Ph.D. in Information Technology
Thesis Defenses

May 25th, 2026
At 11:00 a.m.
Sala Schiavoni - Building 20A

Stefano GAIANI – XXXVIII Cycle

SPACE DIVISION MULTIPLEXED TRANSMISSION OVER MULTIMODE FIBERS TO SUPPORT NEXT-GENERATION HIGH-CAPACITY OPTICAL NETWORKS
Supervisor: Prof. Pierpaolo Boffi

Abstract:

Most of the aspects of our daily life that we take for granted would not have been possible without the tremendous development of optical communications over optical fibers. The technology advance achieved in the last three or four decades have supported the massive connection demand and exponentially increasing data-rates, deriving from the continuous rise of new services that rely on the Internet for their operation. Currently deployed systems are capable of supporting data-rates close to 100 Tb/s, which is generally considered as the capacity limit of single-mode fibers. However, the increasing throughput demand is not expected to stop in the next years, which poses the problem of how to further scale the available capacity in optical networks.

Space division multiplexing is regarded as one of the strongest candidates to overcome this shortening. It relies on the use of multiple parallel spatial paths, which potentially enable throughput gain up to 100 times compared to the 100 Tb/s limit for single-mode fibers. This is mainly achieved with optical fibers that have multiple cores within the same cladding (multicore fibers), that support the co-propagation of multiple optical modes (multimode fibers), or a combination of the two approaches. Multimode fibers have the potential of supporting high-capacity transmission, while ensuring compactness and compatibility with the current infrastructure.

This thesis is focused on the use of multimode fibers for space division multiplexing implementation, tackling mainly transmission and network aspects, and less extensively optical sensing. The main characteristics of multimode propagation, and the following digital signal processing required at the receiver are discussed as well, as they play keys roles in multimode systems. An analysis of transmission performance in case of the loss of one or more modes on the transmitter and/or on the receiver side is carried out for a point-to-point multimode link, showing a different impact depending on the location of the loss, and on the lost mode itself.

The focus then shifts towards an in-depth review concerning the flexibility and processing complexity of multimode systems, and the state of the art of the simplified approaches proposed to overcome them. An innovative simplified approach based on rate-adaptive equalization at the receiver is presented to reduce the complexity of digital signal processing at the cost of a throughput loss. It is demonstrated that a 16% processing simplification is achieved with just a 1.2% throughput loss compared to the standard processing approach for multimode systems. After that, the problem of

heterogeneity of multimode fibers in space division multiplexed systems is considered, showing that the proposed simplified processing approaches are just partially able to support transmission and flexibility in such systems. For this reason, a new simplified processing scheme is introduced and discussed, and it is demonstrated that it helps improving both transmission quality and flexibility in heterogeneous space division multiplexed systems. On one side, this analysis is carried out at a transmission level, showing capacity values higher than 70 Tb/s with the use of only a fraction of the available modes, and of a limited transmission window compared to currently deployed systems. At the same time, processing complexity is reduced by more than 50% compared to the standard processing approach for multimode fibers. On the other side, this analysis is done at a network level, focusing on switching of groups of modes, and on the allocation of resources to support multiple high-capacity tributaries. It is shown that a relevant number of tributaries can be allocated in a variety of network scenarios. In addition, the newly proposed processing scheme also shows a better optimization of the available resources compared to the state of the art algorithm for processing simplification, reducing the required bandwidth for tributaries by a factor greater than 1.5.
Finally, an appendix is dedicated to the topic of communication and sensing coexistence over the same multimode fiber. For the first time, a method that allows to achieve sensing capability for free from data-carrying telecommunication signals is proposed for a system comprising all the elements required to support space division multiplexed transmission over multimode fibers. It is demonstrated the simultaneous transmission of a 10 Gb/s telecommunication signal, and detection of a vibration applied to a multimode fiber.
During my PhD activity, I have been carrying out an extensive experimental activity that contributed to the knowledge of propagation and networking over MMFs, also tackling complex systems with multiple heterogeneous MMFs. The presented results are valuable for the use of multimode systems both for point-to-point links and for heterogeneous high-capacity space division multiplexed networks, paving the way for their deployment and use in the next decades.

Giovanni Simone STICCA – XXXVII Cycle

NEXT-GENERATION OPTICAL NETWORKS WITH MULTI-BAND TRANSMISSION AND HOLLOW-CORE FIBER

Supervisor: Prof. Massimo Tornatore

Abstract:

Next-generation coherent WDM transport networks must evolve under heterogeneous and increasingly stringent requirements. Beyond sustained traffic growth, emerging services impose tight latency constraints, while energy consumption and security are becoming relevant design objectives. Importantly, these goals must be achieved in realistic deployment scenarios, where operators rely on selective and incremental upgrades rather than disruptive infrastructure replacement. This Thesis develops physical-layer-aware, network-wide planning methodologies to guide such selective upgrades through a cross-layer design perspective, jointly accounting for physical-layer transmission constraints and network-layer resource allocation decisions. In this context, multi-band transmission and Hollow-Core Fiber (HCF) are investigated as key technological enablers. The work addresses four core challenges for next-generation optical networks: capacity scaling, support for low-latency

services, energy efficiency, and secure communication via Quantum Key Distribution (QKD) coexistence.

• Capacity Scaling. To scale capacity within existing infrastructures, we investigate incremental spectrum expansion from the C-band to C+L and further to C+L+S, explicitly accounting for wideband physical-layer effects such as inter-channel stimulated Raman scattering. Building on this modeling, we develop physical-layer-aware optimization frameworks to support selective amplifier upgrades toward hybrid fiber amplifiers (i.e., erbium-doped fiber amplifiers/thulium-doped fiber amplifiers and distributed Raman amplification), and show that a targeted deployment strategy can mitigate wideband impairments, increase network throughput, and reduce the need for signal regeneration. In parallel, we assess HCF as a longer-term capacity-scaling option via selective link upgrades. The results indicate that deploying HCF on a limited fraction of links can yield substantial throughput improvements and reduce the network cost per transported bit compared to multi-band or multi-fiber alternatives. Finally, we examine capacity growth from a topology perspective by proposing robust brownfield topology augmentation for data center interconnection under traffic uncertainty. In particular, we show that it is possible to design topologies that sustain high throughput across a broad set of traffic distributions.

• Low latency services. To support latency-critical services, we propose planning frameworks that jointly optimize edge data center placement and selective HCF deployment under HCF budget limits. Stringent delay requirements typically push networks toward dense edge infrastructures to keep services close to end users; by leveraging the lower propagation delay of HCF on latency-critical paths, the proposed methods can reduce end-to-end latency and, in turn, decrease the number of required edge data centers while improving transmission efficiency.

• Energy efficiency. We develop network-wide methodologies to optimize power consumption per transported bit. In particular, we investigate high-power operation in HCF networks, jointly optimizing amplifier placement and operating points, and show that appropriately engineered high-power amplification can simultaneously increase throughput, reduce transponder needs, and improve energy efficiency. We also consider multi-core networks, quantifying when cladding-pumped amplification (with pump sharing across cores) improves network-wide energy efficiency, and showing that such gains depend strongly on traffic routing and load balancing across spatial channels.

• Secure optical networks with QKD coexistence. We address the coexistence of QKD and classical communication in shared optical infrastructures, where weak quantum signals are impaired by nonlinear noise generated by high-power classical channels. Leveraging the reduced Raman efficiency and lower attenuation of HCF, we propose a network-wide optimization framework that jointly determines selective HCF upgrades, quantum-channel provisioning, and trusted-relay placement to minimize the number of required quantum modules while meeting secret-key-rate demands. The results indicate that most of the HCF gains can be achieved with partial deployment (on the order of 30–40% of links), allowing substantial reductions in the number of deployed quantum modules compared to a standard single-mode-fiber-only network.

Overall, this Thesis suggests that the evolution of optical networks can be effectively supported through selective, budget-aware, and physical-layer-aware planning. By integrating accurate transmission modeling into network-wide optimization, the results indicate that partial, targeted upgrades can achieve a substantial fraction of the benefits of more disruptive approaches, while offering practical pathways toward scalable, low-latency, energy-efficient, and secure next generation optical networks.

PhD Committee

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