ELECTRICAL, ELECTRONICS AND COMMUNICATIONS ENGINEERING

PNRR/RESTART/CRT - AI-aided transmission modeling of optical network elements

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Context of the research activity	This project aims to enhance optical networks by extending open network controls with physical layer awareness, focusing on modeling network elements like transceiver, amplifiers and fdiletring elemnts. By characterizing these elements and using machine learning techniques, the project seeks to improve network capacity and efficiency. The project also explores the development of a digital twin, providing real-time network simulations to optimize operations. The findings will contribute to projects like GNPy, enabling more accurate and efficient network planning. Scholarship funded by: PNRR - PNRR M4C2, Investimento 1.3 - Avviso n. 341 del 15/03/2022 - PE0000001 RESearch and innovation on future Telecommunications systems and networks, to make Italy more smart (RESTART) - CUP E13C22001870001

	The project is focused on enhancing open network controls by incorporating physical layer awareness of various network elements, particularly amplifiers. Amplifiers play a vital role in transparent optical networks, allowing optical signals to traverse extensive distances without requiring conversion back to the electrical domain. This feature is crucial for maintaining high-speed data transmission over large networks, as it minimizes latency and energy consumption associated with frequent electrical conversions. Despite the fundamental understanding of the physical principles governing amplifiers, their real-world implementation often varies significantly

Objectives	depending on the manufacturer. This variation leads to discrepancies in performance that are not well-documented. By thoroughly characterizing these amplifiers, it becomes possible to optimize network capacity and efficiency—key objectives for companies that manage expansive and high-speed networks. For example, knowing the precise gain, noise figure, and non-linearities of amplifiers allows network engineers to fine-tune their systems for peak performance, thereby maximizing throughput and minimizing errors. In addition to amplifier characterization, there is substantial interest in developing new predictive models for other network phenomena, such as filtering penalties. Filtering penalties arise when optical signals pass through filters that alter signal properties, potentially degrading performance. Traditionally, these penalties have not been extensively studied, leading companies to adopt conservative margins to guard against unexpected losses in performance. By accurately modeling these effects, networks can be designed with less conservative margins, enhancing both capacity and efficiency. Artificial Intelligence techniques present a promising avenue for improving the accuracy of these models. By leveraging machine learning, network elements can be modeled using a gray-box approach, where known physical laws are combined with data-driven insights to create robust predictive models. This approach allows for the handling of complex, non-linear interactions between network components, which are often difficult to capture using traditional analytical models. Furthermore, the knowledge gained from detailed studies of network devices can be employed to train neural networks and machine learning models that enhance the understanding of the physical layer. These models can transform the network into an active sensor capable of detecting both malicious activities and environmental changes. For instance, optical fibers can be used to detect seismic activities, such as earthquakes, by analyzing the subtle changes in signal patterns. Similarly, they can monitor the integrity of network infrastructure and detect potential threats or failures before they cause significant disruptions. Machine learning models can analyze vast amounts of data to predict and detect potential network failures early, enabling proactive measures to mitigate these issues and restore services promptly, thus minimizing downtime. The comprehensive understanding and control of network elements can be leveraged to create a digital twin of the network. A digital twin is a dynamic software model that represents the real network in real-time, incorporating all the nuances of its physical layer. This model can be invaluable for optimizing network operations, as it provides a virtual environment for testing and implementing new strategies without risking actual network performance. By simulating different scenarios, network operators can explore potential solutions for increasing efficiency, reducing energy consumption, and improving resilience against failures. The digital twin can also aid the SDN (Software-Defined Networking) optical optimized controller in making more informed decisions, resulting in substantial energy savings and improved resource allocation. Achieving this level of simulation accuracy requires an in-depth understanding of all network devices, with each component's contribution being precisely known. This knowledge enables a complete and reliable simulation of network behavior, incorporating a detailed, time-varying physical layer description. The ability to simulate and predict network behavior with such accuracy is essential for modern networks, where dynamic conditions

	and high data volumes demand advanced management strategies. The results of this research and the subsequent advancements have significant implications for projects like GNPy, an open-source software initiative focused on abstracting the physical layer of optical networks. GNPy aims to provide accurate and flexible network planning tools that can accommodate the diverse characteristics of modern optical networks. By integrating new models capable of precise estimations of network characteristics, both through analytical methods and machine learning algorithms, GNPy can enhance its capabilities, offering better tools for network designers and operators worldwide. These improvements will support the development of more efficient, reliable, and scalable optical networks, meeting the growing demands of data-driven industries and global communication needs.

Skills and competencies for the development of the activity	- Fundamentals of digital communications - Optical communications and networks - Open optical networks - Transceiver modeling - Python programming