ELECTRICAL, ELECTRONICS AND COMMUNICATIONS ENGINEERING

DET - Toward Quantum-Safe and Scalable Optical Networks: Multi-Band Modeling and Raman-Aware Design

Funded By	Dipartimento DET

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Context of the research activity	The research focuses on modeling and experimental validation of multi-band optical transmission in standard fibers, with special attention to Stimulated Raman Scattering (SRS). It aims to develop accurate, efficient models integrated into GNPy to build an accurate digital twin. Photonics lab tests will validate key physical effects. The work explores Raman amplification, quantum-classical coexistence, and hollow-core fibers to support scalable, energy-efficient, and quantum-safe networks.

	The proposed PhD project aims to advance the design and performance optimization of next-generation optical networks by focusing on multi-band transmission systems and the physical-layer phenomena that emerge when extending signal bandwidth beyond conventional operational limits. With the exponential growth in global data traffic, current infrastructures face increasing pressure to deliver higher capacity, lower latency, and enhanced energy efficiency. To meet these demands without resorting to costly and disruptive fiber deployment, the research will investigate solutions that maximize the utility of existing optical fibers, particularly by expanding the usable optical spectrum beyond the traditional C band into the O-, E-, S-, L-, and U-bands. A central goal of this research is to develop a physically accurate and computationally efficient model for signal propagation in Standard Single Mode Fiber (SSMF) under multi-band conditions. The focus will be on capturing the effects of Stimulated Raman Scattering (SRS), a nonlinear process that becomes increasingly prominent in wideband systems. SRS induces a dynamic redistribution of optical power along the fiber, significantly impacting the signal-to-noise ratio (SNR) and, consequently, the quality of transmission across channels and bands. A precise understanding and control of this effect is vital to enable scalable and reliable multi-band communication systems. The developed models will be designed for integration into GNPy, an open-source optical network planning and simulation tool widely adopted by both academia and industry. Particular

Objectives	attention will be given to achieving high computational efficiency to support real-time network optimization and adaptive reconfiguration in response to changing traffic patterns. This is a key enabler for next-generation intelligent and energy-aware network architectures. In parallel with simulation and modeling, experimental validation will be a fundamental component of the research activities. Laboratory tests conducted in the photonics laboratories at Politecnico di Torino will be used to characterize SRS behavior under various multi-band configurations and to validate theoretical predictions. Measurements of Raman gain profiles, inter-band crosstalk, and power transfer dynamics will inform and refine the simulation models, ensuring they are grounded in real-world performance. In this way, the research will maintain a strong link between theory, simulation, and practical implementation, accelerating technology transfer into deployable solutions. Another research axis will explore the impact of Raman scattering on Quantum Key Distribution (QKD) systems. As secure communications become increasingly important, QKD offers a theoretically unbreakable encryption method. However, its deployment alongside classical high-power signals poses a significant challenge due to Raman-induced noise. The research will assess spectral coexistence strategies, define minimum safe spectral separations, and explore modulation and filtering techniques that allow secure and robust operation of hybrid quantum-classical systems on the same optical infrastructure. The study will also investigate Raman amplification as an enabling technology for broadband systems. Unlike traditional discrete amplifiers (e.g., EDFAs), Raman amplification allows for distributed signal boosting across the transmission fiber itself, offering gain profiles tailored to specific spectral regions. The project will explore multi-pump Raman configurations, analyze their gain bandwidths and noise characteristics, and evaluate their feasibility in multi-band deployments —especially for bands beyond C where conventional amplifier solutions are limited or unavailable. Additional topics will include the frequency-dependent decay of Cross-Phase Modulation (XPM) effects across the spectrum. While theoretical models often predict a 1/f decay, experimental observations suggest a more complex behavior possibly linked to polarization dynamics not fully captured in current models. This discrepancy will be investigated both theoretically and experimentally, potentially leading to refinements of the Manakov equation and other signal propagation models. Finally, the research will examine the potential of hollow-core fibers (HCFs) as a future transmission medium. HCFs support signal propagation primarily through air, drastically reducing nonlinearities and latency. Their characteristics will be studied both analytically and through testbed experiments to evaluate their compatibility with multi-band and quantum-enhanced transmission. By combining rigorous theoretical modeling, software development, and hands-on experimental testing in advanced photonics labs, this research will contribute to the development of quantum-safe, energy-efficient, and spectrally scalable optical networks, laying the groundwork for future-proof digital infrastructures meeting the demands of society and industry.

Skills and competencies for the development of the activity	- Fundamental of digital communications - Optical communications - Optical Networking - Experience in research activities