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Abstract:

This document is the report of the first year of activities in the VCE-WP14 Virtual Center of Excellence on Optical Switching Systems (VCE S). It includes the achievement of milestone M14.1 and also reports the status of the joint activities proposed within VCE-WP14.
There are 49 partners involved in this workpackage and sixteen joint activities have been proposed so far, each of them involving at least one mobility action or joint experiment.

Keyword list:
Wavelength Converter Usage Reduction, Switching for Network Recovery, Quality of Service in switches, New switching paradigms, Optical Clock Recovery, Wavelength Conversion by nonlinear effects, Optical Multicast Architecture, Switching and network reliability, benchmarking and cost analysis, OCDM encoders/decoders, 2R Regeneration, Optical flip-flops, Optical packet switching, Hybrid Switch Architectures, GMPLS optical switch nodes, Contention Resolution Schemes, Optical Buffering, OTDM time-slot switching, Multi-wavelength regeneration, Optical Cross Connects, Power Issues in Switching Systems.

Disclaimer

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1. Executive Summary :

Recent technology development has unlocked most of the fiber capacity making capacity an abundant resource. However, the majority of WDM (Wavelength Division Multiplexing) deployment has occurred in the form of point-to-point links with amplifiers in between if needed. Optical WDM lightpaths are static and are seen as a scarce resource. Once set up, they remain in place, essentially forever. Therefore, switching is only to transforms the raw bit rates into useful bandwidth. The prime objective of this deliverable is to provide the viewpoint on photonic in switching of the “Virtual Center of Excellence on Optical Switching Systems (VCE-S)”. Within these directions, VCE-S must craft R&D directions and define the position of photonic switching in future optical networks. The questions that must be answered are how and where photonic switching is positioned in future Internet and which problems must be solved to reach this goal. The incentive is to use optical switching to make spectrum efficient in terms of switching and not in terms of only capacity. Towards this goal VCE-S has charted a list of key issues and prime research objectives. Actual implementation was carried out during the project via a number of collaborative projects.

2. Introduction

This document is the first deliverable for the “Virtual Center of Excellence on Optical Switching Systems (VCE-S)”, within the BONE network of excellence. VCE-S has been organized around joint activities proposed by partners after having identifies the key research issues in the field. Partners proposed 16 joint activities, involving mobility actions, joint experimental work, simulation studies targeting a specific journal or conference for disseminating the results. The list of the joint activities and experiments are presented in Section 3, while Section 4 details progress and actions per join activity.

2.1 VCE-S Participants

The following member organisations have allocated manpower in VCE-S as of today.

Participant	WP14 Effort spent	WP14 Effort planned	Participant	WP14 Effort spent	WP14 Effort planned
1 - IBBT	0	1.5	**26 - CORITEL**	0.2	1
2 - TUW	1.001	1	**27 - FUB**	0	0
3 - FPMs	0	0	**28 - ISCOM**	0.1	0
4 - Fraunhofer	0	0	**29 - PoliMI**	1.18	0.75
5 - TUB	0	1.5	**30 - PoliTO**	0.9	1.5
6 - UDE	0	0	**31 - SSSUP**	0.5	1.25
7 - UST-IKR	0	0	**32 - UNIBO**	1.8	2
8 - COM	3	4	**33 - UNIMORE**	0.6	2
9 - CTTC	0	0	**34 - UniRoma1**	0.3	2
10 - TID	0	0	**35 - TELENOR**	0	1.5
11 - UAM	0	0	**36 - TUE**	0.425	1.5
12 - UC3M	1.1	0.25	**37 - IT**	0.15	0.5
13 - UPC	0	0	**38 - AGH**	0	0
14 - UPCT	0.3	1	**39 - PUT**	0.1	1
15 - UPVLC	0.05	0.75	**40 - HWDE**	0	1
16 - UVIGO	2.22	3	**41 - KTH**	0.05	1
17 - FT	0	0	**42 - BILKENT**	0.45	1.5

18 - GET	0	1.25	**43 - UniRoma3**	0.3	1
19 - AIT	0.4	1	**44 - ORC**	0	1.5
20 - ICCS-NTUA	0	1.5	**45 - UCAM**	1.2	2
21 - RACTI	1.5	4.25	**46 - UCL**	0	1.75
22 - UoA	0	1.25	**47 - UEssex**	0	1.5
23 - UoP	0	0	**48 - USWAN**	0	0
24 - BME	0.1	1	**49 - Ericsson**	0.6	0.5
25 - FER	0	0			
Total	**Total Spent**		**Total Planned**		
	18.526		**50**		

3. List of Joint Activities in VCE-S, WP14

JA#	JA title	JA-Leader	Participants
JA1	Power-Cost-Effective Node Architecture for Multicast Light-Tree Routing in WDM Networks.	Gonzalo F.D. Carpio gmfernand@hotmail.com	**UC3M,** UPVLC
JA2	Feasible parallel schedulers for OBS/OPS nodes.	Pablo Pavón Mariño Pablo.Pavon@upct.es	**UPCT**, UVIGO, DEIS-UNIBO
JA3	Performance and complexity analysis of optical switching fabrics	Fabio Neri neri@polito.it.	**PoliTo**, UniBO, PoliMI, TUW
JA4	Performance of optical switching system architectures with shared wavelength converters.	Nail Akar akar@ee.bilkent.edu.tr	**Bilkent**, UNIBO, UniRoma1, UNIMORE, FT, KTH
JA5	Code-based optical nodes.	Gabriella Cincotti, cincotti@uniroma3.it	**UNIROMA3**, UNIMORE, UNIBO, UNIROMA1, GET, NICT
JA6	Repacking and rearranging algorithms for multi-plane banyan	Wojciech Kabacinski, wojciech.kabacinski@et.	**PUT**, POLIMI

	type switching fabrics.	put.poznan.pl	
JA7	Power Consumption and Supply of High-Performance Switching Elements.	Slavisa Aleksic slavisa.aleksic@tuwien.ac.at	**TUW,** UPCT, BME, UNIMORE, PoliTo
JA8	All-optical switches utilizing microring resonators.	Adonis Bogris abogris@di.uoa.gr .	**UoA**, UC3M
JA9	All-optical label processing techniques for ultra-fast optical packet switches.	Piero Castoldi castoldi@sssup.it	**SSSUP**, UNIROMA3, NICT
JA10	Currently inactive / merged into JA12		
JA11	The Optical Switch Architecture with Recirculation Buffer and Wavelength Conversion.	Wojciech Kabaciński wojciech.kabacinski@et. put.poznan.pl	**PUT**, RACTI
JA12	Encompassing switch node impairments and capabilities in dynamic optical networks	Nicola Andriolli nick@sssup.it	**SSSUP**, DTU
JA13	Reliability of various optical switching technology	Rebecca Chandy rebeccapchandy@gmail.com	**Ericsson**, KTH
JA14	Photonic code label processors for ultrafast routing	Ian White ihw3@cam.ac.uk	**UCAM**, TUe, Uniroma3
JA15	Hardware efficient optoelectronic switch fabrics	Ian White ihw3@cam.ac.uk	**UCAM**, TUe, PUT
JA16	Low-crosstalk optical packet-switching architectures based on wavelength-switching and wavelength-sensitive devices	Achille Pattavina pattavina@elet.polimi.it	**POLIMI**, UPCT, POLITO, OVIGO

4. Technical Report on VCE-S Joint Activities

4.1 JA1 - Power-Cost-Effective Node Architecture for Multicast Light-Tree Routing in WDM Networks.

Responsible partner: UC3M
Participants: UC3M, UPVLC

Description of work carried out.

The work carried out has focused on the design of a novel cost-effective multicast-capable optical cross connect (MC-OXC) node architecture that features both tap-and-continue and tap-and-binary-split functionality. This architecture intends to provide an interesting balance between simplicity, power efficiency and overall wavelength consumption with respect to models based on TaC (Tap and Continue) or SaD (Split-and-Delivery). The main component of this node is a novel Tap-and-2-Split Switch (Ta2S). We propose and analyse an implementation of this switch based on integrated optics (namely, MMI taps and MZI switches), and we characterize and compare it with other alternatives implemented with the same technology. The study shows that, thanks to the presented Ta2S design, the 2STC node scales better in terms of number of components than the other alternatives. Furthermore, it is more power efficient than the SaD design and requires less wavelengths than TaC thanks to the binary split capability. On the other hand, simulation results reveal that the 2-split condition does not add a significant additional wavelength consumption in usual network topologies with respect to SaD.

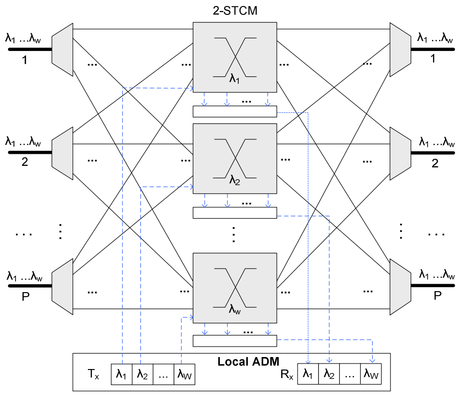

Fig. X. General architecture of a P x P 2-STC MC-OXC node.

Collaborative actions carried out

The incorporation of UPV into the JA is very recent. However several related joint actions were carried out in the multicast light-tree routing topic. In June 2008, prof. Larrabeiti (UC3M) gave a seminar on optical switching at UPV phd-master programme, where optical multicast issues were presented, and a related technical meeting was also held.

Future Activities - Timescale

Expected joint paper at a conference.

Outcome of the joint research activity:

Submission of a paper to Journal of Lightwave Technology (non-joint).

4.2 JA2 - Feasible parallel schedulers for OBS/OPS nodes

Responsible partner: UPCT

Participants:UPCT, UVIGO, UNIBO-DEIS, UNIROMA1

Description of work carried out.

In well-known optical switching architectures such as WASPNET [1] or Input Buffer Wavelength Routed (IBWR [2]), many of the schedulers proposed to solve contention problems have been designed to take scheduling decisions sequentially. Nevertheless, although sequential decisions simplify keeping packet order delivery, they are not able to guarantee wire-speed processing nor switching response time as the optical switch size grows (considering the number of switch ports as well as the number of wavelengths per fibre).

UVIGO, UPCT and DEIS-UNIBO have investigated a new proposal of parallel schedulers for OPS nodes that guarantee packet order delivery of optical packets from node to node. Two schedulers have been proposed: OI-PDBM and OLBWS. These two schedulers are based on PDBM [1] scheduling for IWBR architectures and LBWS [2] scheduling for WASPNET architectures, previously presented by UPCT and UVIGO. In reference [3], packet order issue in WASPNET switch is addressed by UVIGO.

Both OI-PDBM and OLBWS schedulers are simple and allow a practical parallel hardware implementation. OI-PDBM has a good performance in terms of delay, buffer requirements and convergence speed and it guarantees packet order. OI-PDBM scheduler efficiently eliminates the packet mis-ordering in IBWR switches, and endorses the application of this architecture in OPS networks, as a feasible competitor against less scalable OB architectures. OLBWS is fully distributed; it allows switch connections to evolve in a predefined sequence, so that it is possible to forecast delay when packets enter into to the system. OLBWS scheduling has a computational complexity of O(1) iteration and it guarantees packet order.

UPCT and UNIBO are addressing the design of parallel schedulers for switch fabrics operating with variable-length optical packets, not aligned at switch input. Previous knowledge gained by UNIBO on cost-effective OPS/OBS scheduling implementation [4,5] will be integrated with a parallel scheduler architecture devised by UPCT. Preliminary work has been done, which is being prepared for publication.

UPCT studied in [6] the performance evaluation of slotted OPS switching fabrics under self-similar traffic.

[1] Pavon-Mariño P., García-Haro J., Jajszczyk A., Parallel Desynchronized Block Matching: A Feasible Scheduling Algorithm for the Input-Buffered Wavelength-Routed Switch, Computer Networks, vol. 51, issue 15, October 2007, pp. 4270-4283.
[2] López-Bravo C., González Castaño F-J., Rodelgo-Lacruz M. , Pavón-Mariño P., García-Haro, LBWS: a load-balanced distributed scheduler for WASPNET optical packet switches, European Transactions on Telecommunications. DOI: 10.1002/ett.1251.
[3] Miguel Rodelgo-Lacruz, Cristina Lopez-Bravo, Francisco J, Gonzalez Castaño, "Guaranteeing Packet Order in Load Balanced Distributed Schedulers for WASPNET Optical Packet Switches," In proc. 12th Conference on Optical Network Design and Modelling (ONDM 2008), vol. 1, Vilanova i la Geltrú, March 2008. Partners: UVIGO.

[4] G. Muretto, C. Raffaelli, P. Zaffoni, "Effective Implementation of Void Filling in OBS Networks with Service Differentiation," Proc. of WOBS 2004, San Jose, CA, USA.
[5] F Callegati, A. Campi, W. Cerroni, "A cost-effective approach to optical packet/burst scheduling," Proc. of ICC 2007, Glasgow, Scotland, June 2007.
[6] J. Veiga-Gontán, P. Pavón-Mariño, M. Izal, D. Morato, J. García-Haro, "Performance evaluation of slotted OPS switching fabrics under self-similar traffic", Proceedings of the 12th International Conference on Optical Networking Design and Modeling - ONDM 2008, Vilanova i la Geltrú (Spain), March 2008 (*invited talk*).

Collaborative actions carried out

All the partners UPCT, DEIS-UNIBO, UVIGO, UNIROMA1 have attended the WP meetings, where technical discussion took place. Besides, collaboration has been carried out through mails and conferences.

Future Activities - Timescale

UPCT and DEIS-UNIBO will progress in the work of design and evaluation of parallel schedulers in asynchronous networks. The expected schedule is:

- In January, submit the common preliminar work which is being prepared for publication.
- During first half of the year, complete the work, getting deeper into the evaluation process of the scheduler, in a wider range of situations.
- During the second half of the year, results related to FPGA implementation of the scheduler can be possible, depending of the results in the previous studies.

UVIGO: In the next moths will focus on asynchronous (not-aligned), optical networks with fixed packet sizes. To carry out these activities, UVIGO will take as a starting point the Optical Cell Switching paradigm (OCS) first presented in [4]. In OCS time is divided into time slots of fixed size by time-division multiplexing, and the wavelengths in a time slot are all bundled. Thus, each OCS core switch (OCX) requires a single switching plane and performs mere time-space switching. We propose a new OCS paradigm –not-aligned OCS- where the alignment process takes place inside the OCXs.

Research activities will be divided into three main steps:

- Characterizing the assignment of shared fiber delay loops (FDL) in optical switches as a min-cost max-flow problem, providing a method to obtain an optimal performance bound, that will allow us to compare different scheduling algorithms.
- Designing and evaluating not-aligned OCS networks performance, implementing different scheduling algorithms.
- Adapting not-aligned OCS networks to multicast traffic delivery.

Expected schedule:

- By the end of the first quarter of 2009: Characterizing the assignment of shared FDL in optical switches as a min-cost max-flow problem.
- By the end of the third quarter of 2009: Design and performance evaluation of OCS networks.
- By the end of the fourth quarter of 2009: Adaptation of not-aligned OCS networks to multicast traffic delivery.

Outcome of the joint research activity:

- J. Veiga-Gontán, P. Pavón-Mariño, M. Izal, D. Morato, J. García-Haro, "Performance evaluation of slotted OPS switching fabrics under self-similar traffic", Proceedings of the 12th International Conference on Optical Networking Design and Modeling - ONDM 2008, Vilanova i la Geltrú (Spain), March 2008 (*invited talk*).

- Miguel Rodelgo-Lacruz, Cristina Lopez-Bravo, Francisco J, Gonzalez Castaño, "Guaranteeing Packet Order in Load Balanced Distributed Schedulers for WASPNET Optical Packet Switches," In proc. 12th Conference on Optical Network Design and Modelling (ONDM 2008), vol. 1, Vilanova i la Geltrú, March 2008. Partners: UVIGO.
- F. J. González-Castaño, M. Rodelgo-Lacruz, P. Pavon-Marino, J. García-Haro, C. López-Bravo, J. Veiga-Gontán, C. Raffaelli, "Guaranteeing packet order in IBWR Optical Packet Switches with Parallel Iterative Schedulers", accepted for publication to *European Transactions on Telecommunications* journal.

4.3 JA3 - Performance and complexity analysis of optical switching fabrics

Responsible partner: PoliTo (Fabio Neri, neri@polito.it)

Participants:PoliTo, PoliMi, UNIBO, TUW

Description of work carried out.

This Joint Activity is aimed at studying and defining the role of optical technologies in future high-performance switching architectures. The focus is on WDM optical interconnection architectures to be used as a forwarding backplane in future multi-Terabit packet switches. A generic reference architecture was defined, consisting in several transmitters and receivers (corresponding to switch linecards), tuning their optical output to reach other linecards on a packet-by-packet basis in a synchronous way. In this framework, several optical fabric architectures were considered in order to identify the most convenient way to provide optically full connectivity among linecards with minimum impact on the optical signal quality, so as to be able to scale as much as possible the switching capacity (aggregate bandwidth scalability).

Among the alternatives, this joint activity started by first proposing candidate broadcast&select architectures in single-plane configurations [1], which however exhibited tunability and maximum port count limitations. This motivated to consider multiplane architectures [2], that require less wavelengths in the system (and therefore less tunability requirements at linecards), and also can reach higher bitrates by improving optical signal performance.

This approach led us to consider, in addition to WDM, space multiplexing through the concept of switching planes (by having the N linecards distributed in S switching planes) as an option to improve scalability; several multiplane architectures were considered by using different approaches to divide information across the different available planes, i.e., in the space dimension. In each plane WDM is used to separate multiple information flows.

Some relevant considered architectures are depicted on Figure 1.

The first architecture (called WSV after *wavelength selection "V" architecture* – see Figure 1(a)) was firstly proposed for optical packet switched WDM networks inside the e-Photon/ONe project; it connects N input/output linecards by means of broadcast-and-select stages based on Semiconductor Optical Amplifiers (SOAs) used as optical gates that perform actually the wavelength-space selection; it is a blocking architecture, but only the throughput upper bound given by physical scalability is considered in our work.

A second architecture is depicted in Figure 1(b) (it is called MCAD after *multiplane couple, amplify, demultiplex*), that uses passive coupling and implements the distribution stage on linecards by splitting transmitter signals in S copies and then using SOA gates for plane selection. Linecards can therefore use wavelength tunability and plane selection (through SOAs) to reach outputs. A coupling section combines all selected signals in planes; in each plane, signals are amplified and WDM demultiplexed.

The other architecture (Figure 1(c)), called *Wavelength-Routing-Space (WRS)*, takes a passive approach, avoiding active switching in the optical fabric, and using tunable transmitters around passive AWGs to select switch planes. Tunability through several sets of wavelengths is however required in order to avoid the coherent crosstalk that would otherwise limit the maximum number of planes [1].

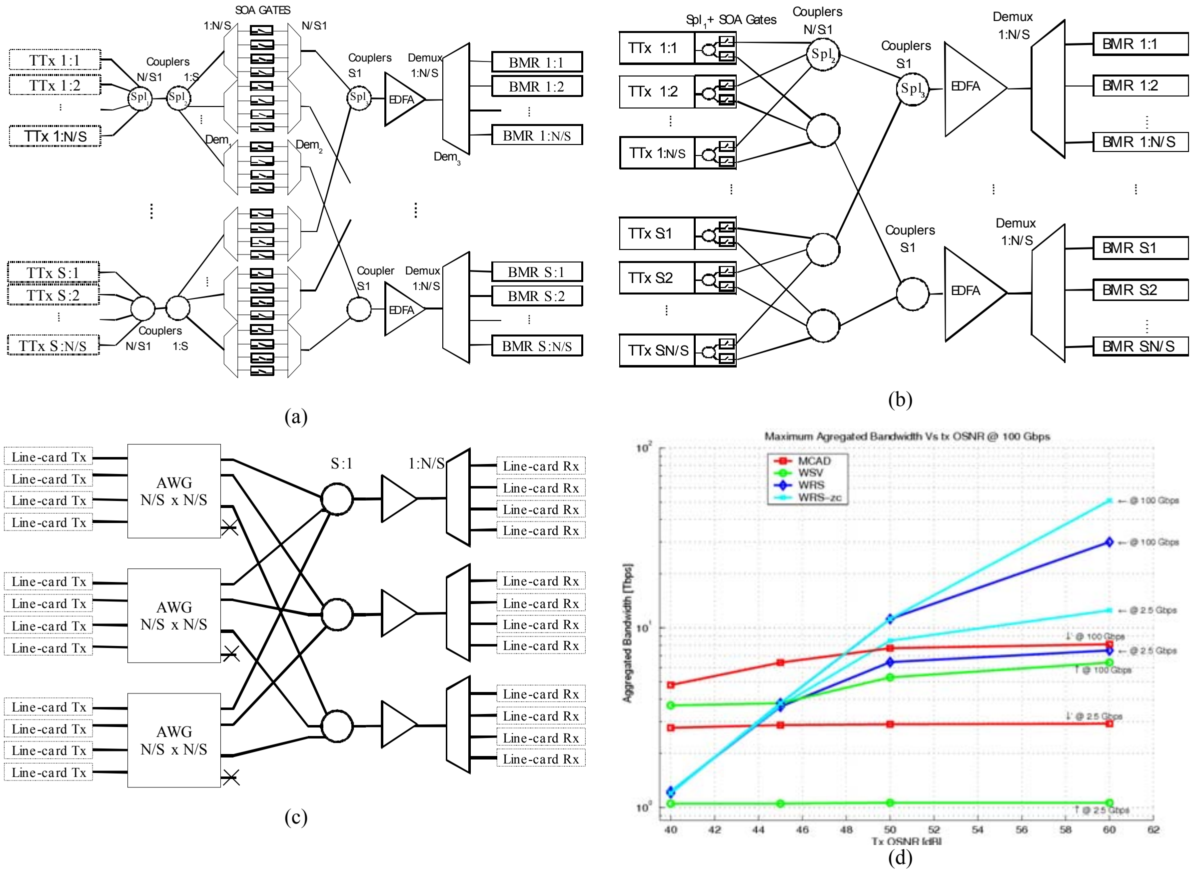

Figure 1. Considered optical switching fabric architectures

A detailed comparisons of the physical-layer behaviour of the three architectures was performed by proper modelling optical components [5]. All architectures were scaled up in terms of number of input/output connections and of bitrate on each connection in order to find the maximum possible aggregate capacity. We found that all architectures are limited by optical signal-to-noise ratio at receivers, while power losses could be recovered by the few optical amplifiers shown in Figure 1; generally it has been studied that residual noise present on transmitters and on amplification is accumulated due to its wide power spectral density. The amount of accumulated noise is different for each architecture, as observed in Figure 1(d), where the maximum fabric capacity is plotted for the three architectures at different interconnection bitrates as a function of the signal-to-noise ratio at transmitters. We can observe that noise on transmitters impacts more the WRS architecture, but other architectures reach a smaller aggregated bandwidth. Overall, aggregate capacities of several Tb/s are possible with optical components available today: this is a very positive result in the direction of a deeper penetration of optics into switching architectures.

Physically there is an optimum operation point for signal propagation on the fabric, corresponding to a pair of values for *N* and *S*, which is typical for each architecture. Also large switches with slow line cards are strongly penalised with respect to high-bitrate connections among less linecards, which should therefore serve several I/O physical lines.

Regarding how much does the implementation of these proposals cost, we performed a cost analysis starting from an estimation of the required number of components, of transmitter complexity and a more detailed cost model for optical component based on commercial or near-commercial devices. In general, also in terms of costs it is more convenient to have high-bitrate linecards in order to build a switch with few line cards rather than with many of them.

Detailed results on these cost and scalability analysis can be found in [1],[2][4][5].

A second topic developed on this joint activity has been the experimentation on control and management plane on these fabrics, since line cards are autonomous to a certain degree, and it is always necessary to trade off performance and the centralisation of forwarding information. A mixed centralised / distributed scheme has been prototyped and it is being extended at PoliTO.

An internal activity at PoliTO related to the topics above studied optimal blends of optical and electronic technologies to implement contention resolution in hybrid electro-optical switches [3].

Another approach carried out by TUW was focused on scalability and performance of optical switching fabrics based on internally interconnected broadcast-and-select optical switching units. The proposed switch fabric architecture shown in Figure 2 consists of P optical switching units each having N input/output ports. The P switches are connected with each other by using a number of internal fiber rings (Q). K input/output ports of each switching fabric are used to establish these internal connections. Multiple connections increase the freedom of choice of appropriate paths through the switch. In the interconnection method depicted in Figure 2, each output port can be reached from any input port by traversing either one or maximum two switching units. The internal structure of an optical switching unit is the one shown in Figure 1(a) taking from second coupler's input to third coupler's output.

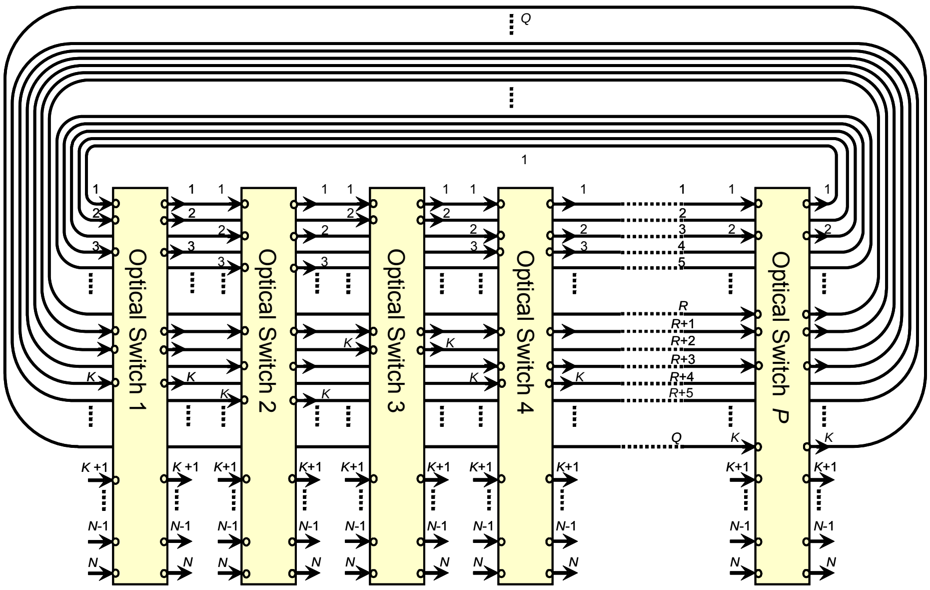

Figure 2: Architecture of an optical switching fabric comprising internal fiber ring-like interconnections.

Simple analytical models that use data of commercially available devices will be developed and used to analyse scalability and feasibility of the structure. The results will be validated using numerical simulations. Additionally, dynamic effects such as transients in switching devices and the pattern effect will also be taken into account during simulations. Details were published in [6].

Collaborative actions carried out

The cost and scalability analysis reported above was a joint effort between PoliTO, PoliMI and UniBO, which started within the Italian national project called OSATE.

Mobility Actions: Michel Garrich from UPC is collaborating with PoliTO since October '08.

Future Activities - Timescale

- Exploring multiblock versions of the proposed architectures to make use of the switch configurations with the best propagation conditions and improve scalability. (Nov 08 – May 09).
- Initial study on rearranging algorithms for different switching fabrics built with microring resonators. Physical modelling of microring resonators switches and their role in optical switching fabrics. (Oct 08 – March 09).
- Further cost/complexity/scalability analysis of hybrid fabrics will be considered. In such hybrid fabrics, different kinds of switching elements (with different switching times), for example, fast devices as Semiconductor Optical Amplifiers (SOAs) will be considered jointly to slow devices as Micro Electro-Mechanical Systems (MEMS). These fabrics can be used to support different granularities in the same switching fabric, so they are suitable for OBS where the flows are managed accordingly to the required latency and also to support fast switching scheme and circuit oriented switching scheme at the same time (OBS/OPS over OCS). Hybrid fabrics require a compromise among fast and slow devices, by taking performance and cost evaluation into account. In addition, signal quality degradation in both fast and slow paths should be analysed, as well as the possible mix of signals. (Feb – July 09).

Outcome of the joint research activity:

[1] J.M. Finochietto, R. Gaudino, G. A. Gavilanes Castillo, F. Neri, "*Optical Fabrics for Terabit Packet Switches*", Proceedings IEEE International Conference on Communications (ICC 2008), Beijing, China.

[2] J.M. Finochietto, R. Gaudino, G. A. Gavilanes Castillo, F. Neri, "*Multiplane Optical Fabrics for Terabit Packet Switches*", Proceedings IEEE/IFIP Conference on Optical Network Design and Modelling (ONDM'08), Vilanova, Catalonia, Spain, March 2008.

[3] A. Bianco, D.Camerino, D. Cuda, F. Neri "*Optics Vs Electronics in Future High-Capacity Switches/Routers*" Submitted Paper, International Communications Conference (ICC2009), Dresden, Germany June 2008.

[4] J.M. Finochietto, R. Gaudino, G. A. Gavilanes Castillo, F. Neri, "*Can Simple Optical Switching Fabrics Scale to Terabit/s Switch Capacities*", ready for submission to Journal on Selected Areas in Communications JSAC 2008.

[5] D. Cuda, R. Gaudino, G. A. Gavilanes Castillo, F. Neri, C. Raffaelli, M. Savi, "*Capacity/Cost Tradeoffs in Optical Switching Fabrics for Terabit Packet Switches*", Submitted work, IEEE/IFIP Conference on Optical Network Design and Modelling (ONDM'09), Braunschweig, Germany, February 2009.

[6] K. Aziz, S. Sarwar, S. Aleksic, *"Dimensioning an Optical Packet/Burst Switch - More Interconnections or More Delay Lines?"*, in Proceedings of ONDM2008, Vilanova i la Geltrú, Catalonia, Spain, pp.129 – 134.

4.4 JA4 – Performance of Optical Switching System Architectures with Shared Wavelength Converters

Responsible partner: Bilkent, UNIBO

Participants:Bilkent, UNIBO, UniRoma1, FT, FUB, KTH, UNIMORE

Description of work carried out.

Bilkent University and the University of Bologna worked on the performance analysis of an asynchronous optical packet switch equipped with a number of wavelength converters shared per node. The wavelength converters can be full or circular-type limited range. Analytical methods are proposed by Bilkent University that rely on the solution of Markov chains of block-tridiagonal type in addition to fixed point iterations to approximately solve this relatively complex system. In this approach, finite number of fiber interfaces are also taken into account using the Engset traffic model rather than the usual Poisson traffic modeling. The University of Bologna supported the validation of the analytical model through estensive simulations. The proposed analytical method provides an accurate approximation for full range systems for relatively large number of interfaces and for circular-type limited range wavelength conversion systems for which the tuning range is relatively narrow. The results are prepared as a journal paper and are submitted to Photonic Network Communications.There are plans to extend this work and in particular the idea of fixed point iterations to other directions including the recently proposed shared per wavelength asynchronous packet switching systems.

Within JA4, the University of Bologna started a discussion on technology enabled optical switching systems with shared wavelength converters, namely TEOS task, aimed at discovering wavelength converter availability and promote interactions between groups involved in research on system and technology aspects. The discussion is meant to give both an up-to-date survey of optical switch architectures as well as a state–of-the-art of enabling optical technology and devices, with particular emphasis on switch architectures with shared wavelength converters. In the last two years of the e-photon project, most participants were involved in activities concerning performance evaluation of switch architectures with shared wavelength converters. Different sharing strategies have been proposed and evaluated, namely shared per output link, shared per node and shared per wavelength, and the relationships between system and technology aspects have been outlined. To proceed with switch design, more detailed inputs from the technology side are now needed. For example it is important to know which kind of wavelength converters are foreseeable, which bandwidth, which delay, and which scalability can be achieved at what cost. A document has been prepared to summarize the most promising switch architectures which employ wavelength converters and the main technology issues. The plan of this task is to continue to solicite the discussion, by contacting new group members involved in technology design.

Collaborative actions carried out

The performance analysis of the asynchronous optical packet switch equipped with a number of wavelength converters shared per node required Bilkent University and University of Bologna to construct scenarios that they can jointly work on both analytically and simulation-based.

Future Activities - Timescale

Bilkent University and the University of Bologna will extend their work on fixed point analysis of shared per wavelength switching systems for the next six months. The technical document on technology on wavelength converters will contnue to evolve throughout the next year.

Outcome of the joint research activity: A journal paper is prepared and submitted:

N. Akar, E. Karasan, C. Raffaelli, “Fixed Point Analysis of Limited Range Share Per Node Wavelength Conversion in Asynchronous Optical Packet Switching Systems", submitted to Photonic Network Communications, Oct. 2008.

4.5 JA5 - Code-based optical nodes

Responsible partner: ROMA3

Participants: UNIROMA3, UNIMORE, UNIBO, UNIROMA1, GET

Description of work carried out.

The use of optical codes in optical packet switching (OPS) and optical burst switching (OBS) networks would solve the electronic bottleneck, related to optical-electrical-optical conversion at each routing node; furthermore, the processing speed of optical codes is an order of magnitude larger than the electronic counterpart, so that code-based optical switches will be able to sustain the development of the next-generation high-speed Internet Protocol (IP) networks. Since the payload's data path, including switches and buffers, consists of only optical devices, OPS/OBS systems guarantee transparency for optical signals at any bit-rate and format.

Some complementary topics are under investigation within this JA, based on a cooperative effort from the participants. Experimental investigations of OPS and multicast label switching nodes have been performed, using a single multiport encoder/decoder (E/D) that is able to generate and process simultaneously up to 50 optical labels. Moreover, the use of the E/D in a multidimensional configuration allows us to exponentially increase the number of labels up to 2^50, that, in theory, would suffice for all the IP addresses in the world wide web. To overcome the interface gap at edge nodes between high-speed OPS networks and slow-speed (10 Gbit/s or lower) metro and access IP networks, we have introduced dense wavelength division multiplexing (DWDM) technologies into the OPS switch. A network-interface composed of a 10Gigabit Ethernet (10GbE)/160 Gbit/s optical-packet converter and arrayed burst-mode optical packet transmitters/receivers have been developed, that encapsulates 16 IP packets into a 160 Gbit/s DWDM-based optical packets, and 64-km transmission and switching has been demonstrated in a field-trial experiment [1].

At each switching node, label recognition and swapping would require a local light source, that increase the equipment cost and the power consumption, destroying the bit-rate, format and wavelength transparency. To solve these problems, we have demonstrated a new technique that places a self-seed pulse between the label and the payload in each optical packet to generate a new label at each routing node [2]. By using a multiport E/D, a fully transparent label swapping has been experimentally demonstrated, and its cascade-ability for multi-hop routing has been verified.

To meet the increasing demand for applications such as video on demand and high definition contents, OPS network should be able to support multicasting techniques, where data route has a tree structure, and when the source node transmits a message, each intermediate node makes as many copies as those requested by the destination nodes. We have proposed and implemented a packet-based multicast system using optical codes, that overcomes the limitations due to the resource shortage and complexity of current wavelength-based solutions [3]. Using a multiport E/D and a multicast-capable matrix switch, we are able to dynamically update the multicast forwarding table and to route optical packets to each destination node both in a multicast and unicast situation.

A switch architecture which employs optical codes to solve internal contentions has been defined, allowing wavelength shifting by wavelength conversion. The solutions proposed aim to simplify the space switching matrix and to reduce costs related to semiconductor optical amplifiers (SOA)s employment. Different kinds of wavelength converters have been considered, namely fixed input/tuneable output or tuneable input/fixed output, to take into account implementation constraints.

A novel buffer-less switch architecture based on optical codes has been proposed and evaluated [4]. Considering the availability of optical codes, it is possible to think to switch incoming packets or bursts by encoding them as a function of the requested output or, in other words, to associate a code to each output wavelength. To this end, each incoming wavelength has to be connected to a tuneable encoder driven by the control unit which decides the code to use, depending on the assigned output wavelength. Of course, the control unit, in order to take this decision, has also to perform the output scheduling. The incoming burst is then fully encoded with the assigned code and forwarded through an optical switching matrix to the desired output where a decoder, configured on that code, recovers the burst. However, it may happen that two or more incoming bursts on the same wavelength are addressed to the same output fibre so that somewhere the wavelength conversion function has to be implemented, since no fibre delay lines are used. Each outgoing wavelength is then equipped with a fixed output wavelength converter (FOWC), which can convert a burst over any wavelength to a fixed wavelength. The switch is then equipped with FOWCs only, from any of the N wavelengths to one. No Tuneable OWC is employed in this switch. The main result of our investigations is that the novel optical code based switch architecture has shown the same performance in terms of burst blocking probability as a Share-per-Node architecture based on TOWCs, but at lower costs, since it does not make use of this kind of expensive converters.

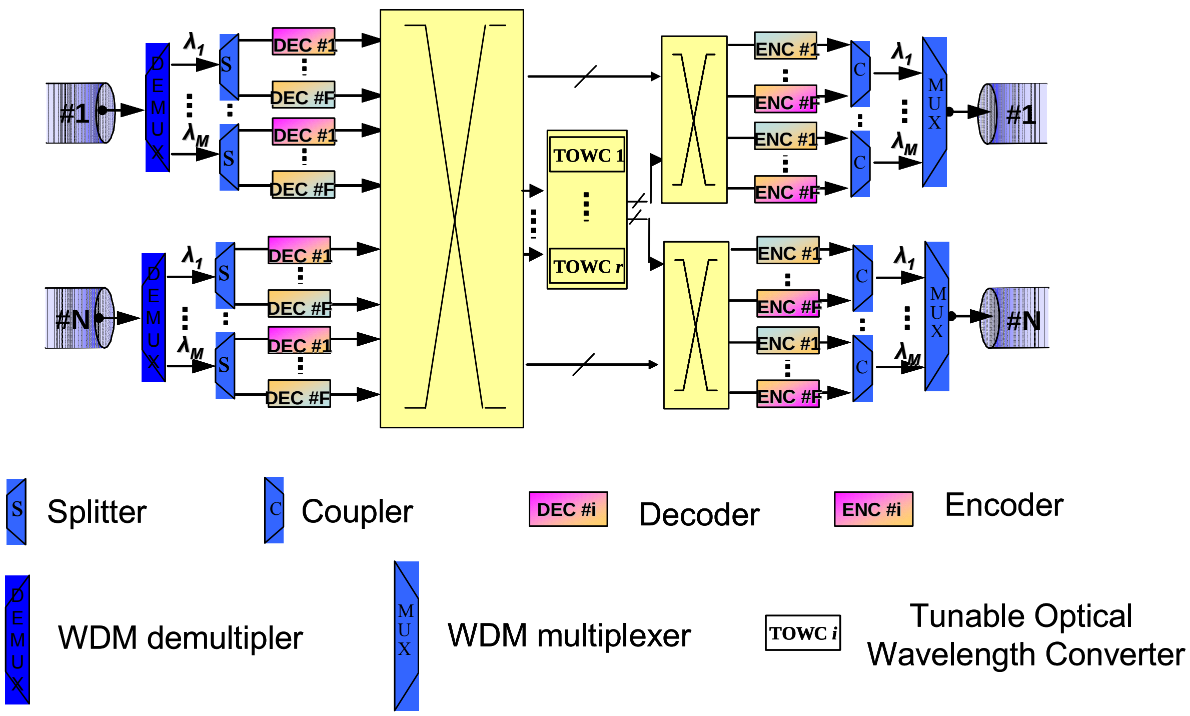

Fig. 1 OCDM/WDM Optical Packet Switch Architecture

Other activities have been focused on the definition of an Optical Packet Switch (OPS) architecture that uses both WDM and OCDM domain to solve the packet contentions. In the defined OPS architecture, illustrated in Fig. 1, the packets are wavelength and code de-multiplexed, next are routed through the switching fabric and the contention resolutions are performed, finally they are multiplexed on the output fiber. One of the advantages of the proposed OPS is to reduce the number of TOWCs used because the control algorithm first tries to solve the contention in code domain by changing the packet code and only if this operation is unsuccessful, the contention is solved in wavelength domain by using one TOWCs of the pool shared according to a SPN strategy.

The following activities have been carried out:

i) Definition of a control algorithm able to solve the output contention at O(*NMF*) complexity, where *N*, *M*, *F* are the number of number of Input/Output fibers, the number of wavelengths and the number of codes carried out on each wavelengths respectively;

ii)Definition of an analytical model to evaluate to dimension the number of codes on each wavelength so that the Bit Error Rate (BER) due to MAI is not too much degraded;

iii)Definition of an analytical model to evaluate the OPS performance; by following a probabilistic approach, the Packet Loss Probability of the switch can be evaluated as a function of the traffic and switch parameters, that is offered traffic, number of Input/Output fibers, number of wavelengths used, code length, number of codes used, number of TOWCs used.

Collaborative actions carried out

Gabriella Cincotti spent two weeks at NICT in October 2008, to test a new encoder/decoder.

A meeting for this JA has been organized on the occasion of the plenary meeting held in Rome between UNIROMA1, UNIBO, UNIMORE and UNIROMA3.

Two call conferences between UNIROMA1 and UNIBO.

Future Activities - Timescale

The physical characteristics of the forwarding path in different architectures and the switch blocking properties are under study; a contribution to a conference at the beginning of 2009 is in preparation.

A new prototype of encoder/decoder is under test in the NICT laboratories and we foresee to perform novel OPS experiments in 2009 [5]. The new device is composed of a input coupler and a set tuneable phase shifters, that spectrally encode the short input pulse. The main advantage, with respect to previous multiport devices, is that the autocorrelation peak is very sharp and that changing the phase values we can generate a larger number of labels.

The analytical models will be used to evaluate the effectiveness of the WDM/OCDM technique to solve the output contentions. In particular we will investigate the following aspects: i) the possible redefinition of the spacing between the optical carries today used in the standard WDM signals; ii) the maximum number of flows discriminated in the code domain that is possible to multiplex over a single wavelength; iii) the overall capacity that is possible to guarantee by means of a mixed wavelength/code division multiplexing; iv) the optimum number of codes and wavelength usable in a single multiplex signal.

Outcome of the joint research activity:

Paper published in international peer-reviewed journals or in international conference proceedings:

1. H. Furukawa, N. Wada, Y. Awaji, T. Miyazaki, E. Kong, P. Chan, R. Man, G. Cincotti, K.-i. Kitayama, *"Field trial of 160 Gbit/s DWDM-based optical packet switching and transmission,"* Optics Express, **16**, 15, 11487-11495 (2008).

2. G. Hayashi, Y. Awaji, N. Wada, G. Cincotti, T. Miyazaki, K.-I. Kitayama, *"Demonstration of multi-hop transparent optical code label swapping by self-seed pulse technique using multi-port en/decoder,"*Proc. Optical Fiber Communication Conference (OFC), San Diego, California (2008).

3. S. Yoshima, N. Wada, G.Cincotti, T. Miyazaki, and K. Kitayama, *"Multicast-capable optical-code label packet switch: Proposal and its experimental demonstration,"* Optical Switching and Networking, 5, 29–37 (2008).

4. M. Casoni, *"A novel photonic switch architecture based on optical codes for optical burst switched networks,"* Proc. IEEE Workshop on Optical/Burst Switching, London (UK), 2008, September 8°.

5. G. Cincotti, G. Manzacca, X. Wang, T. Miyazaki, N. Wada, K.-i. Kitayama, *"Reconfigurable multi-port optical encoder/decoder with enhanced auto-correlation,"* IEEE Photonics Technology Letters **20**, 2, 168–170 (2008).

4.6 JA6 – Repacking and rearranging algorithms for multi-plane banyan type switching fabrics.

Responsible partner: Wojciech Kabacinski, PUT

Participants: POLIMI, PUT

Description of work carried out.

The project aims at control issues of multi-plane banyan-type switching networks. Currently photonic switching is mainly introduced in Optical Cross-Connect Systems (OXCs) and Optical Add/Drop Multiplexers (OADMs). Many of these systems use 2×2 optical switching elements produced in different technologies. Systems of greater capacity are obtained by connecting many such elements in a switching fabric. One of the considered architecture used for constructing optical switching fabrics is the banyan-type switching fabric. It is constructed of 2×2 switching elements arranged in n stages, $n = \log_2 N$, N denotes the number of input and output ports of the switching fabric. The main drawback of this type architecture is their blocking. To obtain non-blocking operation of this switching fabric, many of its copies are being connected in parallel. Such architecture is called a multi-plane switching fabric.

Multi-plane switching fabrics may be rearrangeably, strictly, or wide sense non-blocking. In this joint activity control algorithm for rearrangeable and repackable multi-plane banyan type switching fabrics are elaborated.

In 2008 the research group of Poznan University of Technology and Politecnico di Milano have investigated a rearranging algorithm for multi-plane banyan type switching fabrics with even number of stages. Up till now rearranging algorithms for this type of switching fabrics were based on graph coloring and algorithms proposed by Paull for three stage Clos switching fabrics [1]. Graph coloring algorithm are more suitable for simultaneous connection model [2], where all connections arrive to a switch at the same time. Paull's algorithms are designed for one-by-one connection model, where connections are set up one-by-one. It is also important, that during re-switching of existing connections, transferred data will not be corrupted. Re-switching of existing path also influents the overall connection set up time. So the lower is the number of rearrangements, the shorter is the time a new connection wait for a connecting path.

Rearrangeable networks can be an interesting alternative, especially in those cases in which the number of SEs in the fabric is a critical parameter. This may occur for several reasons, such as cost, mutual interference between the active connections in the fabric (crosstalk), complexity of the control system, etc. For instance, in the particular but very interesting case of the photonic switching systems, a large number of SEs implies accumulation of crosstalk and excess power dissipation in most known technological implementations. Moreover, in integrated photonic technologies the number of switching devices that can be included on the same optical substrate is severely limited by the maximum area allowed.

The advantage of a rearrangeable fabric in terms of cost and signal degradation reduction is paid by the drawback represented by the need to rearrange the already established connections. The disruption of service due to rearrangements implies a certain data-loss which depends on the fabric reconfiguration speed and the frequency of reconfigurations. For example, in the case of an Optical Cross Connect (OXC) in a circuit-switched WDM network based on the current photonic technology, the data-loss ratio due to reconfigurations can sometimes be higher than the data-loss ratio due to transmission errors. For instance, considering a switching time of a few milliseconds, typical of many today's slow switching devices (to be conservative), a reconfiguration period of the connection in the OXC of one day implies a data loss ratio on the order of 10^{-8}.

During the work on control algorithm for multi-plane banyan type switching fabrics we notices, that both graph coloring and Paull's algorithms do sometimes unnecessary rearrangements. Therefore, we tried to elaborate a new control algorithm which allows to omit these unnecessary rearrangements. The first result was to noticed, that when a new connection in the switching fabric is blocked, than there must be three types of connections in the network, some of them may be rearrange to the same switching plane to unblock this connection. Then we concentrated on the switching network with even number of stages. We noticed, that for such switching fabric we can always unblock a new connection by rearranging only one of existing connections. The appropriate theorem was formulated and proved. We have also proposed two versions of the control algorithm which can be used to control the switching fabric (in order to find which connection should be rearrange).

The main results of the current works are subject of the paper submitted to ONDM 2009.

The other non-blocking category considered in the case of the three-stage Clos switching fabric is the repacking one. In this joint activity we plane to enchanced the repacking problem also to the multi-plane switching fabrics. This requires an appropriate control algorithm and also rearranging algorithms. Both kind of networks and algorithms will be investigated in this JA. An important thinks which have to be taken into account are; non-interruptive rearrangements of connections and crosstalk avoidance. Both of them will be considered.

Collaborative actions carried out

The main collaboration actions take place through e-mail exchange, meetings during WP 14 meeting and BONE plenary meetings.

Future Activities - Timescale

(please include work plan for 2nd year with a timeplan for the work proposed.)

During the next year the similar results should be elaborated for switching fabrics with odd number of stages.

The other non-blocking category considered in the case of the three-stage Clos switching fabric is the repacking one. In the second year of this joint activity we plane to enchanced the repacking problem also to the multi-plane switching fabrics.

An important thinks which have to be taken into account are; non-interruptive rearrangements of connections and crosstalk avoidance. Both of them will also be considered in the second year.

Outcome of the joint research activity:

W. Kabacinski, J. Kleban, G. Maier, A. Pattavina, and M. Zal, " Rearranging Algorithms for $\text{Log}_2(N;0;p)$ Switching Networks with Even Number of Stages", submitted to ONDM 2009.

4.7 JA7 - Power Consumption and Supply of High-Performance Switching Elements.

Responsible partner: TUW

Participants: TUW, UPCT, BME, PoliTo, UNIMORE

Description of work carried out.

Power dissipation is a very important task when planning and designing network elements for the future Internet. It is expected that switches and routers will need to provide a very high capacity of hundreds of Terabits or even several Petabits in the near future. Besides the high capacity they also need to be highly reliable. The increased capacity and introduction of new technologies will open new questions and problems related to power consumption and supply as well as protection.

This JA aims in estimation of power consumption of different node architectures for future optical core networks that are based on various transmission and switching technologies (electronic/optical/hybrid implementation, circuit/packet/burst switching, and different switch architectures). Moreover, options for uninterruptible power supply systems (UPSs), battery backup, and alternative energy generation and storage will be examined.

A generic architecture of a high-capacity node is shown in Figure 1. It is composed of a high port-count switching fabric, a large number of input and output interfaces, a switch control module and transmission subsystems. High-capacity links between two core nodes will probably be based on optical wavelength-division-multiplexed (WDM) multi strand fiber transmission systems as it is to large extent already the case in current networks. Transmission efficiency and bandwidth utilization may be even further improved by using hybrid multiplexing techniques and advanced modulation formats. Input and output interfaces, i.e., line cards, could be implemented using different technologies even within one switch to optimally scale costs. A possible implementation option is to strictly follow the O/E/O approach, i.e., to realize line cards completely in electronics. Some functions could also be implemented in optics leading to hybrid implementations. An all-optical implementation would require all functions to be implemented in optics. A very important question is whether electronic or optical buffers are used and what size and type of buffer will dominate?

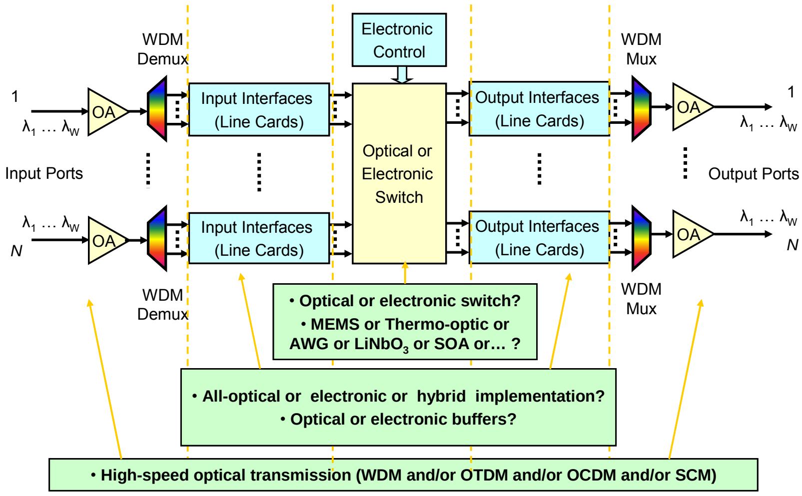

Figure 1: Generic architecture of a high-capacity switching node.

The joint work is divided into 3 phases:

Phase 1: define node architectures to be considered in the study

Phase 2: develop models for estimation of power consumption

Phase 3: discuss and present results obtained for defined architectures and by using the developed models

During the first project year, we almost finished the phase 1 and partly undertook the work in phase 2. The architectures considered so far are:

- Input-buffered wavelength-routed architecture based on AWGR
- Architectures based on combined ROADMs and multi-granularity switching: fiber, waveband and wavelength
- Optical burst-switched node based on encoders/decoders
- Optical packet-switched node based on SOAs
- Optical circuit-switched core node based on MEMS switches
- Electronic circuit-switched core node based on large electronic crosspoints
- Electronic packet-switched core node based on electronic buffered packet switches.

The four latest architectures have already been studied and first results presented in [1] and [2]. Some of the results are shown in Figure 2. Estimated power consumption for large electronic core nodes are shown in Figure 2 a), while Figure 2 b) is related to optical implementation of high-capacity packet- and circuit-switched nodes with and without using optical wavelength conversion and signal regeneration. Additionally, a projection for the year 2018 based on predictions in CMOS technology development that has been issued by the International Roadmap for Semiconductors (ITRS) is shown in Figure 2 a).

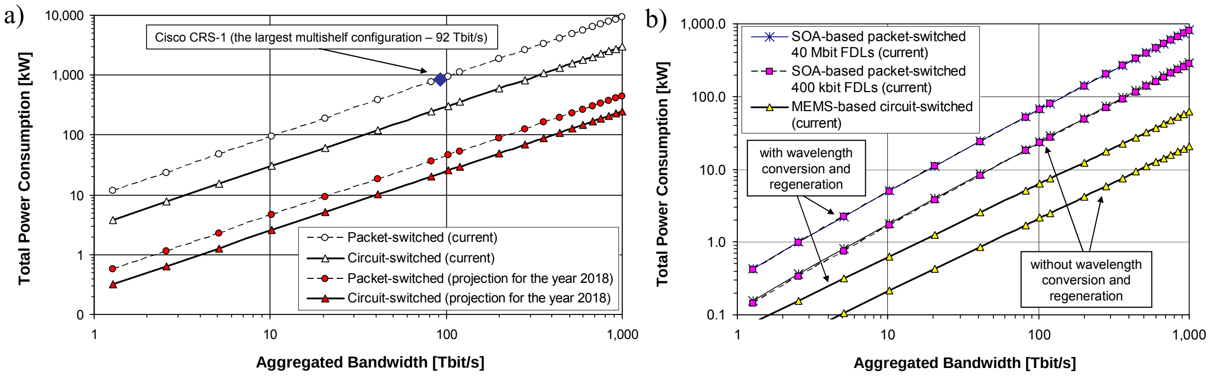

Figure 2: Estimated total power consumption of high-capacity a) electronic and b) optical network nodes.

It can be concluded from these preliminary results that power consumption is an important limiting factor for scaling the current node architectures and implementation approaches to very high capacities. The results obtained for electronic packet-switched nodes show a good agreement to the data of the currently available high-performance routers. The total consumption of a 100 Tbit/s electronic IP router including the power needed for room cooling equipment is above 1 MW. Optical core nodes consume in general less power than electronic ones. The consumption of large electronic core nodes can be reduced to a large extent when taking into account the ITRS predictions for the future development of electronic SiCMOS devices.

Future Activities - Timescale

The work on phases two and three will be continued and if indicated, the set of considered architectures will be extended. We envisage publishing of results in scientific journals (OSA, IEEE, Elsevier) and conferences (ICTON, ECOC).

Outcome of the joint research activity:

[1] S. Aleksic, "Power consumption issues in future high-performance switches and routers", in Proceedings of ICTON 2008, pp. 194 - 198.

[2] S. Aleksic, G. Franzl, B. Statovci-Halimi, "Energy Consumption Related Issues in High-Capacity Network Nodes", in Proceedings of NOC 2008 , Krems, Austria, pp. 52 - 59.

4.8 JA8 - All-optical switches utilizing microring resonators..

Responsible partner: UoA, (Adonis Bogris)

*Participants:*UC3M (Carmen Vázquez)

Description of work carried out.

Micro-Ring (MR) resonators have been demonstrated as all-optical switches in several simple or more complex configurations. The switching is usually achieved by changing the spectral characteristics of the filter. An incoming signal which coincides with the wavelength of a resonant mode of the MR cavity is switched by either the change of the transmittance or the detuning of the mode, or both. The optical characteristics and thus the spectral properties of active MR resonators can be dynamically tuned by changing their refractive indices. Electro-absorption, gain or free carrier injection have been investigated as the modulation mechanisms of the MR resonator characteristics. The thermo-optic or the electro-optic effect can be used as well.

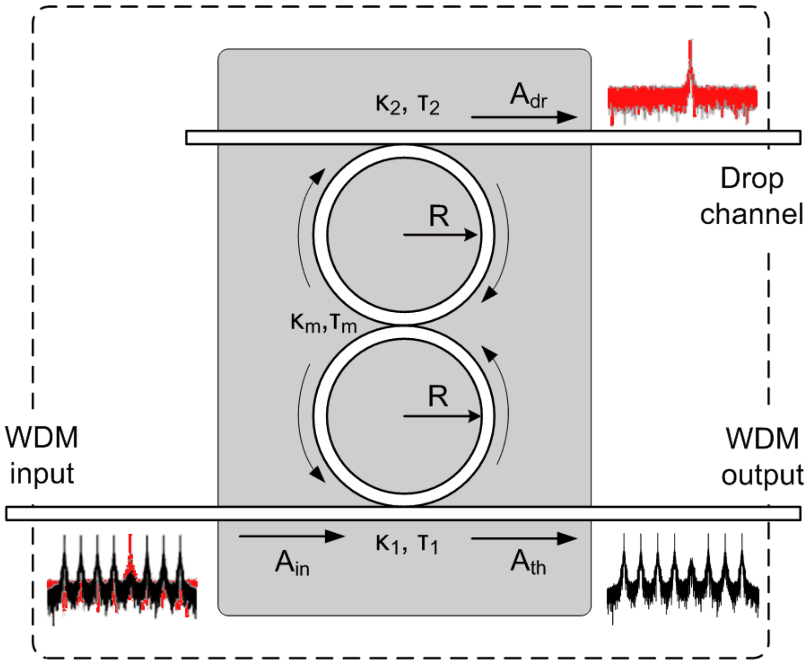

Fig. 1. Novel scheme of a ns all-optical switch.

UoA has developed activity in the investigation of semiconductor-based microring resonators switches, while UC3M has an expertise in complex microring resonators using either liquid crystals or Sagnac loops for enhanced higher-order transfer functions. A novel scheme for ns all-optical switching is demonstrated in fig. 1 and the numerically simulated switching performance is depicted in fig. 2. UC3M has proposed a wavelength router where the aforementioned switch can be integrated. The wavelength router architecture is depicted in fig. 3.

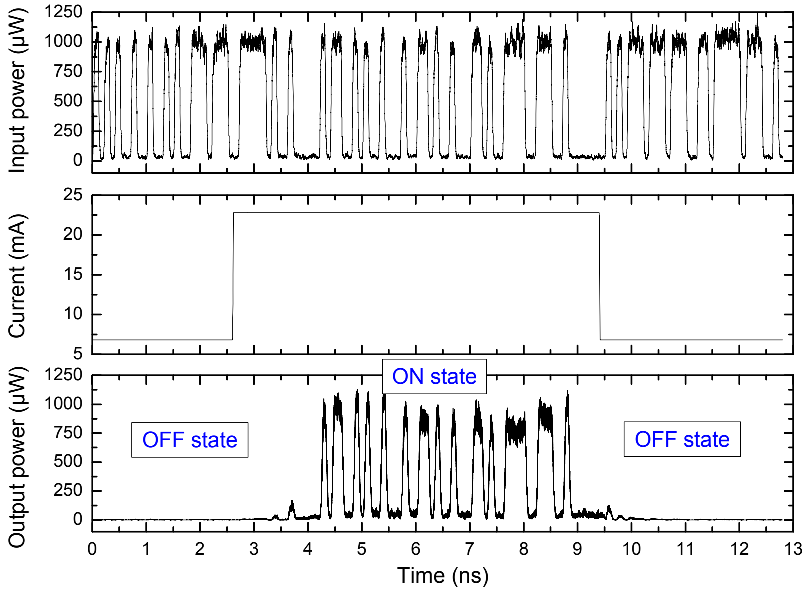

Fig. 2. Simulation of dynamic operation of the proposed switching module: time trace of 10 Gbps NRZ input signal (top), the current pulse for switching from ON- to OFF-state, the transmitted signal on ON-state.

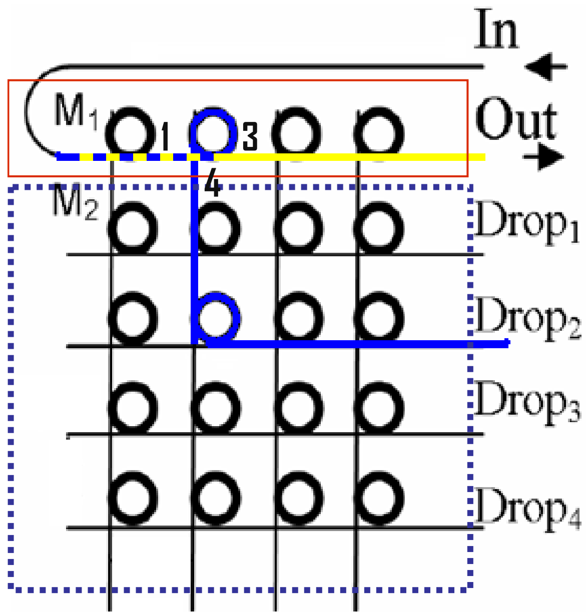

Fig. 3. A wavelength selective router to be utilized in a dynamically reconfigurable broadband access networks.

A model in order to numerically evaluate the performance of the all-optical switch in such a wavelength router configuration is currently under development. UC3M has the expertise in evaluating such space switch architectures using VPIphotonics™ . Some preliminary simulations of ring resonators switches using it physical model and its transfer function model have been developed.

The other configurations proposed by UC3M in order to improve tuning capabilities and on-off contrast ratios are shown in Figure 4.

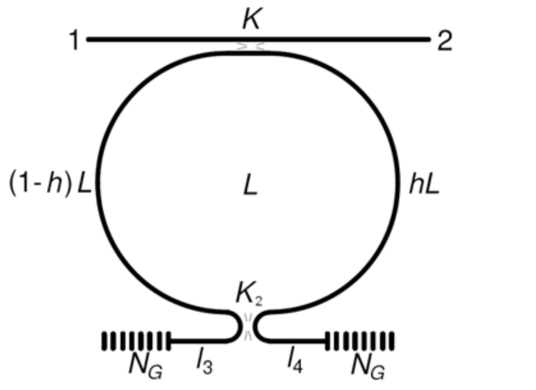	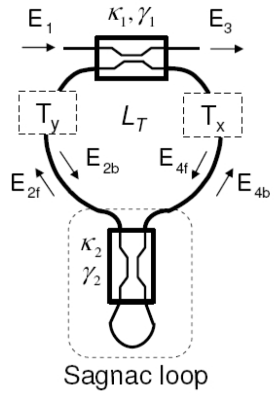
Figure 4.a. Michesol interferometer using Bragg gratings in a ring resonator	Figure 4.b. SIRR Sagnac interferometer in a ring resonator

Even higher order filters can be designed using an optical filter synthesis method proposed by UC3M and based on optical mirror ring resonator (OMRR)-based structures, as building blocks of infinite impulse response (IIR) filters. The method is based on cascading all-pole and all-zero structures, but using an all-pole second-order structure, made of a Sagnac interferometer in a ring resonator, named SIRR. The main advantage of using the SIRR is that there is no need of phase shifters. It also has immunity to variations in the ring lengths. This is a key factor to produce the same time delay in a second-order transfer function realized with cascaded first-order transfer functions. Finally, it also has design flexibility, because this structure permits the synthesis of complex conjugated poles, located in any place, by varying a coupling coefficient and an amplifier gain.

Collaborative actions carried out

The two partners had three meetings up to now where they had initially a discussion on microring architectures in switching and microring technologies. They also decided on the architectures that will be studied and tried to resolve technical issues referring to difficulties in simulating different components and bringing them together in the same simulation platform.

Future Activities - Timescale

1. The first future activity is to assess two or more switching building blocks in terms of their main features, namely switching time, on-off contrast ratio, supported bandwidth etc. and its simulation in a software tool able to scale its performance in complex architectures with reasonable computing times. (second year)
2. The second activity will be to insert the most promising device in a more complex structure such as the wavelength router depicted in fig. 3 in order to assess the performance of the device in more realistic network node architectures. (third year)

Outcome of the joint research activity:

Up to now some individual results on the proposed configurations has been reported such as

1. **C. Vázquez**, O. Schwelb " Tunable, narrow-band, grating-assisted microring reflectors” ***Optics Communications***, 281(19) pp. 4910-4916 , October 2008

4.9 JA9 - All-optical label processing techniques for ultra-fast optical packet switches.

Responsible partner: SSSUP

Participants: SSSUP, UNIROMA3, NICT.

Description of work carried out.

The joint activity has the goal of investigating all-optical processing techniques for the processing of the labels in ultra-fast optical packet switches. In the first part of the activity, the scenario of an optical packet switching (OPS) node with time-division multiplexed (TDM) label is considered.
A combinatorial network for the resolution of the contentions is designed and implemented in a real 2×2 160 Gb/s/port OPS node test-bed at NICT in Koganei, Tokyo, Japan. The structure of the 2×2 160 Gb/s/port OPS node is shown in Figure 1. It is composed by a label extractor, a contention detector, and a 2×2 switch. One input port of the node has a higher priority with respect to the other one. In case of contention, the packets at the low priority input are cancelled. The packets arrive at the input ports synchronously. No void packets are allowed. The packets are generated with a 160 Gb/s PRBS 2^7-1 payload and a 50 Gchip/s label. The 256-bits payload is at 1560 nm, while the 2-chip label at 1550 nm. The separation between label and payload is about 1.75 ns. The packet rate is 19.44 Mpacket/s. If the label bit is '1', the packet is switched to the output port 1 of the switch, otherwise to the port 2. Two label patterns are generated: '10' (label A) and '11' (label B). Two identical packet streams enter the high priority and low priority input ports, being the high priority stream delayed of two packets with respect to the low priority one.

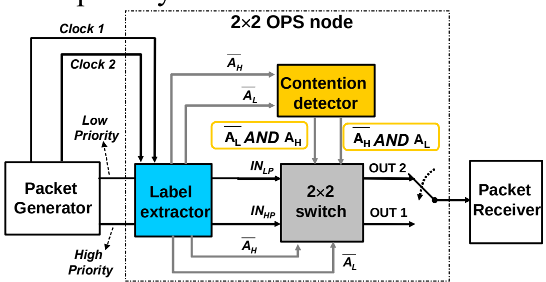

Figure 1: Structure of the 2×2 160 Gb/s/port OPS node.

The scheme of the contention detector is shown in Figure 2.

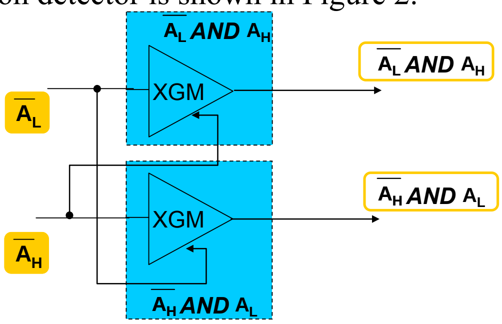

Figure 2: Contention detector

A_H and A_L are the extracted address bit of the high priority and low priority input respectively.

XGM is exploited in 2 SOAs. In SOA4 NOT (A_H) works as a pump, while NOT (A_L) as a probe. The signal at the SOA output corresponds to the logic function NOT (A_L) AND A_H. In SOA3 NOT (A_H) works as a probe, while NOT (A_L) as a pump. The implemented logic function is NOT (A_H) AND A_L. In this implementation the two outputs are kept separated, generating two control signals for the cancellation of the low priority packet in case of contention. If the address bits are equal (contention), both the outputs are a logical '0' and the low priority packet is cancelled. If the address bits are different (no contention) one of the two signals is '1' and no cancellation takes place.

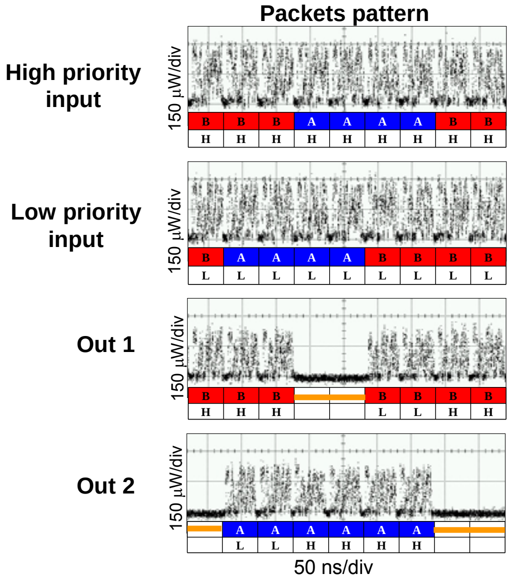

Figure 3: packet stream at high priority input, low priority input, switch output port 1 and 2.

Figure 3 shows the packet stream at the high priority and low priority input port compared with the packet stream at the output port 1 and 2. The label (A, B) and the priority (H: high, L: low) are indicated for all the packets. The sequence of the output packets demonstrates the switch works properly. When a contention occurs the packet with the lowest priority is cancelled, as it is indicated by the void slots in Figure 3 (Out1) and (Out2).

Collaborative actions carried out

Hideaki Furukawa visited SSSUP for a week in March 2008 to perform preliminary experimental activity.

Mirco Scaffardi visited NICT from mid April to mid August 2008 to perform a joint experiment implementing the combinatorial network in a OPS node test-bed.

Gabriella Cincotti visited NICT in October 2008 for two weeks to test the prototypes of the newly developed multiport encoder/decoder.

Future Activities - Timescale

The future activity is focused on an OPS node operating on packets with OCDMA label. UNIROMA3 proposes the use of a new multi-port encoder/decoder to generate and process labels. The encoder is currently under test at NICT laboratories.

The device has 15 ports and can generate and process 15 orthogonal codes. The main advantage with respect to the multi-port encoder/decoders already demonstrated is that the autocorrelation peak has a sharp delta-like shape which coincides with the input short pulse. Therefore the TDM label can be substituted by an optical code. Moreover, since 15 codes are available, it is possible to drive a 15×15 switch, or, alternatively to use some codes to indicate the priority of a packet. The priority can be changed according to output of a scheduling algorithm. The code processing does not require label extraction, i.e. the packet (payload and the label) can just be forwarded to the encoder/decoder.

Outcome of the joint research activity:

M. Scaffardi, E. Lazzeri, H. Furukawa, N. Wada, T. Miyazaki, L. Potì, A. Bogoni, “160Gb/s/port 2x2 OPS node test-bed performing 50Gchip/s all-optical active label processing with contention detection”, In Proc. Photonics in Switching 2008, PDP1, Sapporo, Japan.

G. Cincotti, G. Manzacca, X. Wang, T. Miyazaki, N. Wada, K.-i. Kitayama, “Reconfigurable multi-port optical encoder/decoder with enhanced auto-correlation,” IEEE Photonics Technology Letters 20, 2, 168–170 (2008).

4.10 JA11 –The Optical Switch Architecture with Recirculation Buffer and Wavelength Conversion.

Responsible partner: Wojciech Kabacinski, PUT; Kyriakos Vlachos, RACTI

Participants:, PUT, RACTI

Description of work carried out.

The project aims at the novel switch architecture with optical buffers. Nowadays, telecommunication networks consist of optical fiber links and electronic nodes. The common used technologies such as DWDM enable to transport data with tremendous bitrates, therefore the switching capacity is becoming the bottleneck of the telecommunication networks. Currently, our research group focuses on all-optical switching technologies, where optical/electronical conversions are limited to minimum. To accomplish that, an important issues that we have concerned are the proper switch architecture and buffering issues in optical domain. Currently, buffering is mainly implemented as electronic devices (RAM). To overcome expensive and slow E/O and O/E conversions, we have to store packets in fully optical domain. Such a buffering is typically done by fixed delay lines (FDLs). During this JA we are investigating some switch architectures with FDLs.

We proposed two architectures for implementing optical buffers. Both use multi-wavelength selective elements like quantum dot semiconductor optical amplifiers (QD-SOAs) as multi-wavelength converters and fixed-length delay lines that are combined to form both an output queuing and a parallel buffer switch design. The output queuing buffer design requires less active devices (QD-SOA) when implementing large buffers, but the parallel buffer design becomes more profitable, when the number of wavelength channels that can be simultaneously processed by the wavelength selective switches (QD-SOAs) increases. We also proposed the scheduling algorithm to resolve packet contention in the parallel buffer architecture and carried out a simulation considering mean packet delay, maximum buffer occupancy and packet loss probability

We consider now another buffer architecture with recirculation buffers and wavelength conversion. The FDL architecture with wavelength conversion has been elaborated in PUT for DWDM signal generation. We plan to use this FDL as a buffer now. The work will firstly concentrate on the buffer implementation and performance. We will use a non-resonant, ring optical frequency comb generator employing a three port acousto-optic frequency shifter (AOFS), a single master laser (ML), an erbium doped fiber amplifier (EDFA) and a band limiting filter (BLF). In this comb generator every loop round-trip AOFS splits the optical beam into two and the frequency shifted ray after the amplification and filtration is directed back to the AOFS input. The multiple divisions, spectrum shifting and the optical beam amplification in the ring configuration result in the generation of an optical frequency comb. The AOFS controlled by a RF generator determines the frequency comb interval and the BLF limits the number of frequency lines. The buffer implementation will use each frequency of the comb to store one packet. Each time packet goes through the AOFS it is shifted to the next frequency. Based on this comb generator we propose the feed-back buffer architecture. All packets entering the switch are directed to wavelength shifters (WSs). The WS has two outputs. The first one doesn't change the wavelength, and the signal reaches the output without any conversion. The second output shifts the wavelengths of 1,5 GHz and goes to one packet long fiber delay line (FDL). The optical amplifier is employed to overcome losses introduced by WS and then band-pass filter is used to choose a proper wavelength. The signal from FDL (shifted and delayed) is then combined with the newly arrived packet at the entry and the whole process is repeated. Thus, packet may recirculate multiple times and it appears in output in every allowable wavelength.

Collaborative actions carried out

The main collaboration actions take place through e-mail exchange, meetings during WP 14 meeting and BONE plenary meetings.

Outcome of the joint research activity:

Vlachos K., Kabaciński W., Węclewski S.; "New Architectures for Optical Packet Switching using QD-SOAs for Multi-Wavelength Buffering", in International Workshop on High Performance Switching and Routing, Shanghai, 2008.

4.11 JA12 - Encompassing switch node impairments and capabilities in dynamic optical networks.

Responsible partner: SSSUP-COM

Participants: SSSUP: Nicola Andriolli, Nicola Sambo, Mirco Scaffardi, Piero Castoldi; COM: Martin Nordal Petersen, Sarah Ruepp.

Description of work carried out.

The JA12 aims at studying solutions to cope with node and transmission impairments which complicate the set up of lightpath in all-optical networks. The activity so far has been concentrated on the context definition and on the analysis framework. In particular, in this JA time-variant physical impairments will be studied and lightpath provisioning schemes will be proposed to optimize network performance. Thus, the JA is focused on:

- node impairments;

- transmission impairments;

- node capabilities.

While there exist several interesting impairment types to investigate, it has been decided to focus on polarization mode dispersion (PMD) in the first phase of the JA. For a more detailed description including background of the JA, please refer to the JA proposal.

Focus on PMD dynamics

Previous research results [SA08] show that, considering worst-case cross talk margins instead of dynamically computed values, the number of established lightpaths is significantly reduced, since lightpaths with an actually acceptable QoT are rejected due to worst case margins. Instead, the dynamic evaluation of some impairments that are time-variant (e.g., PMD, node crosstalk) may result in a throughput increase. Indeed, PMD can be lower and less detrimental in particular time ranges. In [BB04] for example, it is shown that the maximum observed PMD change over the monitoring period (48 hours) is 0.5 ps while the average PMD is 0.64 ps.

For our modelling purpose, a PMD dynamic model reported in [AC08] can be used to predict the PMD value in an optical network. So, assuming to monitor PMD on a link l_i at time t', it is possible to assess that PMD will be $PMD_i(t|t')$ with a probability $P_i(t|t')$. Then, given that

i) $PMD_i(t|t')$ is not detrimental for the correct data receipt and

ii) the probability $P_i(t|t')$ of having the $PMD_i(t|t')$ is sufficiently reliable that a light path can be established along link l_i during the lapse of time $\Delta t = t - t'$.

These considerations can be extended and applied to a concatenation of links, i.e. path. In particular, the flowchart in Fig. 1 shows a generic lightpath set up. Upon lightpath request at time t_1, the path computation is performed. If no path with available network resources (e.g., bandwidth) exists, the lightpath request is blocked. Otherwise (i.e., a path *p* is found), given the measured PMD values before lightpath request (i.e., $t_0 < t_1$), the PMD along p is predicted for the lightpath duration T. If the path p is feasible in terms of QoT in the lapse of time T with an acceptable probability (i.e., $P > P_{TH}$), the lightpath can be set up and signalling starts along p. Otherwise, another path is computed avoiding the previous considered paths p.

This work aims to consider the PMD dynamics [BB04, CC98, AC08] instead of considering the average PMD value during path computation and wavelength assignment. The two solutions will be compared in terms of throughput, blocking probability, and monitoring rate.

If an accurate PMD estimation is too difficult, the monitored PMD value (together with a coarse PMD estimation) can be used to force switching on a better path/wavelength when approaching temporary excessive PMD, thus recurring to protection/restoration techniques.

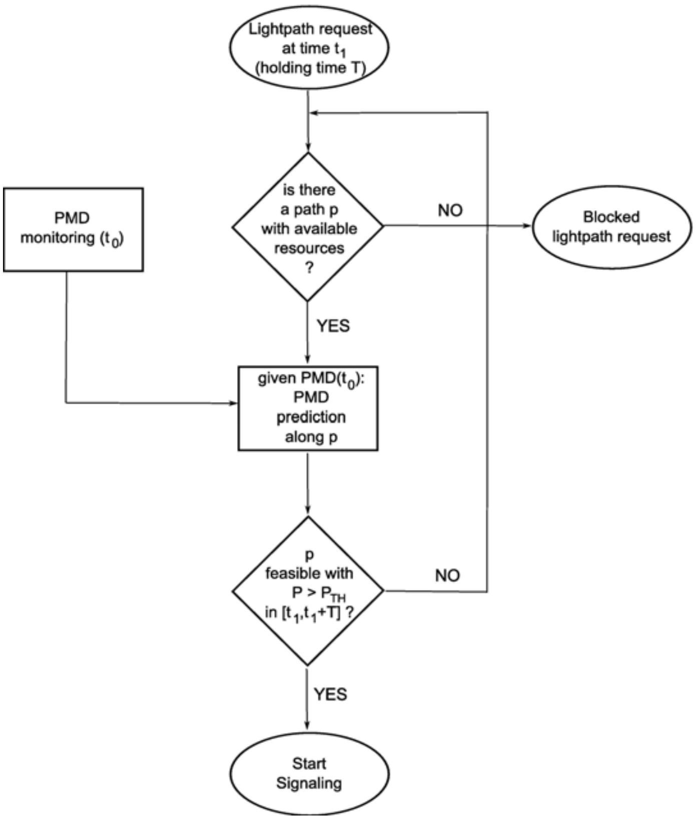

Fig. 2. Flowchart describing the lightpath set up

Analysis methods

The main analysis methods for the proposed activity are twofold:

- Experimental test bed for PMD monitoring
- Network simulation (utilizing the parameters measured on test bed)

At a first stage, the two activities are being conducted in parallel: an experimental set up is being devised to perform the monitoring, while the impairment-aware simulator will be adapted to the scenario under investigation. When the test bed and the simulator are fully ready, it will be possible to feed the simulator with real PMD values.

Collaborative actions carried out

- One tele-conference meeting in October 2008
- Visit and meeting planned for Jan 2009 (at SSSUP) to plan forthcoming mobility activities

Future Activities - Timescale

- Mobility (M.N.Petersen to SSSUP): A mobility is planned in February 2009 in order to carry out lab experiments related to PMD monitoring.

- Mobility (N. Sambo to COM): A mobility is planned in summer 2009 in order to further develop the numerical vector model.

References

[BB04] M. Brodsky, et.al, "A "Hinge" Model for the Temporal Dynamics of Polarization Mode Dispersion", LEOS Ann. Meeting 2004.

[SA08] N. Sambo, et.al, "Introducing Crosstalk-Awareness into GMPLS-controlled transparent optical networks", OFC 2008.

[CC98] J. Cameron, at.al, "Time Evolution of Polarization Mode Dispersion in Optical Fibers", IEEE Photon. Technol. Lett., June 1998.

[AC08] C. Antonelli, et.al, "A Model for Temporal Evolution of PMD", IEEE Photon. Technol. Lett., June 2008.

4.12 JA13: Impact of MEMS VOA reliability on Service oriented optical network architecture

Responsible partner: Rebecca Chandy, Ericsson
Participants:, Ericsson, KTH

Several Micro-electromechanical systems (MEMS) designs and processes have been proposed for various fibre optic applications. Reliability depends on the detailed design of the structures as well as the technologies used to fabricate them. In addition to the silicon MEMS, other parts of the optical switch may have an impact on device reliability. The need for a hermetic housing with a large number of fibre feed-troughs is especially challenging for large-port-count optical MEMS switches. The hermetic seal must prevent any ingress of moisture into the package. Seals based on solder or glass can meet this requirement. If any adhesives are used in the manufacturing of the device, they must guarantee long-term stable fixation of the optical parts as well as prevent contamination of the environment inside the package.

To qualify components and subsystems for use in telecommunications systems, Telcordia Generic Requirements are often used as guidelines. Device qualification tests based on Telcordia's "Generic Requirements for Singlemode Fiber-optic Switches" cover both endurance and mechanical robustness tests. Mechanical robustness tests include fiber integrity testing, mechanical shock, mechanical vibration, humidity, thermal cycling, and thermal shock. Each of these tests must be performed on a statistically meaningful sample, often a "lot tolerance percent defective" of 20% is required, meaning that in a sample of 11 switches, none may fail during the test.

Static reliability of a digital switch concerns the ability to alter states after it has remained in the same state for a long time. The associated failure mode is often referred to as "stiction." Dynamic reliability concerns the ability of the switch to perform a large number of switch cycles, also called durability. Both static and dynamic reliability are strongly dependent on the detailed design of the MEMS structures. It is complicated to estimate the static reliability of all types of optical switches, because there are no clear accelerating mechanisms that allow extrapolation toward normal-use conditions. The best approach, therefore, is to undergo testing of the switches for a lengthy period of time and switch them at certain time intervals.

Telcordia requires this test to be performed over time intervals ranging from 168 hours up to 5,000 hours. It is recommended to extend these tests over a considerable period of time and test a large quantity of devices to verify a low failure rate over the expected life of 20 years. One million failure-free switch cycles are often required for dynamic reliability-equivalent to operation over 20 years in which each switch path is cycled every 10 minutes. By eliminating mechanical contact between the moving parts of the MEMS structure, excellent performance in excess of 10 million cycles has been obtained for digital MEMS optical switches.

Testing the MEMS VOA that was inserted in Sub Rack for network traffic errors

In addition to the requirements laid out in Telcordia standards, there are times when Telcordia tests are not sufficient to ensure the in-service and long term reliability requirements of the product. Further tests are then conducted as shown in this section. The following tests were conducted to assess the effects of mechanical disturbance to the sub-rack in which a card with a MEMS Variable Optical Attenuator (VOA) was fitted. The tests were primarily done to investigate if the cards with MEMS VOA were sensitive to vibration or not. Based on the results of the tests, an understanding of the failure modes in a MEMS VOA could be obtained. This enabled a decision to be made on whether the MEMS VOA could be used as it is or whether an alternative VOA or a redesigned MEMS VOA should be used.

The system used two VOA's, one in the Transmission path to control the Transmission power and one in the Receiving path to maintain an optimum Receiving operating power. Initial test were done with one test card and with the WDM Transmission path split between oscilloscope (via a PIN) and WDM Receiver. Shock was generated by opening and closing card ejectors.

The test done showed that there was an impact and clear effect was seen on Transmission power which affected traffic. It was therefore essential to separate out the Transmission and Receiver effects. A second card was set-up with a separation of about 2m from the first card. One card was set-up as a receiver and the other as transmitter. It was still easy to generate errors by tapping either the Transmission or Receiver unit. Errors caused by opening or closing the card ejectors was only really a problem at very low Receiver powers, however, this was found to be a possibility.

Shocks were applied to the centre of the receiver screening can or front panel. The results of shocks to the Receiver screening can at different Transmission powers or different Transmission VOA attenuation settings were observed. The Transmission power reduced at lower attenuation (higher output powers) of the Transmission VOA. A similar test was performed upon a second card with a VOA which used a different technology, instead of MEMS. Traffic errors were not generated with this card and this card was more resilient to effects of shock. This was attributed to the fact that the first card used a MEMS VOA. Traffic errors could be induced in a traffic-carrying card with MEMS VOA by fitting adjacent cards in the sub-rack.

Redesign of the VOA to ensure end to end QoS

It was agreed that if MEMS VOA had to be used, the way forward would be to use shock absorbers. Since the application of the acceleration to the mother board is very little while inserting an adjacent card, a shock absorber is sufficient to eliminate the problem. Detailed results of these and other reliability tests can be provided.

Further work

This joint activity will study how the optical architectures can be exploited and enhanced to realise service oriented architectures.

The future intention of the joint work is to use the MEMS VOA in the wireless network developed by AIT. The VOA will undergo various tests required to ensure reliability in wireless optical networks. This is to ensure that an end-to-end reliability process is in place. The process starts with design and carries through the operational life of the product in the field. Analysis of failure modes during reliability tests and network tests on MEMS VOA has been presented. By taking a proactive approach to identifying and preventing failure modes as part of the design process, the vendor can attain very low failure rates, which can be a key step towards ensuring optical network reliability.

Other activities completed so far:

The other activities completed so far in this work package are:

- N° meetings and workshops: 3
  - Meetings attended so far: Turin, January 2008; Athens, ICTON 2008, June 2008.
  - ECOC 2008 attended
- 1 conference paper published at ICTON 2008
- N° Joint Experiments: 1
- N° mobility actions (incl. mutual visits): 1 visit (Ericsson to AIT)
- N° joint project proposals: 1 planned
  - Work on a joint proposal for Call 4 of FP7
  - 1 planned joint publication for 2009
- Ericsson are Chapter leader for a book : Chapter on architecture of optical components as part of the BONE project
- Contribution to a book chapter: Also Ericsson are separate authors for a sub chapter on the same book

Targeted call for papers: ECOC 2009, JSAC or JON (open call or special issues, depending on opportunities)

4.13 JA14 - Photonic code label processors for ultrafast routing

Responsible partner: UoC

Participants: Prof Ian White, Prof Richard Penty, Dr Jose Rosas-Fernandez, Prof Gabriella Cincotti (Uniroma3), Prof Kevin Williams (TUe),

Description of work carried out.

In this JA, together TUe and UNIROMA III, we will address the implementation of spectral and BPSK codes in multiple coder device using micro ring resonators technology. We have done simulation on spectral encoders using micro ring resonators and we are discussing how to study common parameters within the microring activity for algorithms, systems and fabrication perspectives.

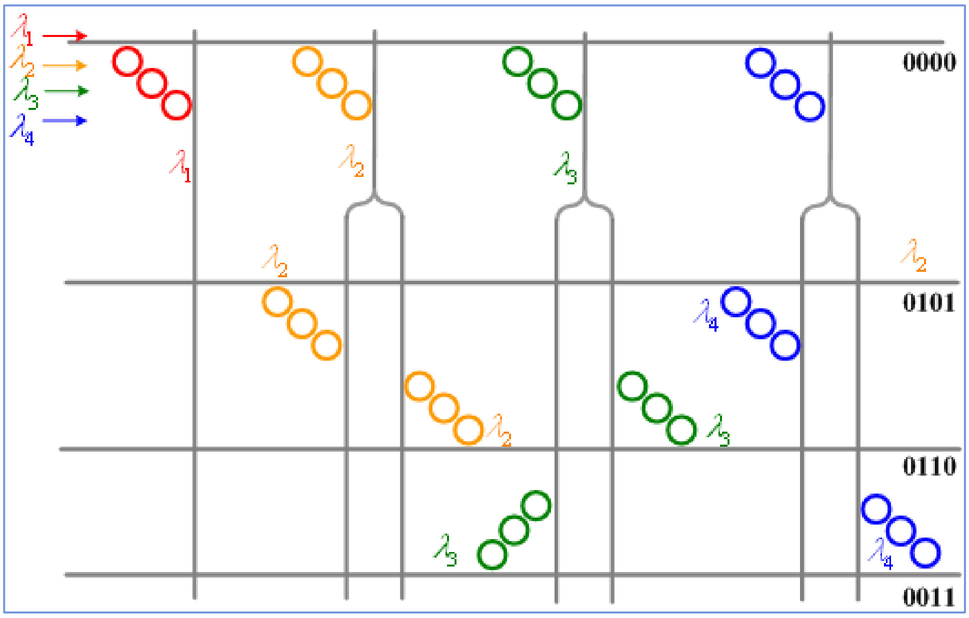

Fig. 1 Structure of a possible multiple SAC encoder for 4 spectral codes

Preliminary results include a proposed structure for spectrum amplitude encoding simultaneously for four different codes (fig. 1).

- By dropping and adding resonant signals, four different codes are generated simultaneously.
- This will not waste the spectrum width, with just increasing the chip size.

Collaborative actions carried out

Meetings (including tele-conferences)

-We had a teleconference to discuss research interest within this JA on October 2nd 2008.

Mobility actions

- Dr Williams (TUe) to Cambridge, one time per month in the last 3 months

Future Activities - Timescale

The research interests for each partner are under discussion. At the photonic circuit level, a multiple encoder/decoder has been designed using an AWG where a short pulse can generate and decode simultaneous 16 codes with 16 chips at 200Gchips/s. In this JA for the next 12 months we will discuss the issues surrounding implementation of such a multiple encoder using micro ring resonators technology. Advantages such as compactness, finesse, and matrix scaling make the microring highly attractive to code recognition. Scaling will be studied in array and matrix form.

Figures of merit will be devised to enable the quantitative comparison of the code family complexity which can be simultaneously generated and recognized in parallel, and how this may impact practical implementation. Possible routes to integrated photonic implementation will also be studied and compared. A particular emphasis will be placed on minimising packaging complexity, identifying fabrication tolerant design and optimising monolithic functionality

Outcome of the joint research activity:

Joint publications:

“Wavelength tuning in a bus-coupled micro-ring laser array", A Bennecer, K A Williams, R V Penty, I H White, M Hamacher and H Heidrich, Semiconductor and Integrated Optoelectronics Conference, Cardiff, 2008

"Study of spectral performance of even-row microring resonator arrays", X Zhang, J B Rosas-Fernandez, R V Penty, I H White, X Zhang and D Huang, Semiconductor and Integrated Optoelectronics Conference, Cardiff, 2008

“Directly modulated wavelength multiplexed integrated microring laser array”, A. Bennecer, K.A. Williams, R.V. Penty, I.H. White, M. Hamacher, H. Heidrich, Photonics Technology Letters, 20, 16, 1411-1413, 2008

“Ultracompact microring laser-based optical-add multiplexer”, A. Bennecer, J. Ingham, K.A. Williams, R.V. Penty, I.H. White, Ehlers, H. Hamacher, M. Heidrich, H., Electronics Letter (44 (9) 593-595 (2008).

“Design of multimode interference coupled polymer rectangular ring resonators with air trench assisted mirrors” Xiaobei Zhang, N. Bamiedakis, J. Beals IV, R. V. Penty, I. H. White, Xinliang Zhang and Dexiu Huang, APOC 2008, Proc. SPIE, Vol. 7134, 71340S (2008).

4.14 JA15 - Hardware efficient optoelectronic switch fabrics

Responsible partner: UCAM

Participants: Prof Ian White, Prof Richard Penty, Adrian Wonfor, Dr Jose Rosas-Fernandez, Mr Eng Tin Aw (UCAM), Dr Kevin Williams (TUe), Prof. Wojciech Kabacinski (PUT)

Description of work carried out.

We have been working with TU/e and PUT in 32 x 32 optimized non-blocking SOA based switches (for 2.56Tb/s aggregate throughput). Also, PUT has designed switching networks with from 8 x 8 to 32 x 32 port counts using 2 x 2, 2x3 and 3 x 3 switches as building block elements.

UCAM has also been working on the development of a monbandwidth of 30nm, and a 5 dB port to port gain for the shortest path. BER measurements on the worst and best case paths at 8 x 10 Gb/s WDM transmission shows an IPDR of >6dB (for a minimum penalty of 1.2dB) at a fibre to fibre gain of -1dB and power penalties of 2dB for a fibre to fibre gain of 2dB. The most recent work has concentrated on optimised cascading of up to three 4 x 4 port switches, this being equivalent to a transmission through a 16 x 16 port multi-stage switch. For 8 x 10 Gb/s WDM transmission we achieved an IPDR > 6 dB with a penalty of < 4 dB.

PUT has also been working on a new switching fabric architecture composed of 2x2, 2x3, and 3x3 switches. This architecture has one stage less than conventional banyan-type switching fabrics composed of 2x2 or 3x3 switches. It requires less SOAs and passive optical splitters and combiners. The cost reduction is for some networks of about 50%.

TU/e has performed detailed physical layer modelling to predict scalability beyond 32 inputs for efficient SOA based fabrics. Calibrations are performed against experimental data from Cambridge. Architectures proposed within the consortium have been studied. Prototype circuits have been designed, fabricated and demonstrated with lower power penalties, with a view to informing architectural constraints for complex photonic ICs in the next phase of the project.

Collaborative actions carried out

We have studied new switch architectures, study of monolithically integrated semiconductor optical amplifier switches and monolithic multistage photonic switches.

Mobility actions:

1) A one week PhD student exchange from Cambridge University to Technical University Eindhoven. For studying high-bandwidth, low-latency system architectures to be adapted for hardware-efficient networks. 17th – 23rd April 2008
2) Dr Williams (TUe) to Cambridge one time per month in the last three moths

Meetings (including tele-conferences) :

The 3 partners had meeting during the Torino Kick-off meeting last January.

The 3 partners had meeting during the WP-13 meeting last June in Athens.

PUT and UCAM had a brief meeting at the Plenary meeting in Rome in October

Future Activities - Timescale

For the next 12 months, the three partners are discussing the most suitable architectures given the physical constraints imposed by SOAs. Also simulation work at system level is envisaged to optimise the number of switching elements, power consumption, crosstalk etc. Simulation studies for the wavelength multiplexed performance of SOA based switch fabrics are anticipated to add further insights into the scalability of the architectures. Studies of mask layout for the integrated building block switch are being considered.

Outcome of the joint research activity:

Joint papers:

"Can Optical Packet Switching Solve the Bottleneck Problem in Electronic Routers?", Ian White, Workshop OME, Optical Fiber Communication Conference in San Diego California on February 26th, 2007.

"High Capacity Demonstration of a Compact Regrowth-Free Integrated 4 x 4 Quantum Well Semiconductor Optical Amplifier Based Switch", Wang, Haibo et. al., ECOC 2008

"Physical layer modelling of semiconductor optical amplifier based Terabit/second switch fabrics", K.A. Williams, E.T. Aw, H. Wang, R.V. Penty, and I.H. White, Post-deadline paper ThPD5, 8th International Conference on Numerical Simulation of Optoelectronic Devices, 2008

4.15 JA16 - Low-crosstalk optical packet-switching architectures based on wavelength-switching and wavelength-sensitive devices.

Responsible partner: PoliMi

Participants: PoliMi, PoliTO, UPCT, UVIGO

Description of work carried out.

This JA focuses on optical switching solutions that entirely or almost entirely rely on the wavelength domain. The actively-switching devices comprise tunable lasers and/or tunable receivers, tunable wavelength converters and/or tunable filters. The interconnection stages are based on wavelength-sensitive passive devices, comprising the well known Arrayed Waveguide Routers (AWGs) (see Fig. xx), the more recent Ring-Resonator Filters (RRFs) and other components. Wavelength-sensitive passive and active devices allow managing the paths inside the switching fabric of several optical connections at the same time in a very cost-effective way.

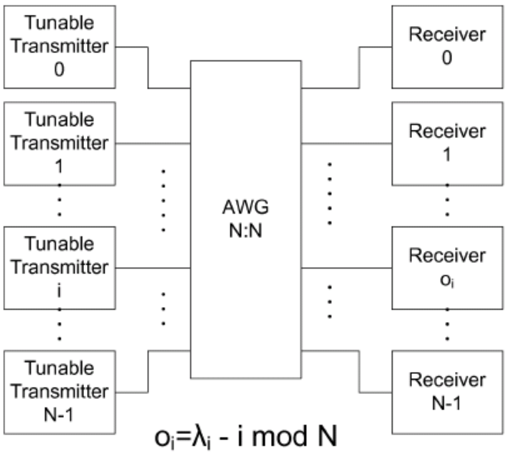

Fig. XX Reference AWG-based switching architecture.

Unfortunately, these kind of switching architectures are often affected by cross-talk impairments. In particular, coherent cross-talk can become a severe limitation to the scalability of the switching systems.

This JA studies optical switching architectures based on wavelength-switching and wavelength-sensitive devices in order to propose and design solutions in which crosstalk is controlled or eliminated. In that regard, the JA will also investigate the trade-offs between less crosstalk and more-demanding requirements on the devices, such as for example wider tuning range of the tunable devices, extended flatness of the transfer function of AWGs, etc. The proposed JA will be mainly dedicated to optical packet-switching architectures, though circuit-switching applications may also be considered in the course of the activity.

Up to this deliverable, **POLIMI** activity has been dedicated to two different research lines:

1. Modelling of physical impairments of single-stage AWG-based architectures.
   The AWG component has been studied by analyzing the most recent literature in order to precisely characterize its physical properties and performance. The goal is to setup a model able to take into account those fabrication and design techniques that allows reducing crosstalk. Once ready, the model will be adopted in the first place to evaluate the scalability of single-stage AWG-based architectures.
2. Study of rearrangeability and strict-sense non-blocking conditions in networks with zero non-filterable crosstalk and wavelength-sensitive switching elements.
   Optical switching fabrics usually consist of several identical planes of switching stages over which optical connections are distributed, so to avoid link contentions. If also crosstalk has to be avoided, it is sufficient to suitably modify (often increase) the number of such planes. The adoption of wavelength-sensitive switching elements gives us the opportunity to collapse the planes on fewer physical planes (possibly a single one) while maintaining the original necessary number of logical planes separated and independent. We are investigating this possibility by referring to banyan switching architectures. As a candidate wavelength-sensitive switching element we are considering the RRF.

POLITO studied the problem of preventing coherent crosstalk impairments in AWG-based optical switching fabrics inside packet switches and routers. A very straightforward study case of non-blocking, cross-bar like, optical interconnection among input and output ports was considered. Each input port is equipped with a single Tunable Transmitter (TT) and each output port with a single wideband receiver. Input Queueing (IQ) slotted operation is assumed: at most one packet can be transmitted from each input in each time slot, using the proper wavelength to reach the chosen output. The adopted switch control (scheduling) algorithm ensures that at most one packet is forwarded to each output at the same time, thus avoiding output contention. This means that at each time the switch implements an input to output ports permutation. Interconnection between input and output ports is obtained through an AWG, whose operation is assumed to be such that a cell sent from input port i with wavelength λ_k is forwarded to output port (i+k) mod N.

Since reusing the same wavelength at several input ports at the same time introduces coherent crosstalk, the notion of k-legal permutation was introduced, in which each wavelength is re-used at most k times. We first found properties of 1-legal permutations, showing that a difference exists between odd and even values of the number of input and output ports N: while N 1-legal permutations can be easily found for odd, there are no 1-legal permutations for even N.

We then showed that uniform traffic patterns can be scheduled in input-queued cell switches using 1-legal permutations with no speedup for odd N and with a speedup equal to 1+1/N for even N. General traffic patterns can be instead scheduled with 1-legal permutations using two-stages load-balancing switches using the same speedup (speedup 1 for N odd; speedup 1+1/N for N even), VOQs between the two switching stages, cell resequencing at outputs, and a fully distributed TDM-like scheduling algorithm.

2-legal permutations were observed to permit to avoid intermediate VOQs and resequencing problems for N<13. This would significantly reduce the complexity of the two stages load-balanced switch. We are currently working to prove that this holds for all values of N.

A draft paper reporting the main results was prepared and will be submitted soon.

UPCT group is investigating scheduling algorithms to mitigate the coherent crosstalk effect in electronic switches where the crossbar fabric is substituted by an AWG-based architecture.

During 2008 the research group of **UVIGO** has investigated on practical scalability limits of wavelength routing switches.

Packet switches with optical fabrics and optical links to interconnect line cards can potentially scale better to higher capacities and overcome electronic switches physical scalability limits. A well-known alternative to implementing hardwired switches is the Wavelength Routing (WR) architecture (Figure xx) that is based on a N×N Arrayed Waveguide Grating (AWG) and a WDM (Wavelength Division Multiplexing) all-optical data path that interconnects N line cards. The WR architecture has an insertion loss that ideally does not depend on the number of input-output ports, thus leading to theoretical "infinite scalability". Nevertheless, the excellent Politecnico di Torino analysis presented in [1] demonstrated that first order scalability assessment based on theoretical insertion loss values gives unrealistic results and the in-band crosstalk limits the realistic useful size of the AWG device to N<20.

The in-band crosstalk that is present at AWG outputs depends on the current connection pattern set by the scheduling algorithm. The limit in [1] is calculated in the worst case, where all the transmitters employ the same wavelength. Nevertheless, most distributed schedulers use predetermined connection patterns, and since we know the connection patterns in advance we can avoid those harmful arrangements. Moreover, centralized schedulers usually select very different wavelengths, and typical in-band crosstalk penalty is far from the maximum. Our work during this last year within the JA was to find a more realistic scalability bound for AWG switches. We calculated the best predetermined permutation patterns taking into account the in-band crosstalk limitations to achieve the largest possible size of the switches with distributed schedulers. We also calculated the probability of every connection pattern taking into account the in-band crosstalk penalty that allows us to dimension centralized scheduling switches discarding the connection patterns with probabilities far below the objective BER. With these results, we found more realistic port count limits for both scheduler types.

References

[1] J. M. Finochietto, R. Gaudino, G.A. Gavilanes Castillo, F. Neri, "Simple Optical Fabrics for Scalable Terabit Packet Switches," Proc. ICC 2008, Beijing, China, May 2008.

Collaborative actions carried out

(joint experiments, mobility actions joint publications, other)

All the involved partners have participated to the following meetings as collaborative actions:

- WP14 – Technical meeting, Athens, 26/06/2008
- WP14 – Technical meeting, Rome, 20/10/2008

Future Activities - Timescale

(please include work plan for 2^{nd} year with a timeplan for the work proposed.)

In the 2^{nd} year **Polimi** is going to make progresses on both the two research lines listed above, achieving publishable results towards the middle of the 2^{nd} year.

In the 2nd year **Polito** is going to make progresses on the research line reported above, submitting results publication soon.

In the 2nd year **UPCT** group is planning to progress on the scheduling problem for electronic switches with AWG-based fabrics, achieving publishable results towards the middle of the second year, possibly enhancing the study with a more diverse type of AWG-based switching fabrics.

In the 2nd year **UVIGO** research activities, in the next months, will focus on design schedulers specifically for WR switches taking into account the in-band crosstalk (while in 2008 research has being focused on finding practical scalability limits of wavelength routing switches under general both distributed and centralized schedulers). The specifically-designed schedulers will use exclusively low in-band crosstalk connection patterns to overcome the previously calculated port count limitation. We have expressed our interest on future collaborations to PoliTO, since our work is directly related to their work.

Thus, our research activities will be divided into two main steps:

- Study what of the existing schedulers are most suitable for using low in-band connection patterns in the WR architecture.
- Design and evaluate a low in-band crosstalk connection pattern scheduler.

This is our expected scheduling:

- The first half of 2009: Study the existing schedulers under the in-band crosstalk constraints.
- The second half of 2009: Design and evaluate a low in-band crosstalk scheduler.

Expected publications of UVIGO partner: 1 journal paper, related to low in-band crosstalk scheduler.

Partners involved will prepare a **joint paper** by the end of the 2nd year

Outcome of the joint research activity:

UVIGO has submitted the following paper for publication:

- Miguel Rodelgo-Lacruz, Cristina Lopez-Bravo, Francisco J, Gonzalez Castaño, “Practical Scalability of Wavelength Routing Switches,” Submitted to IEEE ICC 2009, June 14-18 2009, Dresden, Germany.