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37th Cycle

Design and characterization of silicon photonics integrated switches for transparent optical networks

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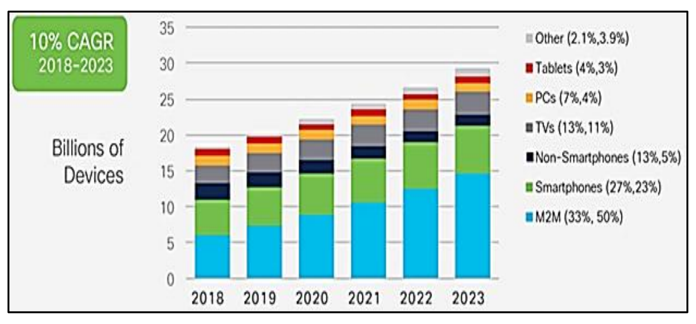
Research context and motivation

The current telecommunication landscape is seeing a **rapid increase in bandwidth and network capabilities requirements**. This trend requires improvement and expansion of the underlying optical networks, which act as the backbone of both wired and wireless systems.

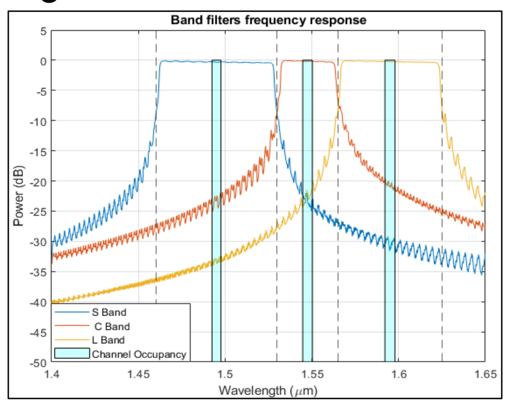


In this context, optical switches are fundamental elements, as their capabilities and cost-effectiveness dictate both the **transmission limitations of the system** (bandwidth and switching speed) as well as **the available protocols** that can be deployed (SDN, topology optimization, physical layer aware impairment routing, and spectrum allocation).
This research work targets the development and characterization of **Silicon Photonics** compatible solutions for optical switching, due to their **cost-effectiveness for mass production, simpler deployment, and wide range of possible implementations**. Silicon Photonics technologies and applications are seeing a rapid increase and growth, as such, an integrated platform for network switching could yield a new avenue with respect to the current technologies, such as Liquid-Crystal (LCOS), Electro-Optical conversion (OEO) and Free-Space Optics.

Addressed research questions/problems

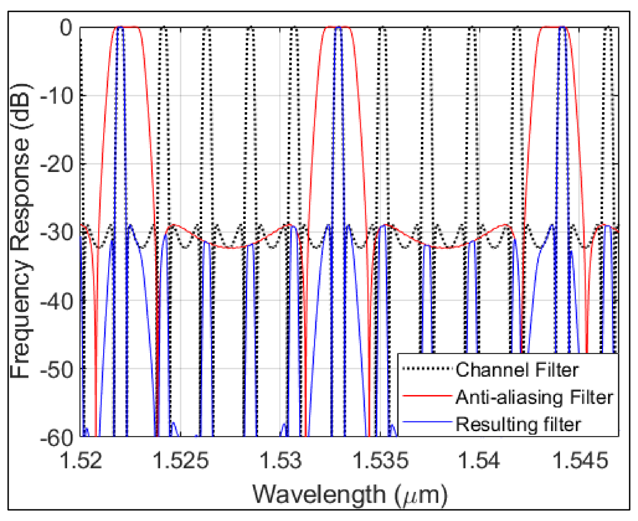
Silicon Photonic switching technologies offer many advantages with respect to traditional electro-optical conversion or more expensive LCOS solutions, although modern telecom applications pose **strict constraints and requirements** for the design of such devices:

- **Large operational bandwidths** are required for frequency-independent elements, covering multiple transmission windows (S+C+L deployment scenario).
- The individual channels need **narrow filtering** (≈100 GHz) elements with **high extinction ratios** and steep on-off transition.



- Envisioning ROADM applications, the switching topology must be both **scalable** to large channel numbers, as well as **flexible**, allowing non-blocking connection for every requested configuration.
- The device performance and penalties must be abstracted as to allow optimization from the network operator.

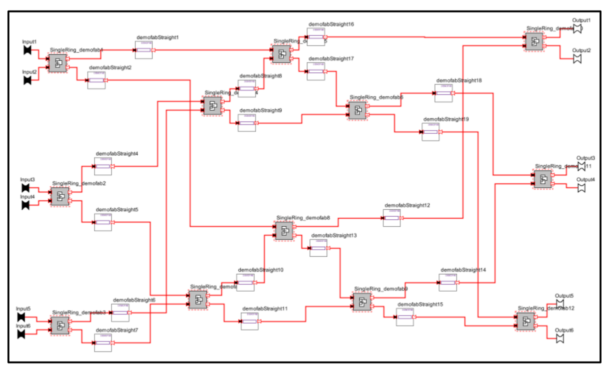
All the previous requirements, together with minimal loss and cross-talk, depict quite a **complex design scenario**, with constraints imposed by both the physical layer and the transport layer as well as the technological limitations of today's manufacturing. Due to this landscape, the research targets not only the device level but a **multi-layer aware solution**, balancing the trade-offs between the different design requirements.

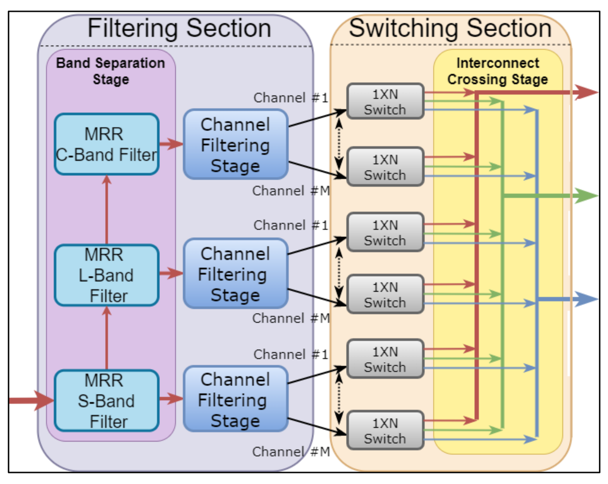


Novel contributions

The research work has led to the characterization and development of models for different switching devices and topology, namely a **wide-band Mach-Zehnder based NxN Beneš switch** and a **multi-band Wavelength-Selective Switch** (400ZR target application).
The novel results obtained through the studies can be roughly divided into two sets:

- The work on reconfigurable switching topologies has led to the development of a **bottom-up custom design strategy**, allowing characterization and **forward propagation** of the effects of the components from the physical layer up to the transmission performance evaluation. This allows not only a **more flexible and faster** design procedure but also the evaluation of **optimal configuration and routing strategies**.

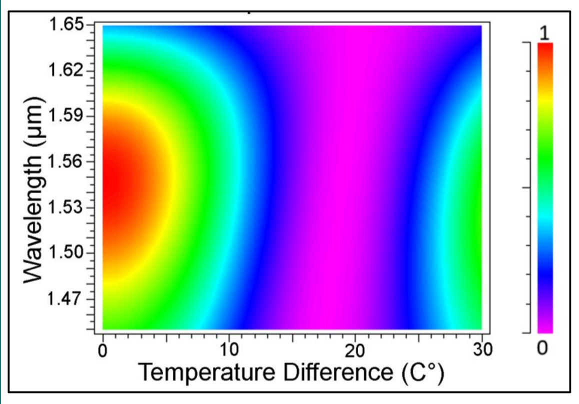




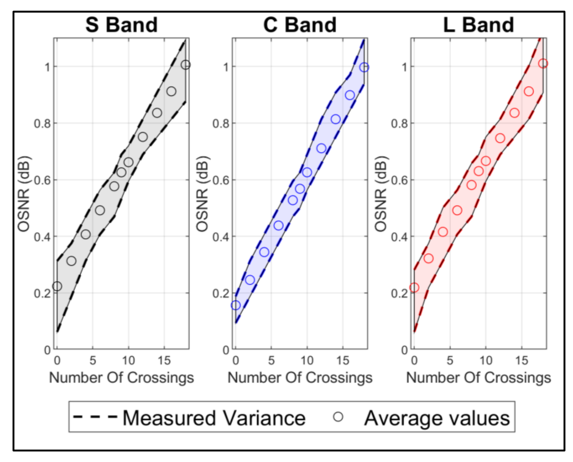
- The investigation and design of the multi-band WSS has led to a **network-level characterization** of the performances of current device solutions proposed in the literature, which have been designed and simulated for an appropriate implementation scenario.

The results highlight both the applicability of photonic devices for modern multi-band DWDM applications, as well as the optimization process that can be applied to tailor the design. Through deterministic means and Machine Learning implementations, both the physical device and the control strategy/topology have been optimized to deliver the required performances.

Adopted methodologies



The device and models simulation have been carried out through **different methodologies, ranging from FDTD, BPM, CMT, and analytical solutions**. The Synopsys Photonic Design Platform (OptSim, RSoft) has been used in conjunction with MATLAB custom scripting to implement the aforementioned **bottom-up design strategy.**
Due to the wide range of elements needed in the switching solutions (MicroRings, MZI, Gratings, Coupler, and interconnects), no homogeneous solution is available, considering the need for **computational efficiency**. As such the general paradigm is focused on a **divide and conquer modular strategy**, designing each component in the most suitable simulation environment and extracting the data to build appropriate models for the **DSP-enabled platform**.



To this end, custom scripting is fundamental to allow a straightforward simulation pipeline, allowing the **transmission evaluation directly on the physical simulation data.**

Future work

The currently developed models can be improved to more accurately compare with the alternative solutions proposed in the literature.
Furthermore, while the simulation results are indicative of the device penalty, a deeper **fabrication tolerance analysis** must be conducted to realistically estimate the behavior of a physical implementation of the proposed structure. Additionally, **the features of the structure can be further expanded**, allowing a higher degree of freedom to the network operator, such as deploying Flex-Grid WDM and more advanced transmission standards.

List of attended classes

01RGBRV - Optimization methods for engineering problems (07/06/22, 6 CFU)
01SCSIU - Machine learning for pattern recognition (22/07/22, 4 CFU)
01TAHIU - Quantum computing (19/07/22, 4 CFU)
01TRARV - Big data processing and programming (6/5/22, 4 CFU)
02SFURV - Programmazione scientifica avanzata in matlab (26/5/22, 6 CFU)
01DOCRV - The Hitchhiker's Guide to the Academic Galaxy. (16/6/22, 4 CFU)
01RISRV - Public speaking (10/1/22, 1 CFU)
01SWPRV - Time management (21/12/21, 1 CFU)
01SWQRV - Responsible research and innovation (25/6/2022, 1 CFU)
01SYBRV - Research integrity (24/6/22, 1 CFU)
01UNXRV - Thinking out of the box (4/12/21, 1 CFU)
02RHORV - The new Internet Society (25/6/22, 1 CFU)
08IXTRV - Project management (6/1/22, 1 CFU)

Submitted and published works

I. Khan, et al., 'Machine Learning Driven Model for Software Management of Photonics Switching Systems' 2021, GLOBECOM, 2021

I. Khan, et al., 'Optimal control of Beneš optical networks assisted by machine learning' SPIE, 2022

I. Khan, et al., 'Machine Learning Assisted Model of QoT Penalties for Photonics Switching System' PSC, 2021

I. Khan, et al., 'Autonomous Control Model for C+L Multi-band Photonic Switch System using Machine Learning' ACP, 2021

I. Khan, et al., 'Optimized management of ultra-wideband photonics switching systems assisted by machine learning' OPTICS EXPRESS,2022

I. Khan, et al., 'Machine learning Assisted Accurate Estimation of QoT Impairments of Photonics Switching System on 400ZR' ACP, 2021

I. Khan, et al., 'Performance evaluation of data-driven techniques for the softwarized and agnostic management of an N×N photonic switch' Optics Continuum,2022

I. Khan, et al., 'A Neural Network-Based Automatized Management of N ×N Integrated Optical Switches' OSA APC,2021

I. Khan, et al., 'Machine Learning Assisted Management of Photonic Switching Systems' (CLEO), 2021

I. Khan, et al., 'A Data-Driven Approach to Autonomous Management of Photonic Switching System' IEEE SUM,2021

I. Khan, et al., 'Automatic Management of N×N Photonic Switch Powered by Machine Learning in Software-defined Optical Transport' IEEE OJCS,2021

I. Khan, et al., 'Softwarized and Autonomous Management of Photonic Switching Systems Using Machine Learning' ONDM,2021

I. Khan, et al,. 'Machine-learning-aided abstraction of photonic integrated circuits in software-defined optical transport' SPIE OPTO,2021

L. Tunesi, et al., 'Automatic design of NxN integrated Benes optical switch' Silicon Photonics XVI,2021

L. Tunesi, et al., 'Novel Design and Operation of Photonic- integrated WSS for Ultra-wideband Applications' IEEE SUM,2022

L. Tunesi, et al., 'Modular Photonic-Integrated Device for Multi-Band Wavelength-Selective Switching' OECC/PSC,2022

I. Khan, et al., 'Performance Analysis of Novel Multi-band Photonic-integrated WSS Operated on 400ZR' SUM,2022

Politecnico di Torino

PhD program in
Electrical, Electronics and Communications Engineering