commercial coherent transceivers. Experimental results show that, for a channel under test with a symbol rate of 52 GBaud, the distance to neighboring WDM channels can be estimated with a root mean squared error of less than 1.5 GHz.

The last part of the thesis explores the use of advanced DSP for blind anomaly detection by sensing the state of polarization (SOP) in optical fibers deployed in an urban scenario. In particular, it introduces an adaptive and spectrally resolved DSP scheme called SOP-PSDG (SOP power spectral density gap). This algorithm can detect anomalous events occurring near the fiber when the generated SOP-PSDG signal exceeds a given threshold, while adaptively tracking the SOP behavior under normal conditions over time. The proposed SOP-based DSP scheme has been evaluated on an experimental setup using optical fibers deployed in the metropolitan area of Turin. Experimental results demonstrate the efficacy of this method, showing superior sensitivity to anomalous mechanical vibrations compared to other conventional SOP-based algorithms, such as SOP angular speed (SOPAS). The thesis concludes by discussing the opportunities and challenges associated with the potential implementation of SOP-based blind anomaly detection using artificial neural networks in future research.