SEVENTH FRAMEWORK PROGRAMME

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Abstract:

This document is the final report of the WP27 "Physical Impairments constrain based routing in packet switching networks". This report contains an overview of the WP27 activities during the second and third year of the project. During the first and second WP years within the course of the BONE project, five joint activities were running. As result of these joint activities, twenty seven conference/workshop papers and thirteen journal papers were published, eleven mobility actions happened and four WP meetings.

Keyword list: monitoring, switching, route, reroute, regenerate, discard, packet, sampling, management level, route level.

Clarification

Nature of the Deliverable

R	Report
P	Prototype
D	Demonstrator
O	Other

Dissemination level of Deliverable

PU	Public
PP	Restricted to other programme participants (including the Commission Services)
RE	Restricted to a group specified by the consortium (including the Commission Services)
CO	Confidential, only for members of the consortium (including the Commission Services)

Disclaimer

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1. Table of Contents

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Table 1 – Joint activity contributors

3. Project Abstract

The main objectives of this work package "Physical Impairments constrain based routing in packet switching networks" are to collect regenerators (packet by packet regenerators; parameter regenerators) and collect actions (rerouting, signaling, blocking, special fields in the protocols dedicated for the control of the packet passing through the router and controllable at physical layer).

This deliverable describes the work performed within the previously referred objectives and summarizes the progress of the joint activities.

After an introduction on the framework of the project, we provide a list of the involved partners in the WP, as well as their involvement. Then objectives and results of each of the described joint activities are presented, within summary sheets.

Finally, complete contributions from partners are reported.

4. Executive Summary

This document is the third and final deliverable of the work package "Physical Impairments constrain based routing in packet switching networks". It describes the WP27 activities during the second and third year of the BONE project, which corresponds to the first and second year of this topical workpackage.

The project has initially gathered five partners and has ended with an expanded audience of thirteen involved partners. Some partners with little demonstrated activity; however most of the involved partners shown increased involvement during the course of this WP. The initial activity of the project was to define joint activities based on the partners expertise and project topics (five), which was adjusted during the course of the project. These activities (JAs) were designed to encompass all the required needs for the best possible achievement of the project objectives having the restrictions on the commitment and interest of the partners.

The topics covered by this work package address the physical impairments based routing in packet switching networks. Main highligths are:

- Packet monitoring techniques based on nonlinear optical preprocessing and filtering were studied and experimentally evaluated, and the prediction of packet accumulated dispersion was performed.

- The interoperability between management, control planes and monitoring functions was proven through an integrated cross-layer solution, accomplishing dynamically assessment of quality of the optical paths. One solution was a clock tone-based PMD monitoring technique, CD and OSNR-insensitive, which provides a cost-effective solution for OPS networks.

- The impact of the fiber link distance in dynamically provisioning connections within a GMPLS-enabled translucent WSON was evaluated. The comparison between two link-cost strategies (uniform and distance-based) was carried out.

- The Routing and Wavelength Assignment (RWA) and Regenerator Placement (RP) in translucent networks were investigated. Experimental tests on the impact of different regenerator placement strategies under dynamical provisioning proved that one proposed solution is optimal and require low computation times.

5. Participants

Partner No.	Member	Country	Joint Activities
2	TUW	Austria	JA1, JA2, JA3
9	CTTC	Spain	JA6
13	UPC	Spain	JA1, JA2, JA3, JA4, JA6
14	UPCT	Spain	JA6
15	UPVLC	Spain	JA2
19	AIT	Greece	JA1, JA4, JA6
21	RACTI	Greece	JA1
24	BME	Hungary	JA1, JA2, JA3, JA4
28	ISCOM	Italy	JA1, JA2, JA3, JA4
29	PoliMi	Italy	JA6
37	IT	Portugal	JA1, JA2, JA3, JA4
42	BILKENT	Turkey	JA1
48	USWAN	United Kingdom	JA1, JA3, JA4
Collaborating Inst.	NICT	Japan	JA1, JA2

Table 2 – Work package participants and their joint activities

There were thirteen partners collaborating in this work package. Table 2 shows the list of participants and the number of the joint activities, in which they were involved. Two new partners joined the project, PoliMi joined to the JA.6 and RACTI to the JA.1. On the other hand, this year, the BILKENT contributions decreased intensity, due to the related student work finish and leave. A detailed description of the joint activities is provided in the following chapters.

6. Description and Main Achievements of Joint Activities

This chapter describes the joint activities in this workpackage. The following table shows key information about these joint activities.

No	Joint Activity Title	Responsible person	Participants	Mobility Action
1	Impairment aware algorithms for optical packet switching (OPS) networks	Gerald Franzl	TUW, UPC, AIT, RACTI BME, ISCOM, IT, BILKENT, USWAN, NICT	Started: M19 Performed: M33
2	Monitoring strategies for OBS and OPS networks	António Teixeira	TUW, UPC, UPVLC, BME, ISCOM, IT, NICT	Started: M13 Performed: M33
3	Decision mechanisms for packet transit in OPS networks	António Teixeira	TUW, UPC, BME, ISCOM, IT, USWAN	Started: M19 Performed: M33
4	Techno-economic study of monitoring techniques in OPS networks	Giorgio Tosi Beleffi	UPC, AIT, BME ISCOM, IT, USWAN	Started: M18 Performed: M33
6	Impact of physical layer impairments on control plane schemes and proposals for optical circuit and packet switched networks	Salvatore Spadaro	CTTC, UPC, UPCT, AIT, PoliMi, IT	Started: M25 Performed: M33

Table 3 – Summary list of the planned joint activities

6.1. JA-1 - Impairment aware algorithms for optical packet switching (OPS) networks

Participants:

G. Franzl, J.A. Lazaro, I. Tomkos, Szilard Zsigmond, G. Tosi-Beleffi, A. Teixeira, Namik Sengezer, K. Ennser, N. Wada

JA Cordinator: G. Franzl (TUW)

JA Initiator: I.Tomkos (AIT)

Objectives:

The aim of this JA is to collect routing algorithms to implement traffic decisions in packet switched networks, based on impairments present in optical systems (PMD, noise, and crosstalk).

Description:

While attenuation can be assumed to be compensated hop by hop using all optical amplifiers other physical layer impairments (degrading the optical signal quality) accumulate hop by hop. In all-optical networks the routing mechanisms, therefore, shall consider the degradation of the optical signal to avoid paths delivering optical signals not receivable with an acceptable bit error rate (BER).

A distinction needs to be made among two types of impairments: a) the load independent physical layer impairments – these limit the maximum path length, and b) the load dependent, which should be considered in short term routing decisions, e.g., load balancing and hop-by-hop admission control, to assure that the remaining packets on a hop are not unacceptably degraded along their individual paths. Latter causes an NP hard optimization problem and likely heuristics need to be found in order to define viable (fast enough) routing mechanisms.

Most of the studies on packet scheduling in the OPS networks do not consider physical layer impairments. The main objective of scheduling in these studies is contention resolution. However, the utilized scheduling mechanisms used may degrade signal quality. As optical packets traverse fiber delay lines, the signal is attenuated and the amplifiers used to compensate the attenuation contributes ASE noise. Each time the packet is switched through the switching fabric, it may experience additional crosstalk. Moreover, signal quality may be further degraded because of load dependent impairments such as cross phase modulation and four wave mixing, along the output fiber. These types of impairments can be avoided by considering them in the scheduling process.

Main Outcomes and Results:

- **Work Summary**
  - **1st Year**
    - Some research related with the implementation of DWP scheme as part of an OPS control plane to ensure the optical packets are individually routed along physical feasible paths.
  - **2nd Year**
    - Study concerning to packet scheduling in synchronous OPS networks in the presence of physical layer impairments;
    - Comparison between the performance of the proposed scheduling algorithm and other packet scheduling techniques that have been proposed in the literature. Contribution to the chapter 3 in WP15 book;
    - Distribution and ranking of ICBR proposals via the JA1 sub-page in BONE portal.
  - **Mobilities**
    - **Proposed and not carried out**
      - none
    - **Accomplished**
      - 1 mobility action between RACTI and AIT: Professor Kyriakos Vlachos (RACTI), hosted by AIT from 15th of November and 31st of December 2010 to study and comparing different approaches for solving the IA-RWA problem. RACTI has developed a Genetic Algorithm for indirectly handling fiber impairments while AIT a Q-estimator tool for accurately estimating Q factor.

        Duration: 1.5 Month

        Type of work: Theoretical (simulation)

        Skills/ facilities available: Simulation tools (RACTI/AIT)
  - **Publications and Meetings**
    - 6 joint papers
    - 4 WP meetings

If interested, contact:

Gerald Franzl (Gerald.Franzl@tuwien.ac.at)

6.2. JA-2 - Monitoring strategies for *OBS and OPS networks*

Participants:

G. Franzl, J.A. Lazaro, Ruth Vilar, R. Llorente, Salvador Sales, Szilard Zsigmond, G. Tosi Beleffi, A. Teixeira, Diana Fidalgo, Mário Lima, N. Wada

Responsible person: António Teixeira

Objectives:

The aim of this JA is to collect monitoring techniques to detect physical impairments, and investigate their effectiveness in optical packet switched (OPS) networks.
Moreover, within a sub-WP the recently merged JA5, it is intended to produce a real time fast monitor, to monitor and generate data able to compensate Chromatic Dispersion in packets (based on an eventually available fast tunable compensator).

Description:

Two distinct scenarios are possible:

- Monitoring at the router level: the techniques to be implemented must be fast enough to detect physical constraints packet by packet, eventually supported by an all-optical structure;
- Monitoring at the management level: for a long-term evaluation of the network impairments, the mitigation techniques used should be route oriented, with a larger time scale.

The individual effectiveness and potential gain from combined consideration could be investigated to outline close-to-optimal strategies given the monitoring options considered available for different scenarios.

Main Outcomes and Results:

- **Work Summary**
  - **1st Year**
    - A methodology for packet monitoring was proposed and studied. Joint efforts for demonstrating the methodology in a laboratory experiment.
  - **2nd Year**
    - Packet monitoring technique for Chromatic Dispersion based on nonlinear optical preprocessing and filtering;
    - A monitoring device and technique was proposed for OSNR-assisted routing

to detect and dynamically set up optical paths taking into account the physical impairments;

- A clock tone-based PMD monitoring technique which can enhance the monitoring sensitivity considerably and is CD and OSNR-insensitive was proposed;
- The potential of modulation instability effect as optical parameter estimation technique was investigated both theoretically and experimentally.

- **Mobilities**
  - **Proposed and not carried out**
    - none
  - **Accomplished**
    - 1 mobility action between IT and ISCOM/UNIROMA2: Giorgia Parca, ISCOM Ph.D. student was in IT between 25th of March and 25th of May to study "On the monitoring and signal processing in packet switched networks" (Monitoring part).

      Duration: 2 Months

      Type of work: Theoretical and Experimental
    - 1 mobility action between IT and ISCOM: Giorgia Parca, researcher at IT, hosted by ISCOM from 27th of December 2010 to 3th January 2011 to study monitoring potential of modulation instability for optical packet/burst switched networks.

      Duration: 7 Days

      Type of work: Theoretical and experimental
- **Publications and Meetings**
  - 7 joint papers
  - 4 WP meetings

If interested, contact:

António Teixeira (teixeira@ua.pt)

6.3. JA-3 - Decision mechanisms *for packet transit in OPS networks*

Participants:

G. Franzl, J.A. Lazaro, Szilard Zsigmond, G. Tosi-Beleffi, A. Teixeira, K. Ennser

Responsible person: António Teixeira

Objectives:

The aims of this JA are to collect actions to be implemented on the reception of optical packets, to coordinate the activity, regarding the costs of monitoring in packet switched networks, in collaboration with IT. Moreover, experiments of QoS on HD Video streams in PONs were planned. This joint activity was carried out with FUB and in joint coordination with WP13 on Access.

Description:

Several actions can be necessary when optical packets are received, prior routing to an output-port, and depending on the information supplied by the monitoring system. Operations like re-routing, signaling, blocking and discard of packet are among the objectives of study.
Moreover, special fields of the communication protocol, dedicated for the control of packet routing, potentially controllable at the physical layer (e.g. TTL in the IP protocol), shall be considered and their usage studied.

Main Outcomes and Results:

- **Work Summary**
  - **1st Year**
    - Activities related to OBS/OPS systems were performed (eg. Performance of switching devices in presence of different modulation formats at high data rate per port 400 Gbit/s/port; Carving for mitigation of transients in optical amplifiers; OBS in presence of lasers with limited tunability);
    - Two mobility actions were performed.
  - **2nd Year**
    - Experiments of QoS on HD Video streams in PONs. This joint activity was carried out with FUB and in joint coordination with WP13 on Access;
    - Modeling and optimization of all-optical switching devices;
    - Design and experimental validation of a novel technique for optical switching implemented in wavelength-routed scenarios;
    - Study the possibility of all-optical phase regeneration, for binary phase-shift keyed (BPSK) signals using phase-sensitive amplifiers based on periodically poled lithium niobate (PPLN) crystals.
    - **Proposed and not carried out**
      - none

- **Accomplished**
  - 1 mobility action between IT and ISCOM/UNIROMA2: Giorgia Parca, ISCOM Ph.D. student was in IT between 25th of March and 25th of May 2010 to study "On the monitoring and signal processing in packet switched networks" (Signal Processing part).

    Duration: 2 Months

    Type of work: Theoretical and Experimental

    Skills/ facilities available: Communication labs (UNIROMA2/ISCOM/IT)
  - 1 mobility action between IT and UPVLC; Ruth Vilar, a UPVLC Ph.D. student in IT between 5th of May and 5th of August 2010 for the evaluation of fast optical wavelength switching for routing functions.

    Duration: 3 Months

    Type of work: Theoretical and Practical

    Skills/ facilities available: Communication labs (UPVLC/IT)
  - 1 mobility action between IT and BME and NICT: Dániel Mazroa, a PhD student at the Department of Infocommunications and Media Informatics (TMIT) of BME, was in NICT between January to September of 2010 to study all-optical 3R and processing for photonic networks.

    Duration: 8 Months

    Type of work: Theoretical and Experimental

    Skills/ facilities available: Communication labs (BME/NICT)

- **Publications and Meetings**
  - 11 joint papers and 5 more were submitted but they are on review
  - 4 WP meetings

If interested, contact:

António Teixeira (teixeira@ua.pt)

6.4. JA-4 - Techno-economic study of monitoring techniques in OPS networks

Participants:

J.A. Lazaro, I. Tomkos, Szilard Zsigmond, G. Tosi-Beleffi, A. Teixeira, K. Ennser

Responsible person: Giorgio MariaTosi-Beleffi

Objectives:

Main aims of this JA are to study techno-economic features of transparent optical networks and to propose energy efficient solutions.

Description:

A techno-economic study on transparent optical network was performed, with the aim to design and prove energy and cost efficient solutions. The main objective is to increase the bandwidth to the end users lowering simultaneously cost and the power consumption.
The impact of the optical technologies and infrastructures on the reduction of the carbon footprint maintaining high level of broadband to the end user was investigated.
Another topic was the study of Long-Reach Passive Optical Network (LR-PON), with the aim to prove a cost-effective solution.

Main Outcomes and Results:

The main focus of the project was changed with regards to the initial proposed ones, due to internal reorganization and it turned attentions to techno-economics in transparent networks.

- **Work Summary**
  - **1st Year**
    - This JA had started by using one of special techno-economic session in ICTON 09 – MARS – Market in Telecommunications. The contributions and authors interested in the topic of OPS were collected/contacted with the objective of attracting attention to the topic.
  - **2nd Year**
    - Establishment of links and actions to increase visibility of the project through special sessions in conferences;
    - Several experiments were carried out by the partners on packet based infrastructures also in collaborations with other projects like EU FP7 SARDANA;
    - Investigations and experimental tests on Broadband future access networks with low energy consumption impact and Long-Reach Passive Optical Network (LR-PON), with the aim to prove cost-effective solutions;
    - Informal meeting during ICTON 2010 and ECOC 2010 International Conferences.
  - **Mobilities**
    - **Proposed and not carried out**
      - none

- **Accomplished**
  - 1 joint activity was planned and performed (IT to ISCOM in September) with the collaboration of AIT;
  - 1 mobility action between ISCOM and NICT: Giorgio Beleffi, ISCOM research scientist PhD will be in NICT between 22th and 27th of January 2011, to study the physical impairments constraint based routing in packet switching networks. The economic aspects related to these networks will be considered too, in collaboration with IT, AIT and other non EU institutions.

    Duration: 6 days

    Type of work: Theoretical and Experimental

    Skills/ facilities available: Communication labs (NICT/ISCOM)
  - 1 mobility action between ISCOM and Etisalat operator: Giorgio Beleffi, ISCOM research scientist PhD will be in Dubai between 27th and 29th of January 2011, for discussion on techno-economics and dynamical networks.

    Duration: 2 days

    Type of work: Theoretical and Experimental

    Skills/ facilities available: Communication labs (Etisalat/ISCOM)

- **Publications and Meetings**
  - 2 joint paper
  - 4 WP meetings

If interested, contact:

Giorgio Tosi-Beleffi (giorgio.tosibeleffi@sviluppoeconomico.gov.it)

6.5. JA-5 - Packet monitoring based on nonlinear optical preprocessing and filtering

This joint activity was incorporated in JA2.

6.6. JA-6 - Impact of physical layer impairments on control plane schemes and proposals for optical circuit and packet switched networks

Participants:

CTTC (R. Muñoz, R. Casellas, R. Martinez), UPC (J. Sole-Pareta, S. Spadaro, J. Perello, D. Careglio), UPCT (P. Pavon Marin, M.B. García Manrubia), AIT (I. Tomkos, D. Klonidis, S. Azodolmolky)

Responsible person: Salvatore Spadaro

Objectives:

The main objective of this joint activity is to investigate the impact of physical layer impairments on control plane schemes for transparent/translucent infrastructures that are suggested or can be considered for both circuit switched and packet switched optical networks.

Description:

Taking advantage of current experiences and advances in both circuit switched (OCS) and packed/burst switched optical (OPS/OBS) networks, we plan to perform several studies. First, we will focus on OCS with the following aims: 1) an experimental analysis of the impact of different network designs (e.g., transparent, translucent, etc.) on the control plane behavior and the network performance, 2) a benchmarking study to assess and compare different control plane approaches with techno-economic considerations. Then, we will address the problem of verifying and adapting the selected control plane architectures/proposals for the effective management in the OPS/OBS networks. Based on the outcome of this second step, a comparative study among the collected proposals will be performed.

Main Outcomes and Results:

- **Work Summary**
  - **1st Year**
    - This JA had not started in this year.
  - **2nd Year**
    - Study of the impact of different network designs on the control plane behavior and the network performance of Optical Circuit Switched (OCS) networks equipped with Ethernet interfaces, and operated by a Carrier Grade Ethernet

control plane, both in core and metro network scenario;

- Efforts on a specific network architecture based on the Multiprotocol Label Switching Transport Profile (MPLS-TP) standard;
- Study of different cross-layer control plane network design algorithms and a study of the impact of different planning strategies on the network cost, and on the control plane implementation;
- Collaboration between UPC, UPCT and CTTC to experimentally test the impact of different regenerator placement strategies under dynamical provisioning in translucent GMPLS WSON networks;
- The joint activities proposals have followed the work planned. The increase in the number of partners and mobility actions contributed to increase the interaction among the research groups.

- **Mobilities**
  - **Proposed and not carried out**
    - none
  - **Accomplished**
    - 1 mobility action between PoliMI and UPC: Domenico Siracusa, PoliMi PhD student, was in UPC between 24th of March and 31st of August 2010 to study the impact of physical layer impairments in an OCS network equipped with Ethernet interfaces and operated by a Carrier Grade Ethernet control plane

      Duration: 5 Months

      Type of work: Theoretical and Practical

      Skills/ facilities available: Communication labs (PoliMi/UPC)

    - 1 mobility action between AIT and UPC: Siamak Azodolmolky, researcher at AIT, was hosted at UPC between 29th of January to 5th of February 2010. The main focus of this mobility action was on benchmarking study to assess and compare different control plane approaches with techno-economic considerations.

      Duration: 7 Days

      Type of work: Theoretical/ Simulation

      Skills/ facilities available: Communication labs (AIT/UPC)
- **Publications and Meetings**
  - 3 joint papers and 6 more were submitted, but they are on review
  - 2 WP meetings

If interested, contact:
Davide Careglio (careglio@ac.upc.edu)

7. JA's framework: introduction

Optical networking evolution is towards the implementation of a transparent dynamic and reconfigurable network.

New generations optical networks are intended to accomplish more efficient and flexible data-oriented solutions, meaning implementing more intelligent and flexible optical networks and mechanisms. This step, should allow achieving requirements such as dynamic and rapid provisioning of connections, automatic topology discovery and network inventory, traffic engineering, and faster optical restoration.

7.1. Optical Packet Switching

Optical Packet Switching (OPS) [1] is expected to offer flexibility and bandwidth efficient architecture, thus supporting a great variety of services, ranging from voice data sensitive to network delay, to bandwidth-intensive services such as video-on-demand, with different quality requirements.

In order to fulfill requested performance, future transport layer must be able to:

- Adapt dynamically to the network status changes in real time;
- Implementing quality of service oriented applications;
- Performing user traffic monitoring, in terms of operational parameters and system requirements, such as bandwidth, jitter, latency and signal quality.

Transmission impairments, which occur in fibers and optical components, may significantly affect the quality of a lightpath so that, performance monitoring is especially important to consider their impact during the entire lifetime of a lightpath.

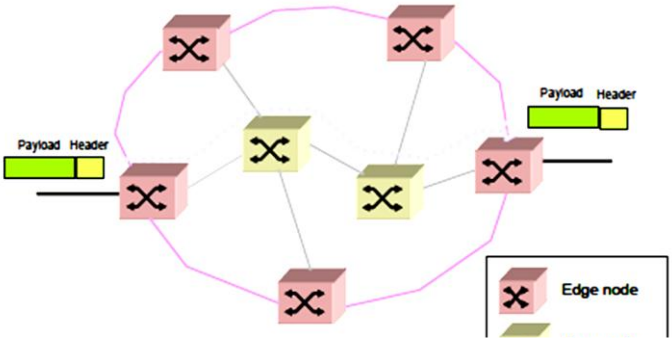

Figure 1 – Optical Packet switched network

Moreover, because of increased transparency of new generation optical network, the reduction of OEO conversions leads to the accumulation of impairments effects while the signal propagates through the lightpath, causing significant signal degradation.

Impairment effects on lightpaths can be strongly different, since fiber links may have different physical characteristics, and also because of network state changes in terms of traffic distribution.

7.2. Impairments monitoring

In this framework, in order to accomplish proper operations and management, it is indispensable to have the capability to monitor impairments affecting networks performances, directly in the optical layer.

The non-ideal behavior of physical layer components may lead to two categories **transmission impairments:** linear and nonlinear [2].

The linear impairments impact is independent of signal power and affects the end-to-end lightpath. An estimation can be extracted from link parameters, and used as a constraint on routing. Amplifier noise sources, polarization mode dispersion (PMD), group velocity dispersion (GVD), component crosstalk, for example, belong to this category.

Nonlinear impairments are more complex, and very hard to quantify, as they depend on a combination of factors such as signal power, number of active wavelengths per fiber, and the channel bandwidth. They arise because of the response of the optical fiber to intense optical signals. Some significant nonlinear impairments are four-wave mixing (FWM), Self Phase Modulation (SPM), Cross-Phase Modulation (XPM).

Nonlinear effects are in general emphasized for high signal power levels and longer transmission distances. In summary, both linear and non-linear impairments are highly dependent on the fiber characteristics which in turn are sensitive to length, temperature and aging.

Through the estimation of impairments impact on lightpath, the control plane of an optical transparent network is able to perform actions in order to restore a connection, according to the signal-quality requirements that must be provided.

In such dynamic scenario, performance management and crucial functionalities must be executed in the optical domain, i.e. service-differentiation applications, signal quality characterization for quality of service (QoS) assurance and service level agreement (SLA) fulfillment, fault detection, alarming.

Optical Performance Monitoring (OPM) [3] is an enabling technology for next generation optical networks, being a potential mechanism capable of improving the degree of transmission control and physical layer fault management that results in enhancing the network reliability.

The potential applications of OPM include the optical path setup, link selection based on physical constraints, signal quality assessment (for QoS assurance), and activation of the restoration mechanisms.

But an important issue is that new generation optical networks require all techniques capable of real-time monitoring, to immediately react to signal failure or signal degradation. Existing techniques cannot offer this feature, on the contrary OPM shows high potential.

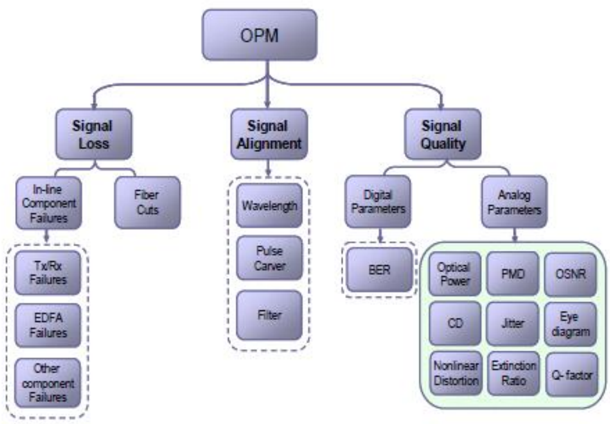

Figure 2 – OPM and parameters classification

OPM can play a major role to perform other functions as well, such as providing information for fault management, which consists of identification, localization, diagnosis, and tracking of faults in a network.

OPM can be used as a feedback to preserve optimum network operating conditions, can perform the signal quality monitoring for quality of service assurance, can act as an alarm to predict network failures and allow traffic to be rerouted before failure occurs. Together with these applications related to quality monitoring and failure tracking, OPM can also assist the control plane to detect and dynamically set up optical paths taking into account the physical impairments. Therefore, OPM is essential for managing the future optical networks since it includes a wide range of functionalities focused on improving network performances.

Monitoring strategies make it possible to estimate system performance and operational parameters. Thanks to these techniques, **Impairment Constraint Based Routing (ICBR)** [5] algorithms are used, in order to consider physical layer impairments during the link selection and connection-provisioning, and to prevent selecting a lightpath with low signal quality.

ICBR algorithms have been intended with the objective to solve the connection provisioning process, called Impairment Aware Routing and Wavelength Assignment (IA-RWA) problem. The objective of solving the IA-RWA problem is twofold: to minimize the amount network resources to be allocated and also to guarantee the required Quality of Service for each connection established.

Without physical-impairment awareness, a network-layer RWA algorithm might provision a lightpath which cannot meet the signal-quality requirement.

7.3. Signal quality monitoring at the optical physical layer

With the aim to perform signal quality monitoring directly at the optical physical layer, new technologies are needed, since next generation OPS networks will require fast response times, not achievable through existing techniques.

Optical packets forwarding is executed hop-by-hop and based on packet header information. In principle, packets follow different routes. Therefore, the introduction of OPS concept leads to new challenges in defining network performance monitoring and maintenance technologies.

Main features of signal quality monitoring designed on packet-by-packet basis are the following.

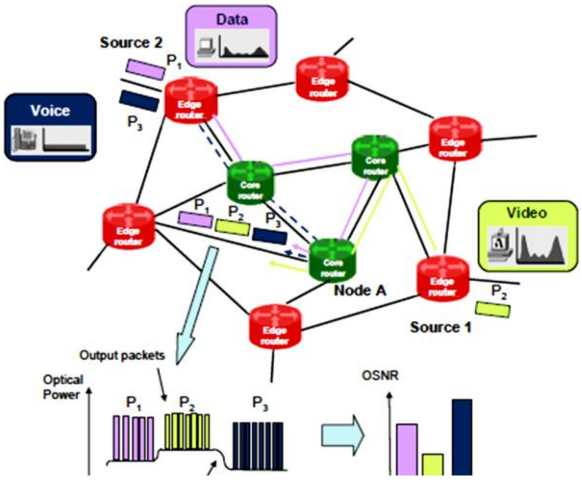

Figure 3 – Packets with different OSNR in an OPS network

Optical packets could originate from diverse sources and travel through different optical links. Thus, different optical packets may be affected by different degradations and the signal quality may change on the short time span of one packet;

The monitoring information could be used for impairment compensation and fault localization. Thus, monitoring information is helpful for signal quality management. Two scenarios can be found: First, if the optical packet is degraded but it could be regenerated optically. Second, if the optical packet is too corrupted to be regenerated, the packet is dropped in the nearest optical packet switching node.

From quality information, each intermediate node could control whether the transmission meets the quality of service and performance requirements specified by the carrier. The future monitoring techniques are focused on requirement as fast response time, and packet-by-packet operation. The problem of the majority of the techniques reported is that they require high acquisition time or they have slow response time, being incapable of estimating the signal quality on the short time span of one packet. Therefore, new monitoring techniques on a per-packet basis must be defined.

A monitoring strategy focused on Chromatic Dispersion (CD) compensation is intended to produce a real time fast monitor, to monitor and generate data able to compensate the CD effect in packets.

In particular it is possible to predict packet accumulated dispersion, through a technique based on nonlinear optical preprocessing and filtering [6].

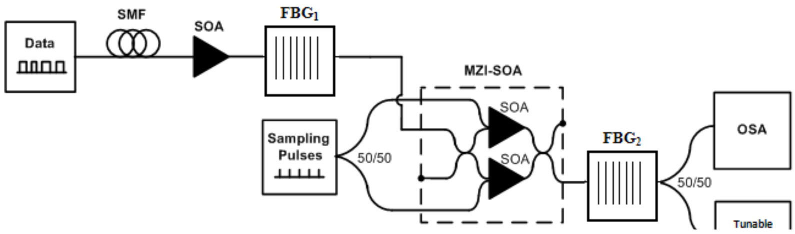

Figure 4 – Configuration for chromatic dispersion packet monitoring

A Semiconductor Optical Amplifier (SOA) is used for CD monitoring, a Mach-Zehnder Interferometer Semiconductor Optical Amplifier (MZI-SOA) performs the sampling on the optical data packet, and two filters have the function to improve the quality of the signal. Figure 4 shows the setup. After the CD estimation, obtained from its relation with output power level, it can be compensated by a tunable dispersion compensator.

An all-optical technique for first-order PMD monitoring in OPS networks is proposed. It is based on the use of an optical logic XOR gate implemented by an integrated SOA-based Mach–Zehnder interferometer (SOA-MZI) for PMD estimation [7]. Figure 5 shows the block diagram. Moreover, the output of the XOR gate can act as the control signal for an all-optical 1x2 packet switch, allowing the node taking real time decisions about packet routing according to the estimated DGD values.

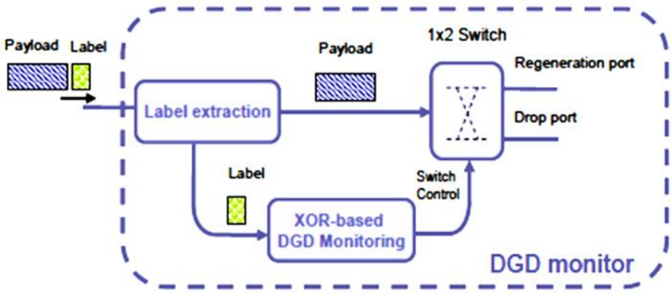

Figure 5 – Block diagram of the first-order PMD (DGD) monitoring system

Generally, networks packets coming from different services may have different quality of service (QoS). Therefore, to accommodate several levels of the services, new monitoring techniques must be deployed as part of service-differentiation functionalities. In fact, the Time To Live (TTL) value (i.e. the maximum number of router hops) can be defined to guarantee that packets do not exceed the maximum degradation acceptable for a certain type of service. Then, packets entering the network must be analyzed to determine their QoS requirements, and thereby setting the TTL value.

A novel method based on the use of optical logic XOR gates implemented in SOA-MZI devices is proposed to accomplish the TTL based monitoring strategy [8].

Therefore, integrated MZI-SOAs are compact devices that show vast potential for application in several optical domains, starting from performance monitoring functionalities just described, but also logical gates functionalities, switching, all-optical processing and signal regeneration, among others.

MZI-SOA-based regeneration has several advantages if compared with other techniques: compactness and ability for integration; regeneration of both “1” and “0” logical levels; reduced input power levels required; high-conversion efficiency; allows the use of differential mode to overcome SOA speed limitations; and wide bandwidth operation. The regeneration is mostly due to the SOA gain compression and the nonlinear characteristic of phase-to-amplitude conversion of the MZI.

For all these applications, one important factor to take into consideration is the Extinction Ration (ER) of the output signal powers. It must be maximized in order to accomplish an effective processing of data signals, that means to obtain the optimum operative conditions with the setup stage, and get a good efficiency for example in regeneration functionalities [9].

An all-optical estimator for the quality of the transmission in optical packet-switched networks exploits an OSNR-assisted routing algorithm and it is based on a set of test packets periodically sent along the network following different paths.

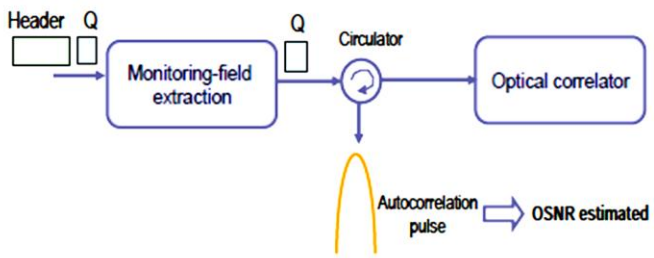

Figure 6 – Block diagram of the OSNR monitor

Packets are processed in each intermediate node to monitor the network performance by using an all-optical correlator, based on fiber Bragg grating (FBG) technology [11]. Then the optical signal-to-noise ratio (OSNR) of these test packets is estimated from the noise statistics of the autocorrelation pulse peak power.

This method, described by the block diagram in Figure 6, can be exploited to get an integrated solution where management and control planes and monitoring functions work together, in order to dynamically assess the quality of the optical paths.

In other words, the signal quality information is sent to the control plane and added as an additional factor in the routing decision. This feature allows the control plane to establish or select lightpaths taking into account physical impairments and thereby sustaining reliability's requirements and keeping the level of quality of service promised to end users.

Beyond the pure QoS provisioning, all signal quality informations could be used by **restoration functionalities** to ensure the fulfillment of the quality requirement [4]. In contrast to other packet-switching networks, in all-optical networks recovery schemes should take into account that not only that bandwidth provided on a link defines if an optical path can be routed over that link, but also if the target node of the link is capable of receiving the optical path and routing it further correctly. Then, the network recovery techniques should search for free spare link capacity as well as spare node capacity.

The network recovery schemes are classified in protection or restoration mechanisms. The former schemes are based on the reservation of network resources and backup path establishment before a failure occurs. Restoration uses signaling after the failure to dynamically assign resources along the backup path. Hence, protection offers fast recovery time (milliseconds) whereas restoration presents higher flexibility and efficiency. Recovery mechanisms are also broadly classified as path recovery or link recovery, depending on where the protection switching is done. In path recovery, the end nodes control the recovery so that the whole path is protected. In local recovery, faults are intercepted locally.

Information on signal quality in real time allows taking immediate actions faced with dynamic network changes. Apart from this feature, the monitoring block can also interact with the **routing mechanisms** to contribute to perform a routing based on signal quality requirements [4]. When discussing routing in all-optical networks, there are strong reasons to consider that not all routes have the required signal quality. First, as bitrates increase, it is necessary to increase power. This makes impairments caused by nonlinearities more troublesome. Second, the optical technology is advancing very rapidly, making larger networks possible. These considerations will lead to the deployment of a network that is too large to ensure that all routes have adequate signal quality. Therefore, there is a strong necessity of a definition of a protocol that takes into account the impairments effects of an optical layer.

The main goal of the routing protocol is to keep the level of QoS required. In this protocol the path selection is based on optical signal quality and on information related to the available bandwidth, enabling the implementation of traffic engineering algorithms.

The protocol combines intelligent routing with the immediate availability of information about signal quality provided by the monitoring module located inside the intermediate nodes. The performance information coming from this module is then disseminated by the control plane and shared among network nodes to assess the status of all connections. Hence, the quality estimation is added as an additional factor in the routing decision. Moreover, information about the available bandwidth is added as a cost factor. By using the quality and the cost factors, the control plane establishes the optimum path.

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8. Joint Activities Technical Detailed Description

8.1. JA-1 ANNEX- Impairment aware algorithms for optical packet switching (OPS) networks

Summary of the previous activities results

In the last year, it was created a private JA1 sub-page in BONE portal to provide an intern platform for remote joint work and discussion. It was collected routing algorithms, ICBR proposals and some research related with the implementation of DWP scheme as part of an OPS control plane to ensure the optical packets are individually routed along physical feasible paths. It was too investigated the influence of the packet scheduling algorithms in OPS networks on signal quality and BER, and design scheduling algorithms that minimize the BER or guarantee a threshold on BER. Furthermore, it was studied the packet scheduling algorithms, that consider dynamics fluctuations in EDFA gain occurring in OPS networks.

Three joint papers were submitted, from which, one was for journal and two for conferences.

Two WP meetings were performed, ICTON 2009 in Azores and BONE Second Plenary Meeting in Poznan.

Summary of the current activities results

This year, it was studied the packet scheduling in synchronous OPS networks in the presence of physical layer impairments. A comparison between the performance of the proposed scheduling algorithm and other packet scheduling techniques that have been proposed in the literature was performed.

In respect to the state of the art, related to routing algorithms, it was performed a comparison between ICBR proposals.

Three joint papers were submitted, from which, one was for journal and two for conferences.

A mobility action and two technical WP meetings were performed, Workshop/Session at CSNDSP 2010 in Newcastle and ECOC 2010 Conference in Torino.

8.1.1. State of the art: routing schemes to implement traffic decisions in packet switched networks, based on impairment present in optical systems

(Gerald Franzl /TUW)

In the following it is presented and commented the principal schemes of some routing algorithms capable to implement traffic decisions based on the impairments present in optical systems (PMD, noise, and crosstalk) recently proposed in literature.

Common sequential IA-RWA

Most IA-RWA approaches recently proposed consider the QoT problem separately from the RWA problem [1], [2]. If the QoT independently found route is feasible, this is the fastest approach; however, if it does not fit it is necessary to find a different path. As every single resource along a path per se commonly provides sufficient QoT, it is not clear which link to exclude for subsequent path searches. Common approaches to this problem are to a) leave out one by one, or b) find several paths in the first step (k-shortest paths) and then check one candidate after the other. The second approach is more efficient only if the time to find k paths in one step is less than the sum of k subsequent path searches, weighted each with the likelihood p(k) of finding in k subsequent routings only infeasible paths. Consequently, for well designed physical layers and not too degradation sensitive signal formats, the single path routing with occasional subsequent path searches is economic. To decrease the probability of not finding a feasible path in the first routing attempt we might adjust the weights used by the routing algorithm to reflect the physical layer's state.

It should be clear that re-routing in case of OPS is not possible and thus such a scheme not applicable. Yet, experts proposed to control the network dynamics by limiting routing freedom. For instance MPLS exactly performs that per-flow (per ingress/egress pair). The routing underlying a label switched path (LSP) typically does not change, and thus the effective effort introduced by finding feasible paths to transport a certain flow type inversely depends on the LSP life-time. Complex set-up procedures for long living LSPs thus actually introduce less effort if thereby frequent re-routing can be evaded.

Q-factor based integration of impairments in routing decisions

A straightforward strategy employed to include physical layer impairments in the routing decisions, is to incorporate impairments into the cost function. However, a cost function correctly considering linear and nonlinear impairments is still an open question. Different analytical models have been developed to describe reference links [2], [3]. Only few studies consider the simultaneous impact of chromatic dispersion (GVD), polarization mode dispersion (DGD), amplified spontaneous emission (ASE) and nonlinear phase shift [4]. Other more universal metrics have been proposed, including the average measured Q [5], and noise variance [3]. In any case, accurate per hop Q estimation is a heavy task demanding offline calculation; monitoring is therefore more convenient but might be costly or even impossible (at intermediate nodes).

The major disadvantage of most integrated IA-RWA approaches is that the physical layer impairments need to be reduced to a single scalar cost value. Thereby the information on individual parameters is lost and it is necessary to define different cost functions that consider specific sensitivities of different signal formats and hardware components (i.e., optical detectors) correctly.

Network kriging

In [6] a method to predict the performance of paths based on collected information on other paths is presented. Relating to the principle known from applied probability and statistics [7] this approach is called network kriging. In [8], [9] it is shown that the approach can be applied to predict end-to-end QoT based on monitored end-to-end QoT of other paths.

This is achieved by setting up and solving an equation system considering how different paths share resources. The more already monitored paths share each resource of the path to be evaluated, the better the prediction approximates the unknown end-to-end QoT. Network kriging can be applied in both distributed and PCE-based path computation scenarios. Flooding of monitored QoT per path is not required, making the approach scalable. However, to predict the end-to-end QoT the entire path needs to be known in advance. Therefore the approach fits best to a scheme where a limited set of candidate paths per ingress egress node pair is a priory defined. Other than the candidate paths are not considered. Seemingly a restriction, this complies with the trend to reduced routing freedom, which can be widely observed in recent proposals and standardization attempts targeting at a more connection oriented IP networks for better traffic engineering options.

Ant colony optimization

Over many years now, ant colony has proven to be a heuristic approach that successfully can be applied for network control and other issues that need to consider a multitude of obviously heterogeneous criteria. Ant colony optimization is based on ant-like mobile agents that cooperate with each other while randomly exploring possible paths. Based on information collected by each agent, and the information left behind at every node by all agents, iteratively decentralized routing information is created. In [10], [11] a distributed IA-RWA scheme based on ant colony optimization paradigm is presented. The next hop (outgoing optical channel) is determined based on a preference value (pheromone-level) derived from the information left behind by ants that previously passed. To not end up in a static routing, the preference values fade over time (alike pheromones evaporate) and therefore need to be refreshed from time to time. The rate at which preferences fade determines how many agents are required to keep a consistent routing information available and, how fast the routing information adopts to abrupt changes like fiber breaks. This approach is rock-solid; but being heuristic it is difficult to optimize and hard to trust in, even though ants are one of the most successful species on earth.

A similar heuristic exploiting routing history instead of agents is presented in [12]. Other heuristics applicable to perform IA-RWA include the genetic algorithm as proposed in [13], [14], stimulated annealing [15], and taboo search [16], [17]. These can not be implemented distributed and are computational exhaustive; but capable to accurately approach the global optimum with increasing computation effort.

Multi-constrained routing (mCBR)

The major disadvantage of most integrated IA-RWA approaches is that the physical layer impairments need to be reduced to a single scalar cost value. Thereby the information on individual parameters is lost and it is necessary to define different cost functions that consider specific sensitivities of different signal formats correctly. More convenient would be considering each physical layer impairment/constraint and how it changes hop-by-hop individually. Firstly that allows finding paths that fit constraint by constraint, secondly identification of specific weaknesses of certain paths. Especially in case of multi-hop paths latter would enable to profitably combine segments that equalize each other.

Distributed wavelength path provisioning (DWP) provides exactly that by replacing the cost value by a vector of constraints and applying lattice algebra [18]. Being a multi-constraint approach (mCBR) dynamic programming rules do not fit and therefore the approach is not scalable and thus limited to small networks in terms of node, link and wavelength-conversion counts. The DWP scheme suggests maximal spreading of the computing effort, to a) split the computation effort to as many processing units as possible, and b) to have real-time access to locally monitored parameters. With DWP all relevant parameters are summed-up along potential paths by distributing path messages; dropping messages where constraints are not met (branch and bound). Being vector based any number and type of constraint can be considered in parallel; for example QoT/BER, delay, and reliability, as typically specified within service level agreements (SLAs). The fulfillment of constraints is guaranteed by DWP, as long as the parameters applied during path evaluation do not change. To cope with parameter changes the selection strategy should be to select the path with sufficient headroom for constraints dependent on dynamic parameters.

ILP based IA-RWA

Today integer linear programming (ILP) is commonly applied to perform off-line IA-RWA [19]. It has heavy computational effort, but with today's calculating power the results are commonly available within minutes. The challenges with ILP are to a) define an adequate linear optimization function, and b) formulate all other demands as side constraints. Once done all these equations are handed over to a software tool and the result pops out. Seemingly this is simple; however, results also pop out if some side constraints were not considered or incorrectly defined. There is no way to formally check problem sanity and completeness; that needs to be done by the engineer manually. Many proposals to solve IA-RWA using ILP have been published [17], [20]-[25]. They differ in the type and number of constraints considered, the optimization target, considered routing demands, and network scenario. However, ILP appears inadequate for dynamic environments and is unsuited for real-time control. The inevitable off-line operation demands synchronized and, more restrictive, considerably delayed changes in compensation adjustments and traffic assignments, a clear contradiction to any dynamic network/traffic management.

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8.1.2. Evolutionary algorithms for solving the impairment-aware routing and wavelength assignment problems

(Kyriakos Vlachos/RACTI; Siamak Azodolmolk / AIT)

Introduction/ Objectives

The objective of this work is to devise evolutionary algorithms like genetic to indirectly handle fiber and node impairments. We have proposed two genetic algorithms. The first is a multi-objective genetic algorithm (abbreviated MOGA) that uses classical multi-objective optimization strategies to jointly solve the IA-RWA problem. This algorithm decomposes the problem into its routing (R) and wavelength assignment (WA) sub problems. It then uses path length and number of common hops, inserted as entries in a multi-objective vector that must be optimized jointly. This allows for the calculation of a global optimum solution that is a set of routes that can serve the requested connections with the minimum number of wavelengths, and also have an acceptable QoT performance. The second IA-RWA algorithm is a single objective, Q-learning scheme. The algorithm, calculates during each iteration, the Q-factor of each lightpath before evolving the genetic population to the next generation.

Such an approach is computationally hard, but is useful for both solving the offline IW-RWA problem as well as for evaluating more heuristic approaches.

RACTI has developed a Genetic Algorithm for indirectly handling fiber impairments while AIT contributed the Q-estimator tool.

At the end of this mobility action, we intend that the joint work will conclude on the performance (in terms of accuracy and convergence speed) of the MOGA algorithm.

Generated WP Papers:

[1] Demetris Monoyios and Kyriakos Vlachos, "Multi-Objective Genetic Algorithms (MOGA) for solving the Impairment Aware Routing and Wavelength Assignment (IA-RWA) problem", to appear to IEEE/OSA Journal of Optical Communications and Networking, Vol. 3, Issue 1, pp. 40-47 , 2011.

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Layer", Photonic Network Communications, Vol. 18, No. 2, pp. 191-210, on-line & print, February 2009 (shared with JA2).

Relevant papers shared from other WPs or previously published on the topic:

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8.2. JA-2 ANNEX- Monitoring strategies for OBS and OPS networks

Summary of the previous activities results

In the last year it was done a collection of monitoring techniques from several partners. A new methodology for packet monitoring based on nonlinear optical preprocessing and filtering was proposed and studied. For this monitoring technique, a joint work between IT and UPVLC was proposed, related to the FBG manufacturing by UPVLC.

It was implemented a Burst monitor in an OBS access optical network which is assessed in terms of applicability to packet switching environment.

A mobility action between IT and UPVLC concerning to the evaluation of fast optical wavelength switching for routing functions, was proposed and planned.

Three joint papers were submitted, two for journal and one for conference.

Two WP meetings were performed, ICTON 2009 in Azores and BONE Second Plenary Meeting in Poznan.

Summary of the current activities results

In this year, it was done a research about monitoring techniques state of the art. Some improvements and experimental validation of the technique, for packet monitoring based on nonlinear optical preprocessing and filtering were performed.

An integrated solution, where management and control planes and monitoring functions work together was investigated. A monitoring device was proposed for OSNR-assisted routing to detect and dynamically set up optical paths taking into account the physical impairments.

A clock tone-based PMD monitoring technique which can enhance the monitoring sensitivity considerably and is CD and OSNR-insensitive was proposed. Furthermore, this method exhibited wide monitoring range as well as providing a cost-effective solution appropriate for the high-speed networks.

It was performed, a joint experiment, two mobility actions and two informal meetings organized during ICTON 2010 and ECOC 2010 International Conferences.

Three joint papers were submitted for conferences.

Furthermore, a paper was submitted to a journal, but it is on review.

8.2.1. Packet monitoring based on nonlinear optical preprocessing and filtering

(Diana Fidalgo, António Teixeira / IT; Salvador Sales / UPVLC)

Introduction

The purpose of this work is to determine the applicability and the related parameters, such as, the packet length, filter bandwidths and detuning of a preprocessing technique, which enables the prediction of the packet accumulated dispersion. The methodology encompasses a Semiconductor Optical Amplifier (SOA), which is used to chromatic dispersion monitoring, a Mach-Zehnder Interferometer Semiconductor Optical Amplifier (MZI-SOA) to sampler the optical data signal packet, and two filters to improve the quality of the signal. The final goal is to conceive a technique which enables real time fast monitor, to monitor and generate inputs to feed an eventual fast tunable compensator.

A work has been done to uncover new methods, for the deployment of desired optical performance monitoring functionalities.

Setup

The methodology is used firstly to perform simulations to optimize the parameters of the system, and afterwards try to implement and validate the predicted results.

The configuration used to simulate the methodology is presented bellow.

As shown in Figure 7, the data signal enters the SOA input after propagating through a single-mode fiber (SMF) to induce accumulated dispersion within the range of 60 ps/nm. The semiconductor optical amplifier (SOA) causes a phase modulation of the output signal (self phase modulation), shown in its spectral broadening, designated by red shift. At the output of the SOA, the signal is band-pass filtered to obtain a specific portion of the spectrum. An optimal filter (OBF1) at the output of the SOA is required to choose on the optimum low-frequency and bandwidth for chromatic dispersion monitoring.

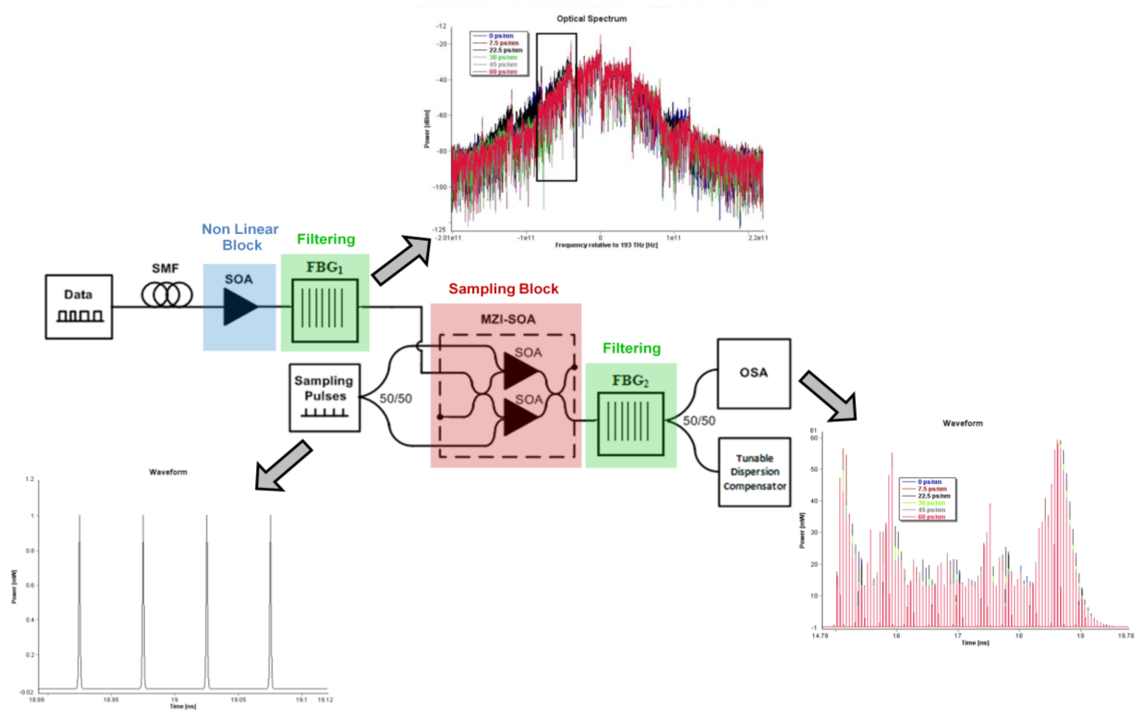

Figure 7 – Configuration for chromatic dispersion packet monitoring

A set of simulations were performed in order to optimize the optical filter aiming to improve the quality of the monitoring signal. It was evaluated the impact of the data and pump powers, along with the optimization of optical filters. The required optimal optical filter should be -60 GHz detuned from the data central frequency and have a 20 GHz bandwidth.

The results are obtained for four different data packet length, 0.8, 1.6, 3.2 and 6.4 ns with inter-packet spacing of 12.8, 25.6, 51.2 and 102.4 ns respectively.

After filtering and packing the transmitted data, is combined with a sampling pulse on the MZI-SOA to generate data samples. The data signal frequency is 193 THz and the data and sampling pulses are 150 GHz spaced.

The output signal of the MZI-SOA is filtered by an optical filter (OBF2) after being sampled by pulses with central frequency, 194.5 THz. A study was performed to get the optimum bandwidth of this filter (0.3, 2, 5 and 10 GHz). The data samples were analyzed, so that the relation between the output power and the accumulated dispersion on the system is determined.

After the accumulated dispersion is estimated this can be compensated by a tunable dispersion compensator.

The simulation results are obtained by VPI simulator.

Simulation Results

Time evolution of the data between 4.5 and 4.8 ns was gathered, for different values of accumulated dispersion between -60 and 60 ps/nm, FBG2 filter bandwidths between 0.01 and 10 GHz and for different packets length, 0.4 and 3.2 ns. It was done ten sweeps, in order to prove that the bit sequence does not change the results significantly. Some of the obtained results are shown in the figures below.

The Figure 8 show us that for both cases, i.e., 0.4 and 3.2 ns packets length, the standard deviation values are small and keep approximately constant for different FBG2 bandwidths. Therefore, we can say that the bit sequence does not change significantly the results, and this method can be used independently of the bit sequence choice. Moreover, for FBG2 filter with bandwidths lower than 0.06 and 0.03 GHz for 0.4 and 3.2 ns packet length respectively, its out power is approximately constant, which that induces us to conclude that, only the spectrum analyzer noise is detected and any filtered power is detected.

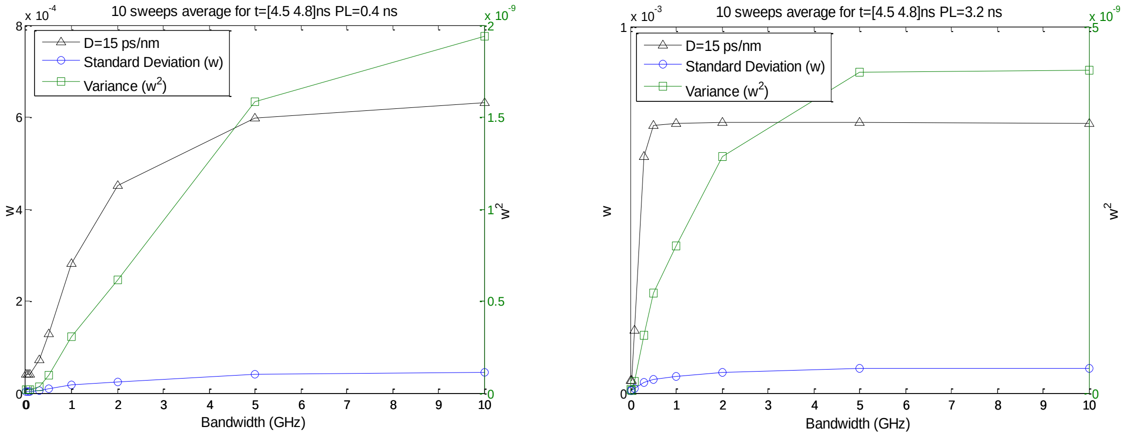

Figure 8 – Out Power FBG2 filter (triangle), Standard Deviation (circle) and Variance (square) for 15 ps/nm accumulated dispersion, for a bandwidth range between 0.01 GHz and 10 GHz, and for 0.4 ns (left) and 3.2 ns (right) packet length.

On the other hand, for FBG2 filter with bandwidths higher than 5 and 0.5 GHz for 0.4 and 3.2 ns packet length respectively, its out power is approximately constant. Thus, the optimal FBG2 bandwidth filter for this method should be between 0.06 and 5 GHz for 0.4 ns packet length and between 0.03 and 0.5 GHz for 3.2 ns packet length. Moreover, this method only can be applied to a maximum accumulated dispersion value of 30 ps/nm, for 0.4 ns packet length and 25 ps/nm for 3.2 ns packet length, due to the divergent behavior for higher values than 30 and 25 ps/nm respectively.

As way to verify if the method resolution is sufficient to monitoring the accumulated dispersion present on the system, it was studied the error bars statistic. For Figure 9, can be conclude that for 0.4 ns packets length, the optimal FBG2 filter should have a bandwidth between 1 and 5 GHz. However, only two different accumulated dispersion values can be simultaneously distinguish, e.g. 0 and 30 ps/nm (Figure 9 - left). For this reason, a 0.4 ns packet length is not suitable for this method. On the other hand, for 3.2 ns packets length (Figure 9 - right), the optimal FBG2 should have a 0.3 GHz bandwidth. For this case, it can be distinguished six different accumulated dispersion values, e.g. -60, -30, -5, 5, 10 and 25 ps/nm.

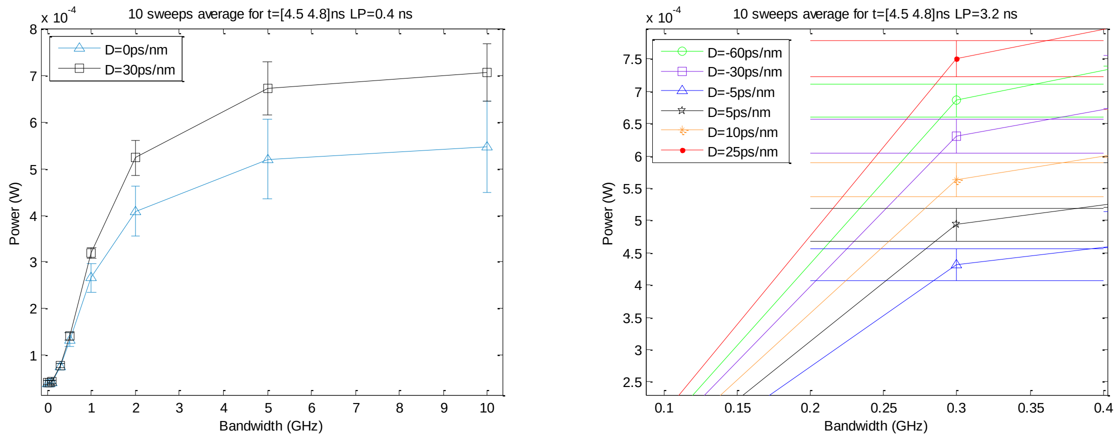

Figure 9 – Error Bars for 0 and 30 ps/nm, and for -60, -30, -5, 5, 10 and 25 ps/nm accumulated dispersion for 0.4 ns and 3.2 ns packet length respectively.

Fiber Bragg Grating Filters Manufacturing

UPVLC fabricated two types of Fiber Bragg Gratings, one is apodizated with Blackman profile and other is a π phase shift that will be used as a filters. The both of two will be used on the experimental work. The first one will be used at the SOA output, FBG1 and the other will be used at the MZI-SOA output, FBG2 as shown in Figure 7.

Both were characterized by an Optical Network Analyzer, and the results obtained are shown in the Figure 10 and Figure 11.

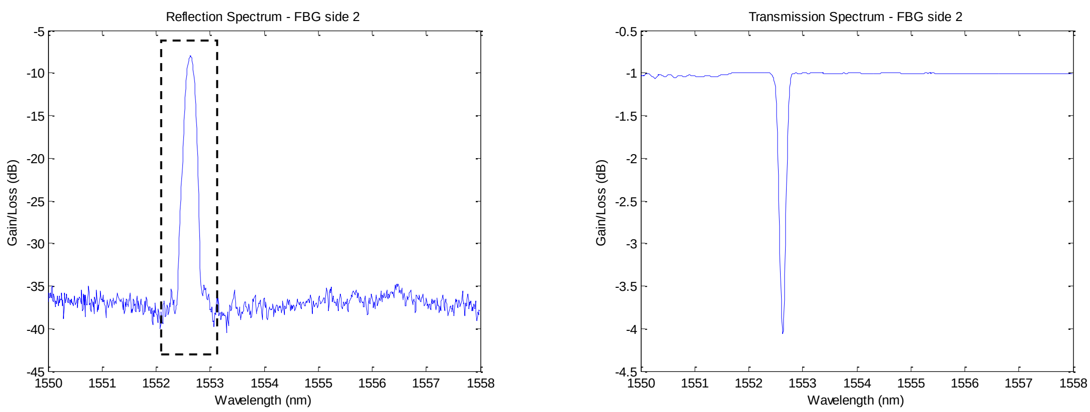

Figure 10 – Reflection and transmission spectra of a Blackman Apodizated Fiber Bragg Grating.

The FBG with Blackman apodization is 193.1 GHz centered and has 17.4 GHz of bandwidth. This FBG will be used on reflection mode.

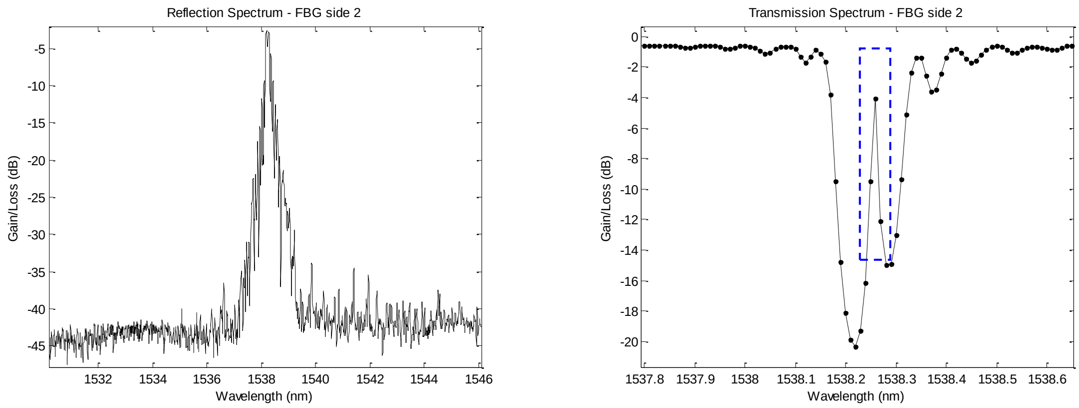

Figure 11 – Reflection and transmission spectra of a π Phase Shift Fiber Bragg Grating

The π Phase Shift FBG is 194.9 GHz centered and has 8.0 GHz of bandwidth. This FBG will be used on transmission mode, because it is required a narrow bandwidth filter at the MZI output.

Conclusions

The performed study provided us to know the methodology validity. For lower packets length, the optimal bandwidth is higher, between 0.06 and 5 GHz, and for higher packets length, the optimal bandwidth is lower, between 0.03 and 0.5 GHz. On the other hand, for 3.2 ns packets length, higher number of accumulated dispersion values can be simultaneously distinguished. Thus, it can be concluded, that this method can be applied and provide better accuracy to intermediate packets length, i.e., approximately 3.2 ns and for 0.3 GHz FBG2 filter bandwidth. The next steep, will be to experimental implement this setup.

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8.2.2. Monitoring devices for OSNR-assisted Routing in Optical Packet-Switched Networks

(Ruth Vilar,Roberto Llorente / UPVLC)

Introduction

Due to the high transmission capacity and dynamic traffic demand, network management is becoming more and more important. In this context, an integrated solution where management and control planes and monitoring functions work together must be deployed. We propose a novel technique to dynamically assess the quality of the optical paths. This technique optimizes network performance by selecting the most adequate optical route based on periodically sending a set of test packets along the network following different paths. These packets are processed in each intermediate node to monitor the network performance by using an optical correlator based on fiber Bragg gratings (FBG).

Then the optical signal-to-noise (OSNR) of the test packets is estimated from the noise statistics of the autocorrelation pulse peak power. This signal quality information is sent to the control plane and added as an additional factor in the routing decision. This feature allows the control plane to establish or select lightpaths taking into account physical impairments and thereby sustaining reliability’s requirements and keeping the level of quality of service promised to end users. Experiments performed on a 10-ps pulse-width 40 Gb/s return-to-zero ON-OFF (RZ-OOK) system, confirm that OSNR can be monitored with an error less than 0.5 dB.

Principle of operation

The OSNR monitor which interacts with the control plane to contribute to the supervision of service level agreement (SLA) fulfillment and efficiently perform routing based on signal quality requirements. Figure 12 shows the proposed interaction between the control plane and the monitoring system.

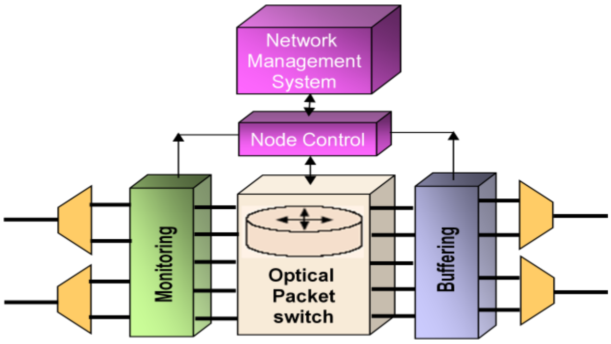

Figure 12 – Interaction between control plane and OPM functions

Concretely, the monitoring module is located inside the intermediate nodes. Then, the link performance information coming from this module is disseminated by the control plane and shared between network nodes to assess the status of all connections. Moreover, the quality estimation is added as an additional factor in the routing decision. Then, every link, i, is characterized by a parameter α_i which includes the signal quality estimated. Since the impairments are additive, the quality of a path is determined by the sum of the α_i of the traversed links. A maximum value α_{MAX} associated with QoS requirements is defined. Therefore, for a dynamic path setup, the control plane investigates the value of this monitoring parameter to calculate potential routes. Among them, lightpaths whose accumulate physical impairments do not exceed α_{MAX} are possible candidate while the others are no longer considered. Finally, one of these feasible routes is selected.

Regarding the monitoring module, we propose a novel technique to dynamically assess the quality of the optical paths. Figure 13 shows the principle of operation of the proposed monitoring system.

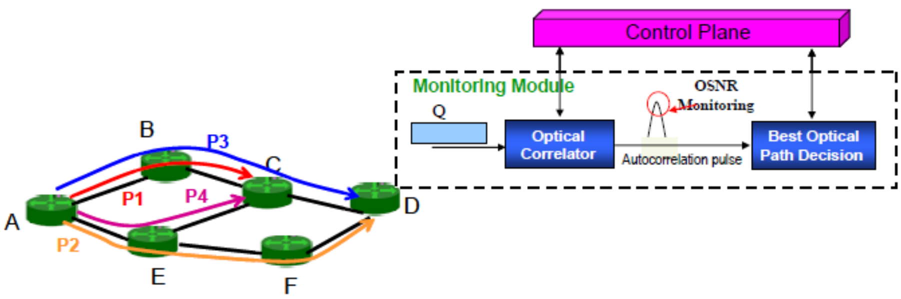

Figure 13 – Proposed monitoring system

In particular, a set of packets are periodically sent along the network following different paths. These test packets transmitted over optical paths are labeled with a specific data word, Q, composed of N bits with $q_i = 0$ or $q_i = 1$ $\left(Q = \left[q_0\, q_1 \dots q_{N-1}\right]\right)$, which are processed in each intermediate node to monitor the signal quality by means of an optical correlator. Note that the precise data word used for monitoring purposes (i.e., Q) could travel at different bit rate than the packet. Then, to increase the network transparency, this monitoring field could always travel at the same bit rate, making the monitoring module independent of the data bit rate. As said previously, the signal quality monitoring is based on using an optical correlator. In optical correlation the received signal $r(t)$ is correlated in the optical domain with the sent signal $s(t)$ so that the correlation function is a measure of how similar $r(t)$ and $s(t)$ are. The received signal exhibits the accumulative impairments effects that the link can impose. Once the node receives this degraded signal (test packet), it is correlated with an unimpaired version so that a maximum autocorrelation peak will be produced if the input signal is an exact match to the stored one. Then the OSNR of the incoming test packet can be calculated by using the statistics of the autocorrelation pulse peak power. The OSNR is defined as:

$$OSNR = \frac{mean^2}{\sigma^2} \tag{1}$$

where $mean$ is the mean value and σ is the standard deviation of the autocorrelation pulse peak power.

The main advantages of the proposed OSNR monitoring technique are simple implementation, relaxed speed requirements with respect to typical BER techniques as it only measures the autocorrelation pulse (i.e., the system work at the packet rate), and the possibility of integration with other functions related to the control plane.

Optical Correlators

A simpler, easily manufactured, and manageable correlator was constructed by writing a series of fiber Bragg grating mirrors into a single length of fiber in order to validate the OSNR monitoring technique. In these applications the array of gratings reflects back part of the signal at different times, resulting in multiple replicas of the input signal spaced in time with the delay increment τ. The reflectivities of the FBGs provide the same weighting function as the optical correlation and their values are designed so that the light reflecting of each FBG has equal power when it exits the correlator, following this recursive equation:

$$\frac{R_n}{(1-R_n)^2} = R_n + 1 \tag{2}$$

Since the light makes a double pass through the array, the spacing between FBGs must match half the bit period to produce a round-trip delay of 1-bit.

A FBG-based correlator can be constructed by using thermally controlled FBGs as tunable-reflectivity mirrors. However, this solution presents some disadvantages associated with polarization dependence, time-delay variation with reflectivity and dispersion. To solve these problems, our correlator was also constructed by writing a series of FBG into a single length of fiber but each grating had the desired reflectivity thereby avoiding the thermal tuning and the inconvenience associated with operating at the edge of the FBG spectrum. The response of the array of gratings was designed by using the matrix transfer approach.

Experimental Results and Discussion

To demonstrate the feasibility of the system, a 40 Gb/s correlator configured to match the pattern [10001011] was chosen whose design is shown in the Figure 14. The test packets used to monitor the signal quality are labeled with this pattern. Then, each '1' of the pattern is represented by a uniform FBG. The optical fiber length between two successive FBGs is proportional to the bit period in order to recognize the desired pattern, i.e fiber length proportional to T_b, $2T_b$ and $4T_b$ where T_b is the bit period. One aspect of novelty of our correlator is the design with unequal grating spacing, i.e. with different time intervals, in order to reduce the sidelobes and the effect of secondary reflections over the autocorrelation pulse. By means of simulations, a study of the correlator output as function of the pattern was carried out in order to decide which pattern provided better performance and less overhead choosing the pattern [10001011].

The FBG-based correlator was realized by exposure of the fiber to ultraviolet (UV) laser light with the phase mask scanning method. All the FBGs were tuned to the same wavelength (λ = 1553.8 nm). The reflectivities were fixed to 16%, 23%, 38% and 100% and (using (2)). The grating with the highest reflectivity FBG_4 (R_4 = 100%) was firstly written. Then, the fiber was moved along its axis over a length corresponding to the required '0' in the pattern and the FBG3 ($R_3 = 38\%$) was written. The grating FBG2 ($R_2 = 23\%$) and FBG_1 (R_1=16%) were written following a similar process. The optical fiber length between the successive gratings were $L_1 = 2.5810$ mm, $L_2 = 5.162$ mm and $L_3 = 10.324$ mm, measured from the beginning of one grating to the beginning of the following one, Figure 14. These lengths correspond to time intervals of T_b, $2T_b$ and $4T_b$ at 40 Gb/s. The length of the gratings were $L_{FBG_1} = L_{FBG_2} = L_{FBG_3} = 1$ mm and $L_{FBG_4} = 4$ mm. The accuracy of the FBG positioning along the fiber was in the micrometer range. The bandwidth of the FBGs corresponded to a FWHM of 10 ps.

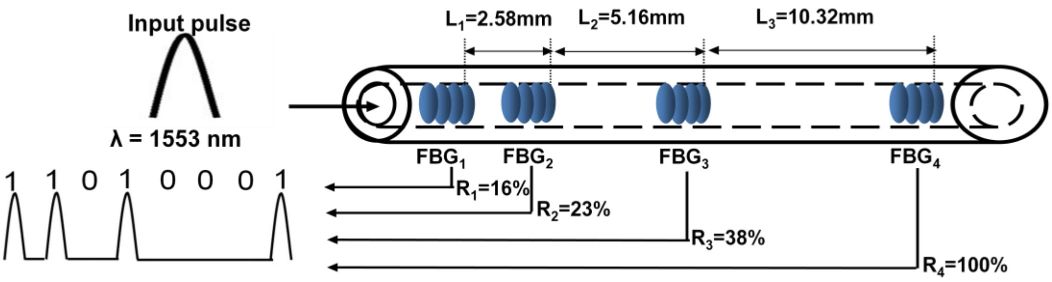

Figure 14 – FBG-based correlator design

The output of the fabricated correlator at 40 Gb/s is shown in the Figure 15 (b). The pattern, [10001011], inserted in the test packet, is processed in the node to perform the correlation function. When this field matches with the pattern stored in the array of FBGs, an autocorrelation pulse appears, Figure 15. The optical correlator is sensitive to the fluctuations in the received signal due to the fiber impairments. The inset of the Figure 15 (b) shows the statistics of the autocorrelation peak used to estimate the OSNR.

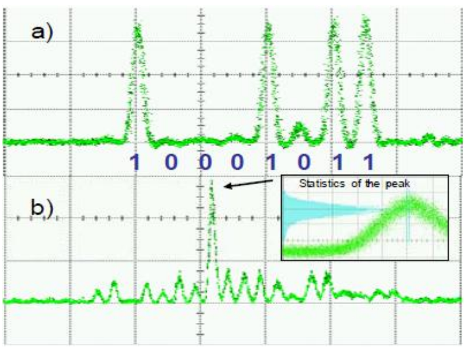

Figure 15 – a) Input sequence 10001011 (50ps/div); b) Correlator output (100ps/div)

The principle of operation of the quality monitoring technique is validated experimentally by means of the setup shown in Figure 16. The pattern inserted into the test packets, Q=[1 0 0 0 1 0 1 1], is generated through external modulation of an RZ Gaussian pulse source at 1553.8 nm. The modulating signal driving the Mach-Zehnder modulator (MZM) is obtained from a 40 Gb/s electrical PRBS equipment. An optical circulator is placed at the array input to route the counter-propagating correlation output to the sampling scope. The signal out from the transmitter is coupled with a second EDFA to simulate the link noise. Thus, the OSNR of the optical signal can be changed by combining the signal with different ASE noise levels adjusting the gain of the EDFA pump laser. The optical signal degraded with the noise passes through a 1-nm bandwidth filter and enters the optical correlator. The OSNR can be evaluated by measuring the statistics of the autocorrelation peak, more specifically using the mean value and the standard deviation. These values are extracted by means of a high-speed sampling scope. Despite using a sampling scope, the technique allows high-speed bit-rate operation as it only measures the autocorrelation pulse, so the system works at the packet rate and thereby alleviating speed requirements with respect to typical BER techniques as it was mentioned previously.

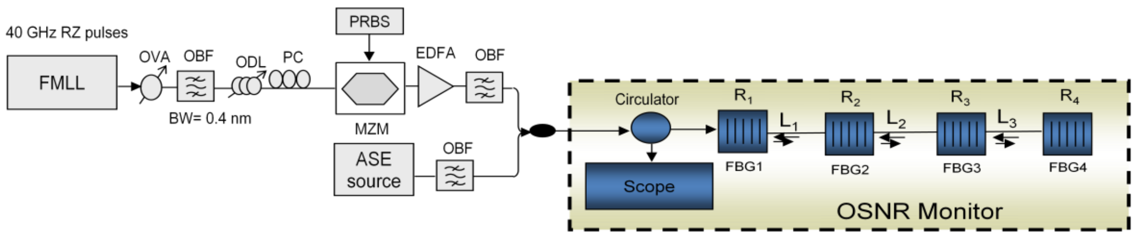

Figure 16 – Experimental Setup

Figure 17 shows the OSNR values for the incoming signal versus the estimated OSNR using the autocorrelation pulse and confirms the OSNR monitoring functionality of our proposed scheme. The OSNR monitoring errors are the difference between the OSNR measured from the input pulse and from the autocorrelation output pulse.

From the curve the maximum error for the measurement of different OSNR values is 0.5 dB in the 15 dB to 25 dB OSNR range (Figure 17). The slight deviation in lower OSNR values can be explained by the noise filtering behavior of the FBG-based correlator. The optical signal degraded with the noise passes through a 1-nm bandwidth filter and enters the optical correlator whose bandwidth is approximately 0.6-nm.

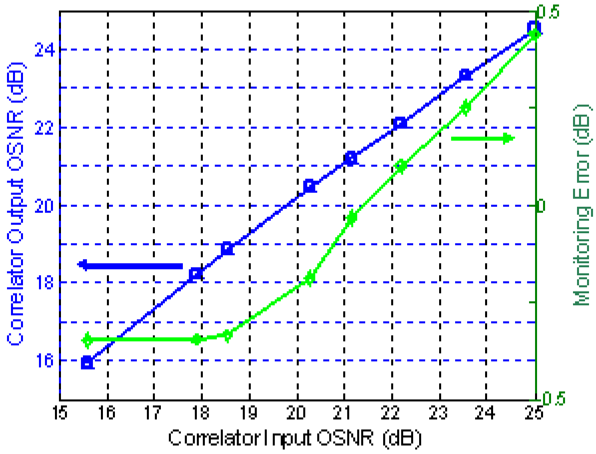

Figure 17 – Experimental OSNR monitoring

Therefore, for lower OSNR values the output of the correlator is less sensitive to the degradation than the input, primarily due to the narrower optical passband of the FBG-based correlator providing a smaller noise background. In contrast, for higher OSNR values, where the noise background is practically negligible, the difference is due to the insertion loss of the gratings which slightly affects the power of the correlator response. Therefore, monitoring errors are caused by noise at lower OSNR values and by insertion loss at higher OSNR values.

As it has been commented before, the information obtained from the optical monitor could be disseminated by the control plane and shared between network nodes being included when calculating new routes. Indeed, monitoring information could be added as an additional factor in the routing decision in order to establish optical paths based on quality requirements.

Conclusions

We propose an OSNR monitoring technique, which can work together with the control plane and provides an estimator of the signal quality, to be used for the routing algorithm. Among all possible routes, the routing mechanism only takes into account those ones, whose quality is better than a specific QoS requirement. The quality of the transmission depends on simple accumulative parameter such as OSNR. This strategy can be further elaborated taking into account other transmission impairment affecting the OPN, like polarization-mode dispersion (PMD).

The monitoring technique is based on optical correlation. A FBG-based correlator was fabricated to experimentally demonstrate the proposed system. By measuring the noise statistics of the autocorrelation pulse peak power, the OSNR can be estimated with an error lower than 0.5 dB. Therefore, the autocorrelation peak can be a feasible indicator of the signal impairments. The advantages of the proposed OSNR monitor are in-band measurements, relaxed speed requirements with respect to typical techniques, simple implementation and possibility of using this monitoring information to sustain the network reliability, establishing optical paths based on quality requirements.

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8.2.3. DGD monitoring technique for high-speed data using a low-speed detector

(Ruth Vilar/UPVLC)

Introduction

Polarization Mode Dispersion (PMD) is notably critical for next generation high bit rate optical networks. Given the stochastic nature of PMD, it is desirable to monitor PMD in order to dynamically tune a compensator and also to isolate the PMD effects from other physical impairments such as chromatic dispersion (CD).

Many monitoring techniques use spectral-tone-based RF spectrum measurements for signal quality monitoring. These techniques are very attractive due to their potential fast response time (sub-ms), its simplicity, and the fact that these spectral tones travel the complete optical path with the baseband signal so that are subject to the same degradations as the baseband signal. Among the parameters that these techniques can monitor, it has been reported the PMD monitoring with high-frequency tones [1] and also with the clock tones [2]. The former techniques have some limitations, including: a) the spectral tone could interfere with the spectral components of data and cause power penalty, b) there are difficulties in making the effect of chromatic dispersion (CD) and PMD independent, c) the system performances could be deteriorated by the cross-gain modulation (XGM) of an erbium-doped fiber amplifier (EDFA) and/or stimulated Raman scattering (SRS) due to the ghost tone creation, and d) using high-frequency tones demand high bandwidth electronic devices [3]. The last techniques, based on clock tones, solve some of these limitations since they do not introduce any extra tone, but for high bitrates they still require high-frequency devices, increasing the cost of the system. In this work, we propose a clock tone-based PMD monitoring technique which is CD and OSNR-insensitive and provides a cost-effective solution appropriate for the future optical packet-switched networks

Study of the applicability of the monitoring techniques based on RF spectrum measurement in optical packet-switched networks

OPS networks are characterized by dynamic traffic scenarios where packets follow their own route along the network, being necessary the monitoring on a packet basis. Additionally, these networks require monitors with fast response and wide dynamic range. In this section, a study about the applicability of the monitoring techniques based on RF spectrum measurements is carried out. The analysis considers that the monitoring is performed on a packet basis which adds new challenges in terms of synchronization issues, time response of the monitor, and measurement sensitivity.

- **Synchronization issues**

The monitoring system must exactly know when the packet arrives at the node in order to perform the monitoring tasks on the short time of one packet. In practice, synchronization function in the optical packet switching node can play a major role to control when a packet is present. The monitor should then cooperate with the synchronization function and the packet header processing unit should recover the clock on the packet, and in turn provides the timing information to the monitor to locate the packet.

- **Response time**

In OPS networks it is necessary to obtain fast response time for monitoring the optical packets. An RF power detector can directly measure the RF power in a frequency range. By using a fast RF power detector, a response time in the range of few nanoseconds can be obtained. For example, commercial power detectors, such as a crystal detector, offer a time response of about 10 ns.

- **Sensitivity analysis**

To analyze the sensitivity of the RF-spectrum-based techniques, a simulation study is carried out. The objective is to determine what the minimum packet length required by obtaining accurate measurement is. To this end, the simulation study is based on sending an RF tone attached into the packet. By varying the packet length, the impact of this parameter on the RF tone power is measured. In particular, Figure 18 shows the dynamic range, which is measured as the extinction ratio of the RF tone, as a function of the packet length.

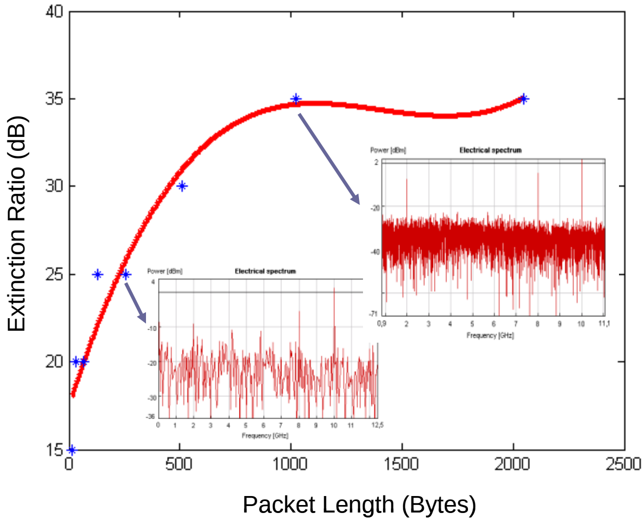

Figure 18 – Dynamic range measured as the extinction ratio of the RF tone vs packet length

From Figure 18 it can be seen that the dynamic range and, therefore, the measurement sensitivity increase when increasing the packet length. From a packet length higher than 1 Kbyte, the dynamic range stabilizes, obtaining good sensitivity for packets longer than 500 bytes. Note that the usual IP packet length varies between 500 bytes and 1500 bytes.

After the simulation study, it seems that the RF-spectrum-based monitoring techniques can be applied to the OPS networks since they provide fast response time and good sensitivity for the usual packet lengths travelling along the network

Principle of operation

The proposed first-order PMD monitoring technique is based on adding an additional optical carrier shifted with respect to the data carrier, but at the orthogonal polarization state in order to be in-band with the data and not to affect their recovery. After detection, the added carrier beats with the upper and lower clock tones of the data generating beat signals at frequencies $R_b \pm f_{shift}$ (R_b is the bitrate and f_{shift} is the shift between the data carrier and the additional carrier), whereby the resulting RF power of these beat signals depends on the PMD value.

The first-order PMD causes different propagation velocities for the signal travelling on two orthogonal states of polarization. Due to DGD, the polarization states of the both clock tones are rotated ±θ degrees with respect to the optical carrier. The rotation is given by:

$$\theta = 2\pi\Delta f \mathrm{DGD} \quad (3)$$

where Δf is the frequency difference between the clock tones and the optical carrier [4].

Thus, without DGD, the rotation is equal to zero; so that the clock tones and the optical carrier remain orthogonal resulting in no beat RF tones at the receiver. Conversely, the DGD depolarizes the clock tones and the optical carrier increasing the power of the beat RF tones significantly. In addition, by placing the added optical carrier close to the clock tone, a very low-frequency beat tone (i.e. $R_b - f_{shift}$ tone) can be selected, and used for DGD monitoring of high-speed data with a low-speed detector, providing a cost-effective solution. A conceptual diagram of the proposed technique is illustrated in Figure 19.

On the other hand, since the upper and lower optical clock tones are asymmetric with the added shifted carrier, accurate CD-insensitive DGD monitoring is performed.

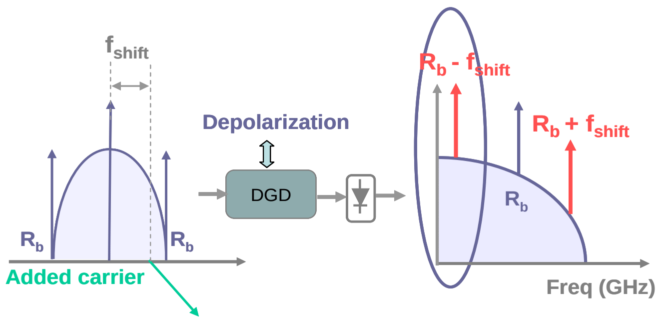

Figure 19 – Conceptual diagram of the PMD monitoring technique based on adding an additional optical carrier at the orthogonal polarization

The proposed PMD monitoring technique was validated by means of simulations using the Virtual Photonics Inc. software. Figure 20 shows the response for the detected RF power versus DGD value for RZ and RZ-DPSK modulation formats for two different Δf values (Δf = 2 and 5 GHz). From this figure, we can extract that both modulation formats have the same behaviour when increasing DGD. For low DGD values, the technique improves the monitoring resolution compared to traditional RF-tone-based techniques. Then, for both Δf values the monitoring system provides high dynamic range; however, the monitoring range is inversely proportional to Δf.

Moreover, since the upper and lower optical clock tones are asymmetric with respect to the added shifted carrier, accurate CD-insensitive DGD monitoring is performed. This technique could be also applicable to NRZ, CSRZ and other advanced modulation formats such as RZ-DQPSK.

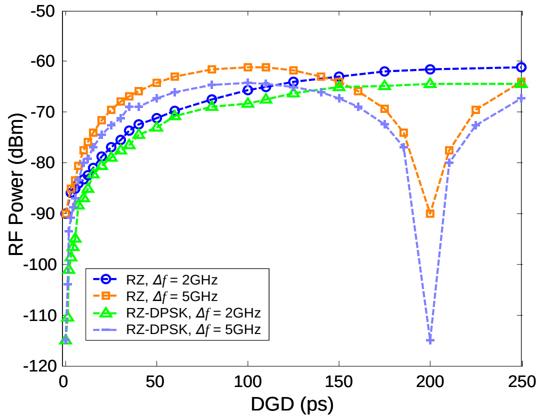

Figure 20 – RF power response as a function of the DGD for RZ and RZ-DPSK data formats

Experimental results

The experimental demonstration of the method for 40-Gbit/s RZ data was performed by the setup shown in Figure 21. At the transmitter, a continuous-wave laser at 1551.7 nm was externally modulated using a 40-GHz intensity modulator and then an RZ pulse carver driven by a 20-GHz clock source generated the 40-Gbit/s RZ signal. An additional DFB laser at 1552.005 nm was combined with the data using a polarization beam combiner (PBC) assuring that they were in orthogonal polarization states. The frequency difference between both optical carriers was around 38 GHz. The signals were then coupled with amplified spontaneous emission (ASE) noise to adjust the OSNR values. These channels were then passed through the tunable CD and DGD emulators. The DGD monitor consisted of a low-speed detector (2.5-GHz) and an RF spectrum analyzer. The RF power at low frequency content (i.e. $R_b - f_{shift}$ ~ 2 GHz) was measured for DGD monitoring.

Figure 22 shows the RF power in the presence of DGD. We observed that the power was very low (noise floor) when no DGD was present in the transmission link whereas the RF power increased significantly as the DGD got higher due to the DGD-induced depolarization, indicating that the RF power change in the beat signal can be a feasible indicator of the DGD imposed by the fiber.

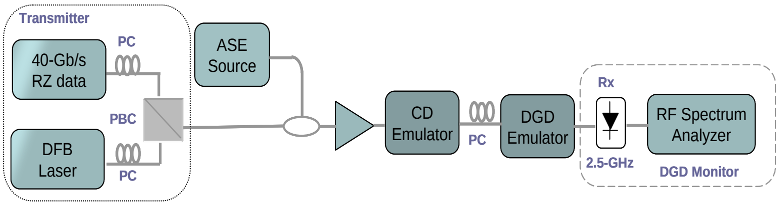

Figure 21 – Experimental setup

As shown in Figure 22, the RF power increment around 18 dB was obtained for the DGD range from 0 to 25 ps. Additionally, we measured the RF power under different CD values of 0 ps/nm, 160 ps/nm, 440 ps/nm and 860 ps/nm detecting a variation less than 1 dB as shown in Figure 23 (a). Similar insensitivity to OSNR was obtained when the OSNR changes from 15 to 25 dB, see Figure 23 (b).

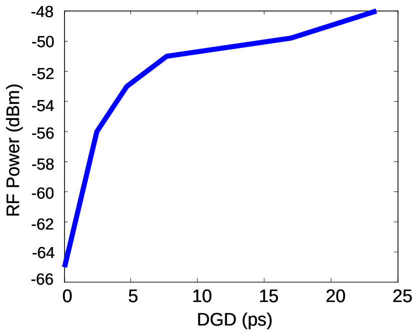

Figure 22 – RF power response as a function of DGD

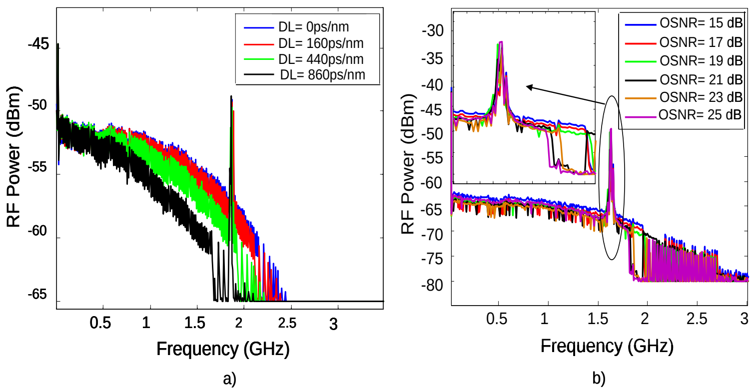

Figure 23 – RF power for a DGD of 23 ps under: a) different CD values (0 ps/nm, 160 ps/nm, 440 ps/nm, 860 ps/nm); b) different OSNR values (from 15 to 25 dB)

Conclusions

A CD and OSNR-insensitive DGD monitoring technique using a low-speed detector was proposed for a 40-Gb/s RZ data. A new RF tone generated by the beating between the clock tone and an additional orthogonal shifted optical carrier was used for DGD monitoring observing an increment of 18 dB in the range from 0 to 25 ps. The measurements were insensitive to CD and to OSNR as well. This technique did not require high-speed components for DGD monitoring of data at high bit rate which provided a cost-effective solution.

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8.2.4. Optical parameters estimation through Modulation Instability

(Giorgia Parca/Uniroma2; António Teixeira / IT)

In order to accomplish the prediction of optical system parameters, several methods have been proposed for the fiber characterization in terms of nonlinear coefficient or Chromatic Dispersion coefficient, mainly based on measuring the impact of Kerr effect through Self Phase Modulation (SPM), or Cross Phase Modulation (XPM).

Modulation Instability (MI) is a nonlinear instable phenomenon arising in dispersive fiber optics under proper conditions, and can be exploited for optical fiber parameters estimation.

MI effect can be seen as interplay, based on Kerr effect, between a strong pump CW signal and a small perturbation propagating in anomalous dispersion regime.

When the pump signal is injected in an optical fiber, the small perturbation, initially negligible, for example ASE noise, undergoes amplification if proper conditions are satisfied.

This phenomenon is characterized by a spectral gain that arises as sidebands around the pump CW signal.

The measurement of MI gain as a function of input power allows estimating the non-linear coefficient. Moreover, maximum MI gain in optical fiber occurs at a certain pulsation that is directly related to the Chromatic Dispersion coefficient of the fiber, and can be extracted as well.

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8.2.5. Monitoring potential of modulation instability for optical packet/burst switched networks

(Giorgia Parca/Uniroma2; António Teixeira / IT)

Main focus of this work was to study the potential of Modulation Instability based techniques for the prediction of optical fiber parameters.

The nonlinear effect model is available in literature and describes the interplay between a CW pump signal propagating together with a small perturbation in Anomalous Dispersion Regime. So far, the not-CW pump based effect is not well explored, especially concerning the theoretical analysis.

From the available model [2] important relations for MI characterization can be derived, and together with measured spectrum properties, fiber parameters estimation can be performed [3].

When the MI is triggered by a CW pump signal, the noise floor under the gain spectrum function [1] undergoes amplification.

From the theory, it is easy to obtain that the maximum gain is proportional to the nonlinear coefficient γ and to the pump power. Therefore, from the peak gain measurement, the slope can be directly extracted and corresponds to the nonlinear coefficient γ.

Moreover, the peak gain is located at a wavelength, whose expression can be obtained from the theory; it is related to the Dispersion coefficient β and can be evaluated, as well.

Experiments were carried out at the Italian Istituto Superiore delle Comunicazioni (ISCOM) in Rome, using an optical cable installed from Rome to Pomezia. The measurement was carried out on a NZD fiber with GVD=2.2 ps/km/nm (Dispersion Coefficient) and α = 0.26 dB/km (Fiber Attenuation). The fiber was chosen in order to guarantee $\beta < 0$, which corresponds to the Dispersion regime needed in order to give rise to MI. The goal of the experiment was to measure the fiber gain spectral characteristics, in case of strong CW feeding the system; used setup and system parameters values are shown in Figure 24 and Table 4 respectively.

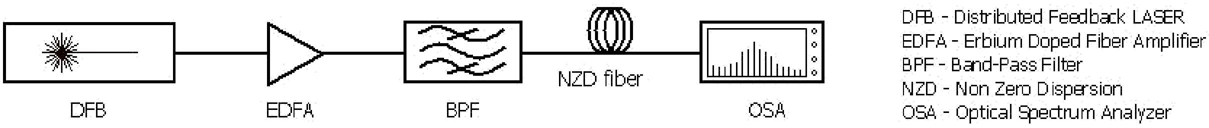

Figure 24 – Experimental setup

Wavelength	1544.52 nm
Fiber length	50-100 Km
CW Power	16-33 dBm
GVD	2.2 ps/nm.Km
Nonlinear coefficient	~ 1 1/W.m

Table 4 – System parameters

The optical source is a DFB laser generating a CW carrier @1544.526nm, one ITU-T grid wavelength. A narrowband optical pass band filter, placed before the amplifier, reduces source noise, in order to not interfere with the ASE spectrum. ASE generated by the Erbium Doped Fibre Amplifier (EDFA) is a good candidate to measure the gain spectral characteristics.

We found experimentally that the pump signal is able to feed the nonlinear phenomenon leading to the growth of sidebands, whose shape depends on the spectral gain characteristic.

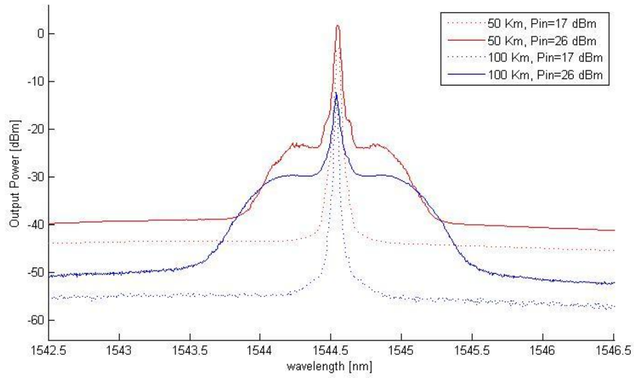

Figure 25 – Experimental MI spectrum

MI spectrum is showed in Figure 25, and it is possible to observe that increasing the input pump power, the pump signal feeds the growth of MI sidebands.

Moreover, we observe that the sidebands peak gain approach a saturation point with the increase of pump power, as shown in Figure 26, and this means that their relation cannot be considered linear anymore, and that the nonlinear coefficient estimation described before is no longer valid.

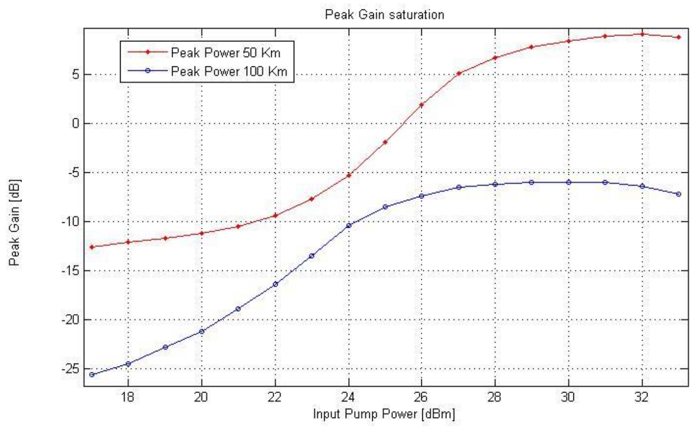

Figure 26 – MI peak gain as function of input pump power

In particular, after the gain saturation, this estimation method cannot be accurate because the formalization models only the first phase of the effect, without describing both the gain saturation and the pump depletion.

Conclusions

The results of the experiment show that the common models are not fully suitable for describing the main parameters. If the common model is used, parameters prediction is valid under certain operative conditions in terms of limited input pump power.

In order to exploit the parameter estimation methods based on Modulation Instability, the theoretical model must be generalized taking into account the gain saturation effect.

This investigation has to be extended to time analysis, both theoretically and experimentally in order to assess its validity in the context of OBS/OPS.

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[1] R. Vilar, N. Nadarajah, A. Nirmalathas, R. Llorente, F. Ramos and J. Marti, "Cost-effective DGD Monitoring Technique for High-speed Data Based on an Orthogonal Optical Carrier," submitted to J. Lightwave Technology in 2010.

Generated WP Papers:

[1] Ruth Vilar, Roberto Llorente, and Francisco Ramos, "Monitoring devices for OSNR-assisted Routing in Optical Packet-Switched Networks", in Proc. of Future Network & Mobile Summit, Florence (Italy), 2010.

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8.3. JA-3 ANNEX- Decision mechanisms for packet transit in OPS networks

Summary of the previous activities results

In this year, activities related to OBS/OPS systems were performed. It was studied the performance of switching devices in presence of different modulation formats at high data rate per port (400 Gbit/s/port); carving for mitigation of transients in optical amplifiers; and OBS in presence of lasers with limited tunability.

Two mobility actions were performed, one between IT and NICT concerning to all-optical tunable wavelength conversion of a 160 Gb/s RZ OTDM signal, and the another between BME and NICT to study the cascadeability of OPS node for different modulation formats. On the other hand, two new mobility actions were proposed and planned, one between BME and NICT related to all-optical 3R and processing for photonic networks, and another between UNIROMA2, ISCOM and IT to research all optical switching technology.

Two WP meetings were performed, ICTON 2009 in Azores and BONE Second Plenary Meeting in Poznan and three joint papers were submitted for conferences.

Summary of the current activities results

In this year, experiments of QoS on HD Video streams in PONs, experiments and simulations on optical processing and monitoring in switched (packet and/or burst) networks, and all-optical phase regeneration for binary phase-shift keyed (BPSK) were achieved.

It was designed and experimental validated, a novel technique for optical switching, implemented in wavelength-routed scenarios and modeling and optimization of all-optical switching devices.

Eight joint papers were submitted, from which, one was for journal and seven for conferences. Furthermore, three papers were submitted, but they are on review, from which, one was for journal and two for conferences.

Three mobility actions were performed and two informal meetings were organized during ICTON 2010 and ECOC 2010 International Conferences.

8.3.1. *Unbundling and Quality of Service Control in Ethernet Passive Optical Networks based on Virtual Private LAN Service Technique*

(Tosi Beleffi/ ISCOM)

Introduction

In this work we experimentally demonstrate how to achieve logic point-to-multipoint paths in Gigabit Ethernet (GbE) networks with access based on Passive Optical Networks (PON), guaranteeing upstream/downstream bandwidth and quality of service also in condition of traffic congestion. Such a method is based on the combination of the Virtual Private LAN Service (VPLS) forwarding process in the metro-core network and of the VLAN tagging one in the Edge-PON segment.

The pervasive introduction of optical fibres in access networks is one of the fundamental requirements to deliver wide bandwidth services. For such an aim, Passive Optical Networks (PON) are fibre access architectures that are simple to be implemented and with low costs. However, it has to pointed out that the current versions of PON, as Ethernet PON (EPON, IEEE 802ah) and Gigabit PON (GPON, ITU G.984), have some drawback, mainly due to the transmission capacity (1-2.5 Gb/s), that could be insufficient when it is shared among many users (32-64), and to the fact that PONs do not permit physical unbundling, without using a WDM approach, limiting competition among operators. Therefore, for current PON we need the introduction of techniques both to control the Quality of Service (QoS) to assure Service Level Agreements also in conditions of traffic congestions, and to allow reliable logical paths to introduce unbundling procedures. For such an aim, networks need procedures to guarantee End-to-End QoS properties, from access to the core and in Ethernet environment, the Virtual Private LAN Service (VPLS) [2] is a very suitable technique since it provides multipoint Ethernet connections employing MPLS Label Switched Paths (LSPs), allowing to achieve excellent network performances in terms of traffic management and QoS. VPLS is a Layer 2 Virtual Private Network (VPN) where the customers seem to belong to the same LAN, regardless of their real geographic position. VPLS works on routing elements called Provider Edge (PE), and VPLS procedures can be extended, by means of VLAN tagging technique, to routing elements (Costumer Edge, CE) that do no support VPLS. Therefore, by means of VPLS-VLAN tagging we can define Class of Service (CoS) in End-to-End paths, crossing access and core networks.

In this paper we experimentally show that by means of VPLS-VLAN tagging technique used in wide area GbE networks, including EPONs, we are able to set-up upstream/downstram data stream that maintain bandwidth and QoS characteristics, also when traffic congestion occurs in some network segment.

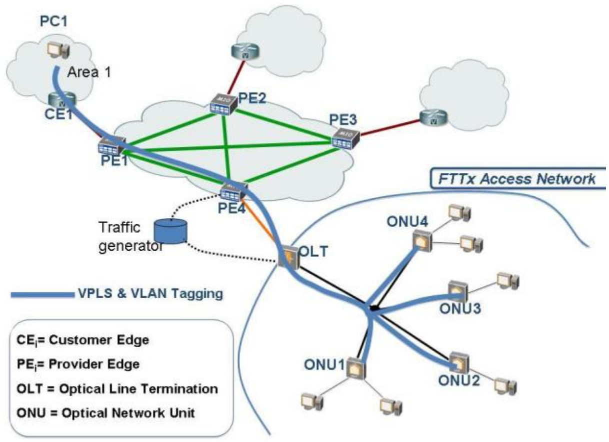

Figure 27 – Experimental set-up representing a core (PEs) network with FTTx access network based on EPON. The bold tree line among PC1 and ONU1, 2, 3, 4 indicates the VPLS-VLAN tagging environment

Helpful Hints

The Test-Bed shown in Figure 27 is composed of a core and access section [3]. The core part consists of four routers, Juniper M10 with ZX GbE interfaces (1550 nm), that operate as PEs and are fully meshed using the fibers deployed in the cable Roma-Pomezia-Roma (50 Km with round trip in Pomezia). The edge (metro) part is composed of three Cisco 3845 edge routers (that behave as CEs), connected with three Juniper routers by means of GbE fiber transmission. The access section is a Fiber To The x (FTTx) access network consisting of an Ethernet Passive Optical Network (EPON), AN5116-03 ePON FiberHome, with an Optical Line Termination (OLT) and eight Optical Network Units (ONU). The OLT and the ONUs are connected by means of a single mode fiber with the downstream wavelength at 1490 nm and the upstream wavelength at 1310 nm.

On all routers, OSPF (Open Shortest Path First), MPLS and BGP (Border Gateway Protocol) protocols have been configured.

Network measurements were carried out by using a software network analyzer, NetIQ

Chariot,that allows us to evaluate some network parameters like throughput, jitter and data loss. However, here we only report, for sake of brevity, throughput measurements.

To test the impact of the network congestion, a traffic generator (Smartbits 6000) is included in the Test Bed for introducing a background traffic of 1 Gb/s between PE4 and the OLT.

Results

As shown in Figure 27, we set the VPLS-VLAN tagging, with a higher priority Class of Service that we called Gold Class as reported in [4], among CE1 and the ONU 1, 2 3 and 4, corresponding to a typical configuration for an operator that delivers services from a server to the users. In this configuration, we considered the upstream/downstream scenario sending flows from/to PC1 to/from the user at the ONU2 output. The advantages of our method are illustrated by the Figure 28 and Figure 29 where we report the throughput at the ONU2 (downstream) and CE1 (upstream) respectively for 40 Mbit/s fluxes both in the absence (default Class of Service, i.e. Best Effort) and in the presence of VPLS-VLAN tagging, when the congestion occurs. When the VPLS-VLAN tagging is applied (with a Gold Class that allows to achieve the best QoS performance), the throughput does not show any reduction. Conversely, without VPLS VLAN tagging the services supported by a PON would be strongly degraded (both in upstream and in downstream) by a congestion. Measurements carried out on jitter and data losses confirmed such aspects.

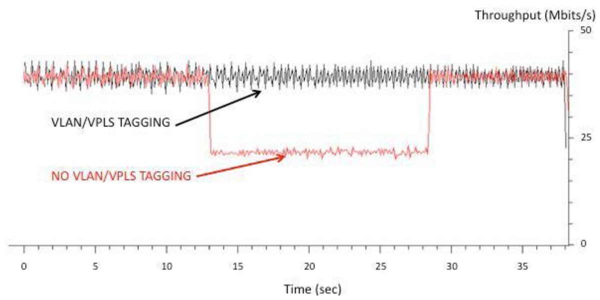

Figure 28 – Throughput of the 40 Mb/s flows at the ONU2 output (downstream) with and without VPLS/VLAN tagging

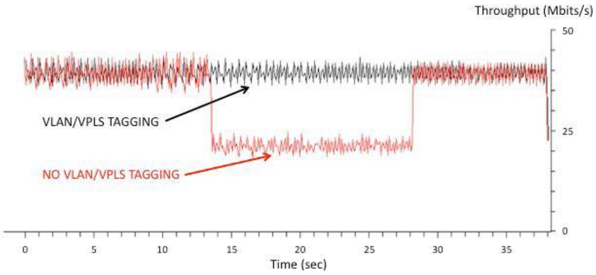

Figure 29 – Throughput of the 40 Mb/s flows at the CE1 output (upstream) from ONU2 with and without VPLS/VLAN tagging.

Also measurements of perceived quality were carried out. In particular, we sent MPEG2 High Definition (HD) video streamings both with and without VPLS-VLAN Tagging. As shown in Figure 30 and Figure 31, when the VPLSVLAN Tagging is applied, there are no degradations and the video is received with a perfect quality; conversely, when we have no tagging, the video is strongly degraded.

Figure 30 – Screenshot from MPEG HD video with VPLS-VLAN Tagging

Figure 31 – Screenshot from MPEG HD video with no VPLS-VLAN Tagging

Conclusions

We believe that illustrated architecture, based on VPLS–VLAN Tagging in wide area GbE networks, allows PON networks to well satisfy requirements of both users and operators in terms of QoS. Such results suggest that by means of such an approach very reliable paths can be defined in PONs, guaranteeing QoS and bandwidth, and therefore VPLS VLAN tagging technique can be assumed as an enabling technique for unbundling procedures in PONs.

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8.3.2. On the monitoring and signal processing in packet switched networks

(Giorgia Parca / ISCOM / UNIROMA2; Tosi Beleffi / ISCOM; António Teixeira / IT)

Introduction

Integrated MZI-SOAs (Mach-Zehnder Semiconductor Optical amplifiers) are compact devices with a vast potential for several application, such as logical gates, digital phase modulation, switching and wavelength conversion, all-optical processing and signal regeneration. In all these applications, the interferometer has to be previously biased, in order to set output power and power/phase change as a function of the available inputs.

MZI-SOA is an integrated device, which encompasses couplers, guides and SOA's, each element with its own tolerances and asymmetries. These issues have some implications in MZI-SOA functionalities, for example on the maximization of extinction ratio (ER) between the interferometer output ports.

MZI-SOA Methodology

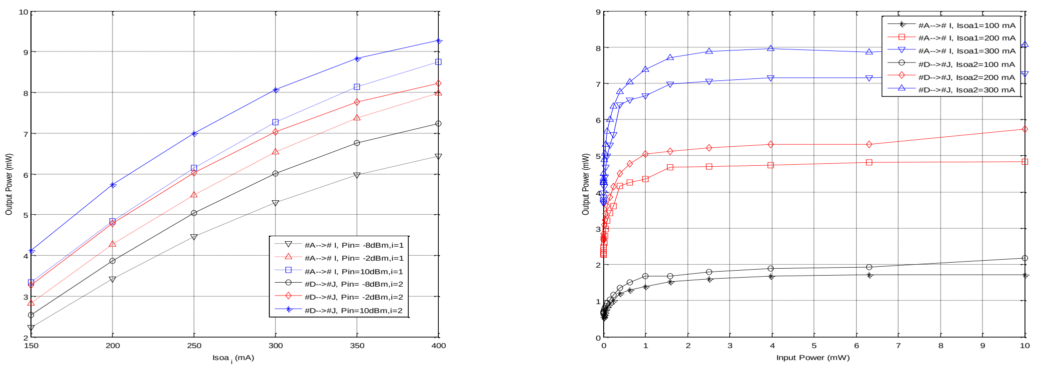
A methodology for the MZISOA characterization in terms of operational parameters and a black box static model for MZISOA output signals are presented.

In order to carry out the analysis on MZI-SOA asymmetry properties, we used a 6 ports hybrid device (#A,#B,#C,#D as input ports, #I, #J as output ports).

Due to the interferometric structure of the device, the power distribution along the device will affect the output interference depth and its potential optimization.

We observed from the passive parts characterization that couplers are not 50%-50% as ideally would be expected in an interferometric structure and their splitting factors are all different. This induces an asymmetric power distribution along the interferometer arms.

After passive paths characterization, the active devices characterization was carried out with the evaluation of MZI-SOA output power as function of input power and SOA current. The trends of the SOA output power vs. SOA current and MZISOA input power are found and obtained curves are shown in Figure 32 a) and b).



(a) (b)

Figure 32 – #I, #J Output power as function of (a) SOA1, SOA2 current variation and (b) #A, #D input power

Output power levels are highly dependent on SOA currents because SOAs gain is affected by current variation. Moreover, a phase shift on SOAs output signals is induced due to the dependence of SOAs refractive index on carrier density.

Our aim is to characterize these effects and model the working characteristic for a MZI-SOA, in order to evaluate which parameters actually control the interference depth, thus providing a tool for operational point optimization. Therefore, starting from interferometric structure principles, considering the couplers yield and also some path difference, next expression represents the relation between output power, PI,J as function of SOA1 current:

$$P_I(Iso\alpha_1) = (1-\alpha_4)P_1(Iso\alpha_1) + \alpha_4 P_2(Iso\alpha_2) - \sqrt{\alpha_4(1-\alpha_4)P_1(Iso\alpha_1)P_2(Iso\alpha_2)}sin[\Delta\phi(Iso\alpha_1) + \delta_1] \quad (4)$$

$$P_J(Iso\alpha_1) = (1-\alpha_4)P_2(Iso\alpha_2) + \alpha_4 P_1(Iso\alpha_1) + \sqrt{\alpha_4(1-\alpha_4)P_1(Iso\alpha_1)P_2(Iso\alpha_2)}sin[\Delta\phi(Iso\alpha_1) - \delta_2] \quad (5)$$

where

$$P_I(Iso\alpha_1) = g_i(p_i Iso\alpha_i + q_i) \quad (6)$$

$$\Delta\phi(Iso\alpha_1) = mIso\alpha_1 \qquad i = 1,2 \quad (7)$$

and α_4 is the splitting factor of coupler K_4. P_1 and P_2 are power levels at the output of SOA1 and SOA2, respectively, and are dependent on current, which can be approximated through a linear curve, equation (6), derived from experimental data (Figure 32). g_i coefficient takes into account an adjustment of P_i, due to the experimental measurements made. $\Delta\phi$ is the phase shift induced by changing SOA1 current, again modeled through a linear approximation, equation (7), because of the linear relation between SOA induced phase and carrier density, through refractive index variation. The δ_i parameter is a phase mismatch on paths or coupler crossing factors, it affects the output interference by means of a reduction of maximum ER achievable.

To fit the remaining unknown parameters, extra measurements were performed. Figure 33 shows experimental data compared with values estimated through equation (4) and (5). In both cases we observe a misalignment between output minimum and maximum power levels. This is a clear result of the gain change in the SOA with the changing current and also to both the unbalanced splitting factors and phase shift of the couplers.

Moreover, the minimum output power does not reach the zero, impacting the maximum achievable ER.

The model prescribed, even considering the approximations made, gives out a very precise fitting of the output power values.

g_1 (−)	g_2 (−)	p_1 $(W \cdot A^{-1})$	p_2 $(W \cdot A^{-1})$	q_1 (W)	q_2 (W)	m $(rad \cdot A^{-1})$	δ_1 (rad)	δ_2 (rad)
1.63	4.01	$2.20 \cdot 10^{-2}$	$2.33 \cdot 10^{-2}$	$-5.01 \cdot 10^{-4}$	$-3.56 \cdot 10^{-4}$	7.48	$4.49 \cdot 10^{-2}$	$1.57 \cdot 10^{-1}$

Table 5 – Parameters extracted from the fittings and used in the final validation. Input power of 3dBm, fixed SOA2 current of 200mA.

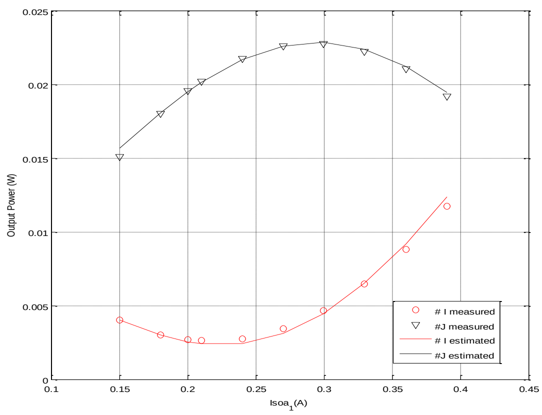


Figure 33 – Measured and estimated power levels on #I, #J output ports with 3dBm optical input power at #B.

Publication

[1] G. Parca, R. Dioníso, C. Reis, S. Betti, G. Tosi Beleffi, A. Teixeira, "Inherent Fabrication Yields and Asymmetries impact on MZI-SOA static modeling", 12° International Conference on Transparent Optical Networks 2010, ICTON 2010.

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8.3.3. Evaluation of fast optical wavelength switching for routing functions

(Ruth Vilar/UPVLC; António Teixeira / IT)

Introduction

The research work focuses on the design and experimental validation of a novel technique for optical switching implemented in wavelength-routed scenarios. This technique means a step forward to the implementation of optical re-configurable networks with network intelligence as well as including optical layer functionalities such as multicast.

Rationale

- Difficult for OCS networks to respond to fast changing traffic
    - Reconfiguration of optical switches is time-consuming
- Next generation optical networks
    - High-speed and dynamic traffic
    - Optical switching in the range of pico-seconds
- Objectives
    - The design and experimental validation of a novel technique for optical switching implemented in wavelength-routed scenarios.
    - This technique means a step forward to the implementation of optical re-configurable networks with network intelligence as well as including optical layer functionalities such as multicast.

Architecture

The architecture design of the switch is composed of two main stages: a multi-wavelength converter stage and a select stage, as shown in the Figure 34.

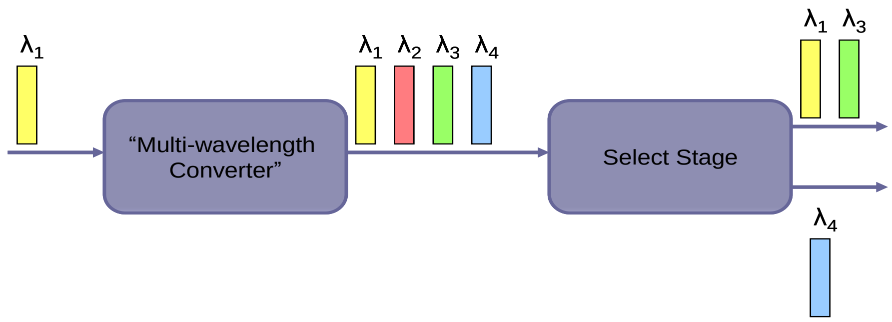

Figure 34 – Optical wavelength switching for routing functions architecture

This optical switch operates in a similar way to broadcast-and-select architectures. The incoming data (wavelength division multiplexed signals) placed at a specific wavelength is "converted" onto multiple wavelengths by using an optical comb. Afterwards, the same optical data information on different wavelengths is then simultaneously forwarded to the select stage where one or many optical signals are selected by means of crossbar-like switching fabric and optical filters. This select stage is based on fiber Bragg gratings.

With this approach, transparent optical wavelength switching can be easily realized by optical one-to-many wavelength "conversion" followed by a select stage. The optical wavelength converters enables wavelength reuse in different light paths and with no added complexity in the switch design, optical layer multicast functionality can be also introduced and implemented inside the nodes.

Multi-wavelength converter

The conventional technique for multi-wavelength generation based on an optical comb is achieved by using an electro-optic phase modulator (PM), whose operating principle is as follows. When a CW light of angular frequency w_0 is phase modulated by a sinusoidal signal of frequency f_m, the modulated light field, E_{out}, is given by:

$$E_{out} = E_{in}\exp[j\omega_0 t - j\Delta\theta\sin(2\pi f_m t)] = E_{in}\sum_{q=-\infty}^{+\infty} J_q(\Delta\theta)\exp\{j(\omega_0 - 2\pi q f_m)t\} \quad (8)$$

where $\Delta\theta$ is the modulation index and $J_q(.)$ denotes the q^{th}-order Bessel function. This phase modulation leads to a frequency modulation of the optical signal which results in the generation of new optical frequencies spaced symmetrically around w_0 with a separation equal to a multiple of f_m [1].

To validate the capability of replicating the incoming data placed at a specific wavelength into multiple wavelengths, the experimental setup shown in Figure 35 was used. The output signal from a laser was encoded with 2^{31}-1 pseudorandom binary sequence (PRBS) by an intensity modulator to form the 1.25 Gb/s nonreturn-to-zero (NRZ) data signal, and then was phase modulated by a sinusoidal signal of f_m = 10 GHz. An optical spectrum analyzer (OSA) monitored the output spectrum. As illustrated in Figure 35, the spectrum obtained at the output of the phase modulator is composed of new wavelengths transporting the input modulated data. Higher frequency spacing and thus higher bitrates can be achieved by increasing f_m. The MWC operation was validated at 1.25 Gbit/s and 10-GHz spacing as a proof of concept. These values were imposed by the available experimental equipment. Together with switching functions, a number of desirable optical network functionalities, such as transparent data multicast, can also be enabled by using the optical-comb-based MWC. The implementation of multicast can be easily introduced into the optical switch using passive waveguides such as arrayed waveguide gratings (AWGs).

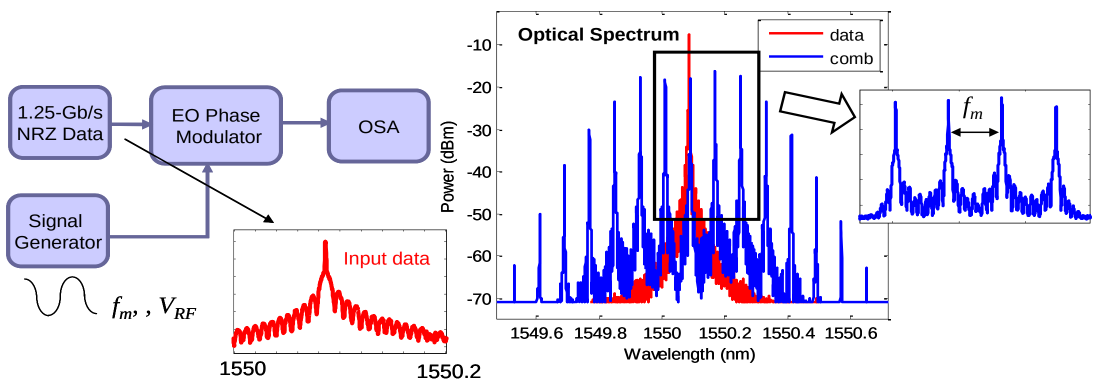

Figure 35 - Experimental setup for validating multi-wavelength conversion of incoming data

Select stage

As commented previously, after multi-wavelength conversion, the generated channels are then simultaneously forwarded to the selected stage where one or many optical signals are selected by means of crossbar-like switching fabric and optical filters based on fiber Bragg gratings, as shown in Figure 36.

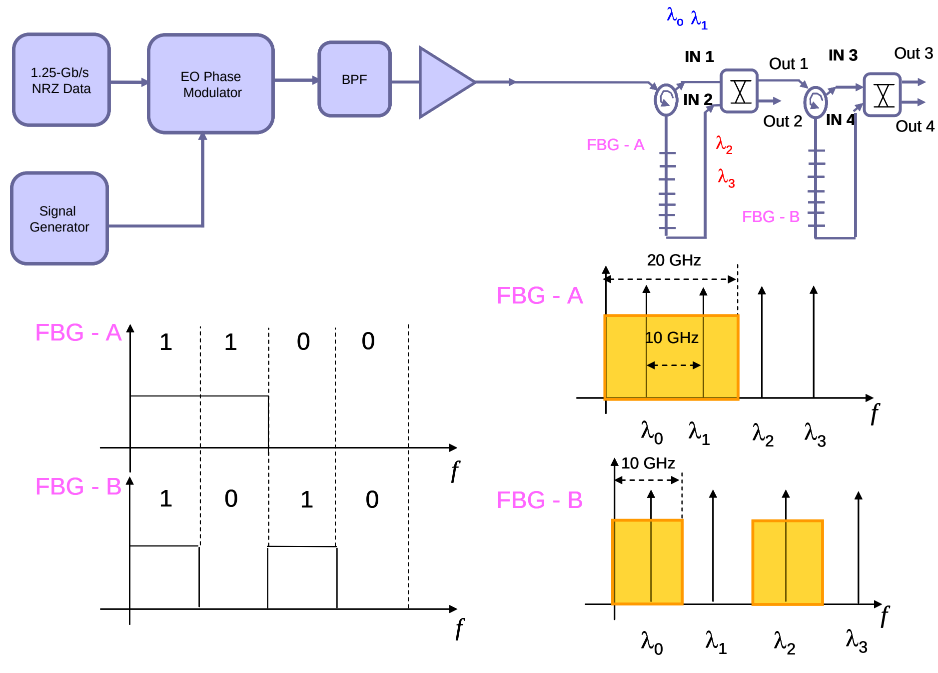

Figure 36 – Select stage

Considering 4 channels (λ_0, λ_1, λ_2, λ_3), the select block is comprised of two FBG-based optical filters and two optical switches to allow total flexibility in the choice of the output wavelength and port. Fast switching speed can be achieved by using optical switches based on electro-optic effects [2]. The FBG-A grating performed a coarse filtering to split up λ_0 and λ_1 from λ_2 and λ_3 (Figure 36). After the first filtering stage, an optical switch is used to select either IN 1 or IN 2 (Out 1). This signal is then sent to another grating, FBG-B, which performed a fine filtering to select only one output wavelength (Figure 36). To this end, the FBG-B is composed of two cascaded gratings with 10-GHz bandwidth and centred at λ_0 and λ_2, respectively. Finally, the signals coming from the FBG-B are sent to a second optical switch for flexible routing to the desired output port.

Experimental results

The experimental setup used for switching operation demonstration is similar to that shown in Figure 36 . The NRZ data signal was generated by externally modulating a tunable CW laser source tuned to 1550.17 nm and sent to a 10 GHz phase modulator. The sinusoidal modulation frequency was set to 10 GHz obtaining new wavelengths placed symmetrically around 1550.17 nm with 10-GHz spacing. After multi-wavelength conversion, the generated channels were then filtered to prove the switching operation for 4 channels. These 4 channels (λ_0, λ_1, λ_2, λ_3) were routed to the select block after being amplified. An example of operation is as follows. If the reflected signal of the FBG-A (IN 1) is routed to Out 1 and sent to the FBG-B, λ_0 is obtained at IN 3 and λ_1 at IN 4 ports (Figure 37). Otherwise, i.e., if the signal passing through the FBG-A (IN 2) is routed to Out 1, λ_2 is obtained at IN 3 and λ_3 at IN 4 ports (Figure 37).

To check the quality of these switched signals, we measured the bit-error-rate (BER). Every channel was extracted and sent to a photoreceiver. The obtained BER curves are reported in Figure 38. As it can be seen, all channels exhibited a limited penalty (2.5 dB in the worst case at BER= 10^{-9}). This penalty was mostly caused by the characteristics of the fabricated filters used since the measured channel was not perfectly filtered and thus a slight interference from adjacent channels appeared. Indeed the channels that suffered most from this effect were those ones having lowest difference between the pass and rejected bands (Channels placed at λ_0 and λ_3).

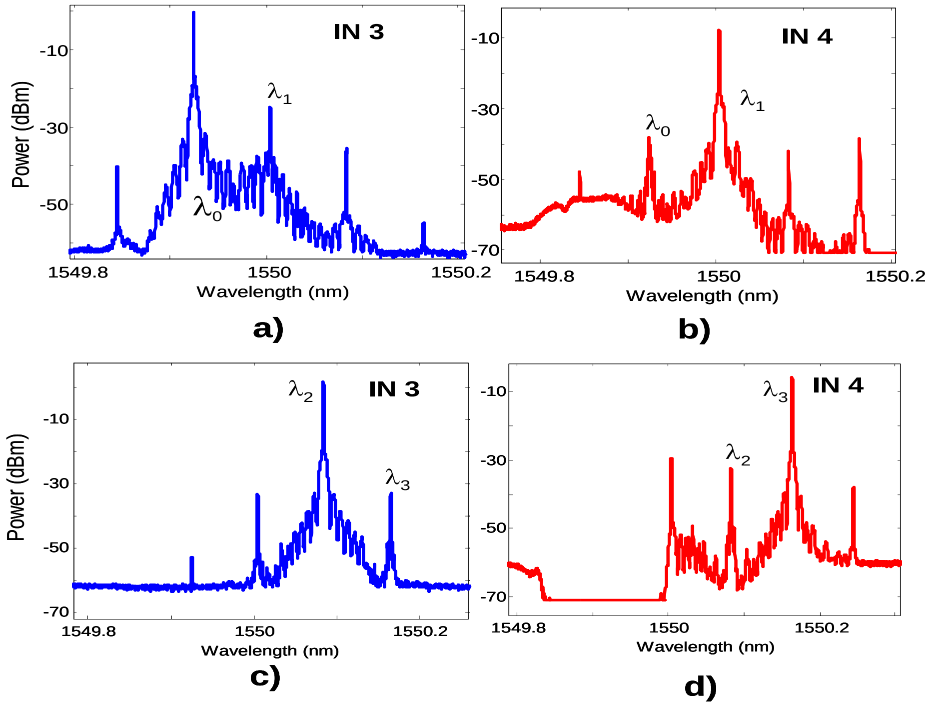

Figure 37 - Optical spectrum at the system output: a) and b) when IN 1 is redirected to the Out 1; c) and d) when IN 2 is sent to Out 1

All the channels showed clear and open eye diagrams for BER values lower than 10^{-9}, as shown in the inset of Figure 38 (Lambda 0).

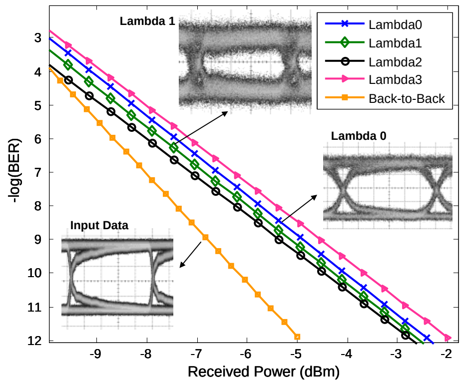

Figure 38 - BER performance of one-to-four multi-wavelength conversion compared with the back-to-back configuration

Conclusions

Optical-comb-based multi-wavelength conversion can be suitable for several applications in next generation networks, such as optical switching and multicast. In this work, optical switching of an NRZ signal at 1.25 Gbit/s was experimentally demonstrated. By using an optical comb, the input signal was transferred into multiple wavelengths transparently. To increase the flexibility of the system the generated signals were sent to a select block responsible of selecting one or many output wavelengths and of routing them to a specific output port. All the converter channels showed good performance and clear eye diagrams.

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8.3.4. All-optical phase regeneration for binary phase-shift keyed (BPSK) signals using phase-sensitive amplifiers based on Periodically Poled Lithium Niobate (PPLN) crystals

(Dániel Mazr / BME; Photonic Network Group / NICT)

Introduction

It was thinking the possibility of all-optical phase regeneration, for binary phase-shift keyed (BPSK) signals using phase-sensitive amplifiers based on periodically poled lithium niobate (PPLN) crystals. The PPLN-based phase regenerators have great advantages over current fiber-based proposals. However, it had never been deeply investigated or experimentally used for the purpose.

A PPLN-based phase-sensitive amplifier with a dynamic range large enough for practical phase regeneration is shown below. A phase regeneration was analyzed both by experiments (focusing on PPLN-based phase regenerators), and numerical simulations studying phase regenerators from a more general aspect.

The efficiency of the phase-sensitive amplifier have been increased, and realized a more compact design based on a PPLN and a semiconductor optical amplifier (SOA).

It will be expected to build a theory for and experimentally realize highly efficient PPLN-based phase regenerators superior to current fiber-based solutions.

Experimental setup and results

The first step towards realizing a PPLN-based phase regenerator was to investigate the strength of the phase-sensitive cascaded nonlinearities in the chip. The setup for evaluating the quasi-static phase sensitive operation can be seen if Figure 39.

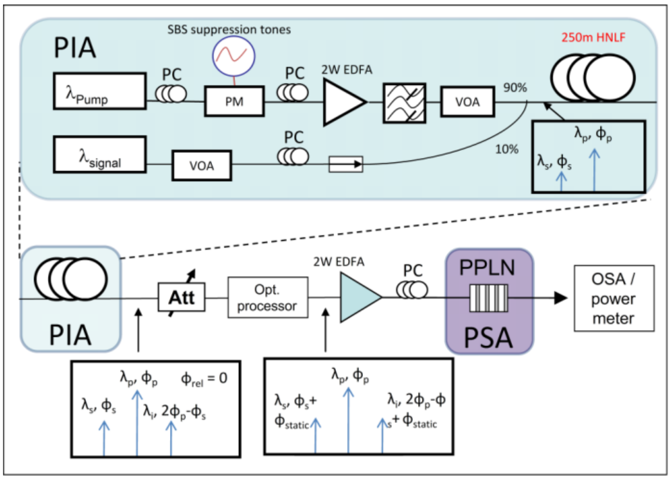

Figure 39 – Block scheme of the experimental setup

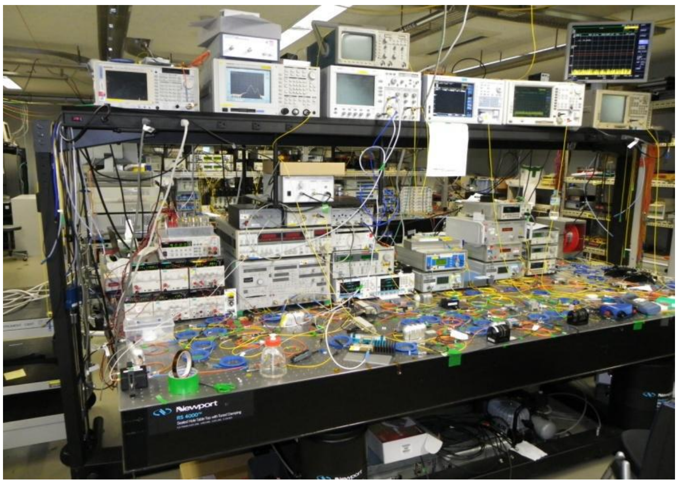

Figure 40 – Photo of the experimental setup

The continuous wave (CW) signal and pump were generated by two tunable lasers. We used highly nonlinear fiber (HNLF) for generating a phase-correlated idler wave after a high-power erbium-doped fiber amplifier (EDFA) with 2W optical output power. The pump phase was modulated by three sine tones (300, 900, 2700MHz) in order to overcome the effect of Brillouin scattering. The polarization states of both waves were aligned by polarization controllers (PCs). After the HNLF section the signal, pump and idler relative phases were adjusted adjusted by a liquid crystal on silicon optical processor (OP).

In addition to controlling the waves' relative phases the OP made it possible to equalize the signal and idler powers. Before passing all three signals through a second high-power EDFA in order to reach the nonlinear power regine of the PPLN waveguide.

We first presented our results at OptoElectronics and Communications Conference (OECC), in July 2010. Since then we have further increased the efficiency of the phase-sensitive amplifier and realized a more compact design based on a PPLN and a semiconductor optical amplifier (SOA). We are currently working towards experimentally realizing a world-first PPLN-based phase regenerator. Our results for quasi-static operation summarized in Figure 41.

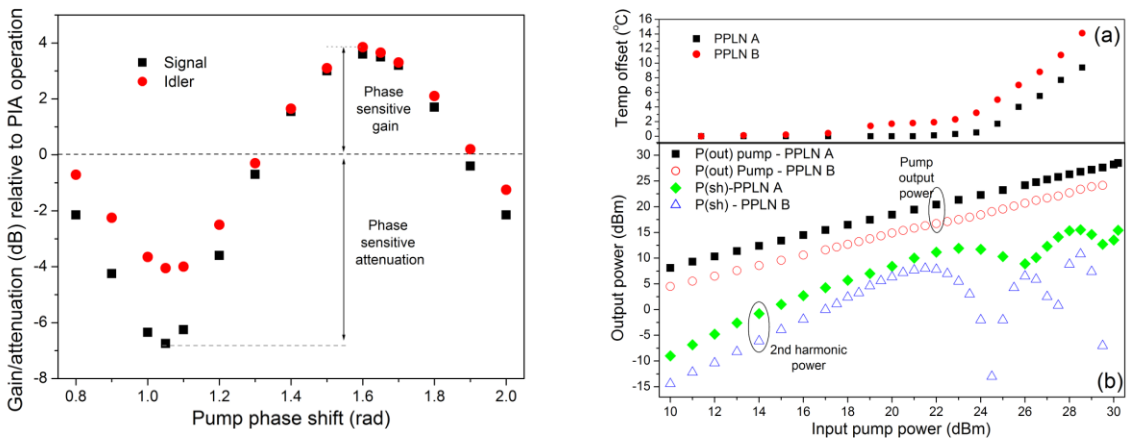

Figure 41 – Block scheme of the experimental setup

Simulation setup and results

In addition to the experimental study of phase regeneration we developed a simplified Matlab-based simulator for evaluating the performance of cascaded phase and/or intensity regenerations on a longer transmission line. In this model we used a general model for phase regeneration with a phase-sensitive amplifier and a linear intensity regenerator model for binary phase-shift keyed (BPSK) modulation. The simulated transmission line can be seen in

Figure 43. The model uses an ideal laser source and phase modulator for generating the BPSK signal carrying pseudo-random binary sequence (PRBS) pattern.

Before each transmission line we added Gaussian noise to the signal before launching it into the next fiber span. Each span consisted of 80km standard optical fiber and a regenerator.

Each regenerator had an ideal dispersion compensating unit (ECU), and an EDFA for reamplifying the signal. Nodes containing no more devices are referred to as 1R regenerator nodes, 2R regenerators had additonal phase regenerator and intensity regenerator stages as well.

Intensity noise is converted into phase noise through the Kerr effect – often referred to as nonlinear phase noise. Although this does not affect the performance of intensity-modulated systems, it may cause great degradation for phase modulation formats. Examples for the distortion in the noise distribution for BPSK signals can be seen in Figure 42. The bit error rate variation after 20 spans of 80km fiber and 2R regeneration stages can be seen in Figure 44 for 5 and 10mW signal power. As expected, absolutely no intensity regeneration greatly decreases the overall performance. However, minimal intensity regeneration effectively combats nonlinear phase noise, thus, improves the bit error rate.

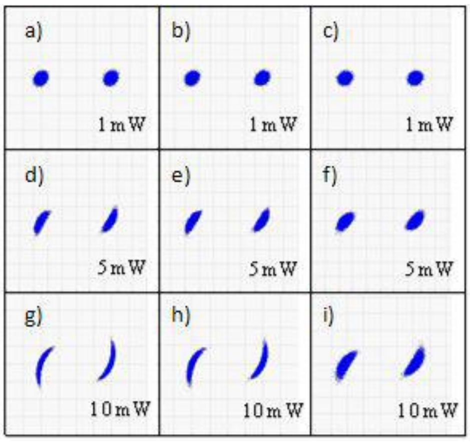

Figure 42 – Nonlinear phase noise altering the Gaussian noise distribution

In overall we can deduct that intensity regeneration is relevant for phase-modulated systems as well, and even at low efficiencies effectively reduces the bit error rate.

As the research is expected to span a longer timescale, the cooperation is maintained between BMETMIT and NICT Photonic Network Group. We believe that on a longer timescale we will be able to build the theory for and experimentally realize highly efficient PPLN-based phase regenerators superior to current fiber-based solutions.

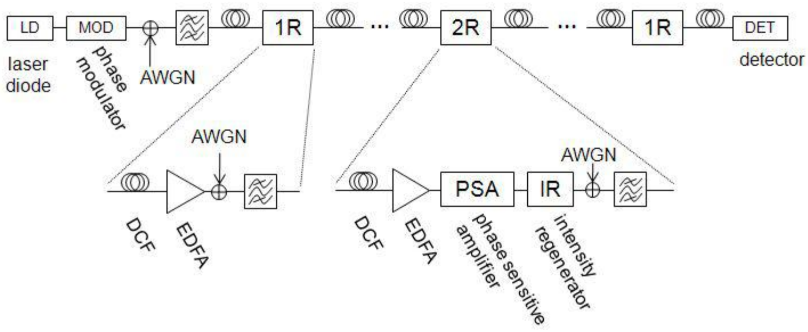

Figure 43 – Simulation block diagram

Summary

During my internship stay the problem of phase regeneration was analyzed both by experiments (focusing on PPLN-based phase regenerators), and numerical simulations studying phase regenerators from a more general aspect. Results from the latter were presented at BONE Summer and Master School in Budapest.

As the research is expected to span a longer timescale, the cooperation is maintained between BMETMIT and NICT Photonic Network Group. We believe we will be able to build the theory for and experimentally realize highly efficient PPLN-based phase regenerators superior to current fiber-based solutions.

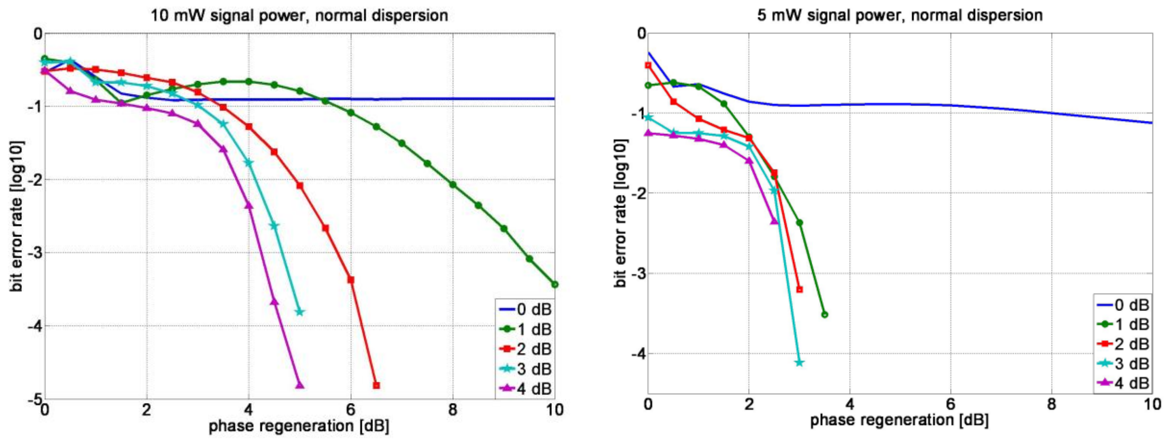

Figure 44 – Bit error rates for different phase and intensity regeneration efficiencies after 20 80km 2R spans

WP Papers (submitted but not yet accepted):

[1] R. Vilar, C. Marques, R. Nogueira, A. Teixeira, R. Llorente and F. Ramos, “Flexible optical-comb-based multi-wavelength conversion for optical switching and multicast,” submitted to Optical Fiber Communication Conference (OFC), March 2011.

[2] R. Vilar, C. Marques, R. Nogueira, A. Teixeira, R. Llorente and F. Ramos, “Fast optical switching using multi-wavelength conversion” submitted to Photonics technology Letter in 2010.

[3] B. J. Puttnam, D. Mazroa, S. Shinada and N. Wada, "Large Phase Sensitive Gain in Periodically-Poled Lithium-Niobate with High Pump Power", Photonics Technology Letters.

[4] D. Mazroa, B. J. Puttnam, S. Shinada and N. Wada, "Effective Phase-Sensitive Amplification in a PPLN Waveguide with SOA-based Idler Generation", Optical Fiber Communication Conference (OFC), March 2011.

[5] B. J. Puttnam, Guo-Wei Lu, D. Mazroa and N. Wada, "Evaluation of a Fiber-Optic Parametric Amplifier with Optical Feedback in Multi-Channel Dynamic Networks", Optical Fiber Communication Conference (OFC), March 2011.

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[1] G. M. Tosi Beleffi (ISCOM), S. Di Bartolo (ISCOM - Tor Vergata), G. Incerti (ISCOM - Tor Vergata), V. Carrozzo (ISCOM - Tor Vergata), A. Andò (UNIPA), A. Busacca (UNIPA), A. L. Jesus Teixeira (IT), L. Costa (IT), A. Valenti (FUB), S. Pompei (FUB), "Remote Optical Monitoring in Remotely Power Assisted Passive", IEEE ICTON 2010 Conference, June 2010.

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[8] D. Mazroa, S. Zsigmond, B. Puttnam, S. Shinada and N. Wada, "Optimal Regenerator Spacing in BPSK/DPSK-Modulated All-Optical Networks", BONE Master and Summer School, Budapest, 2010.

Relevant papers shared from other WPs or previously published on the topic:

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8.4. JA-4 ANNEX- Techno-economic study of monitoring techniques in OPS networks

Summary of the previous activities results

This joint activity started by using one of special techno-economic session in ICTON'09.

A contact with NICT was established, in order to set up a joint cooperation on the themes of this JA. The contributions and authors interested in the topic of OPS were collected, with the objective of attracting attention to the topic.

Two WP meetings were performed, ICTON 2009 in Azores and BONE Second Plenary Meeting in Poznan.

Summary of the current activities results

Several experiments were carried out by the partners on packet based infrastructures also in collaborations with other projects like EU FP7 SARDANA.

The impact of the optical technologies and infrastructures on the reduction of the carbon footprint maintaining high level of broadband to the end user was investigated

Another focus was the study of Long-reach passive optical network (LR-PON), with the aim to prove a cost-effective solution.

One joint activity was planned and performed (IT to ISCOM in September) with the collaboration of AIT and one mobility action between ISCOM and NICT.

Two mobility actions will be performed at the end of January 2011.

Two Informal meetings were organized during ICTON 2010 and ECOC 2010 International Conferences and two joint papers were performed for conferences.

8.4.1. Broadband future access networks with low energy consumption impact

(Giorgio Tosi Beleffi/ISCOM)

The current power consumption of the worldwide network, depending on several factors, is at 2.4% of the global electricity consumption; the bandwidth hungry sectors are leaded by: the Access, the Mobile and the Data Centers. In Core and Metro Networks the most power consuming element is the router (packet processor and routing engine) while, in the Access and Local Area Networks (LAN), the presence of Personal Computers (PC), Servers, Data Centers represent real points of energy consumption. Adopting optical processing at wavelength and/or packet level, hybrid switching matrix, pushing the fiber close to the end-user

Fiber To The-X -> Fiber To The Home (FTTx -> FTTH), increasing the efficiency in the transport technology and protocols can be possible solutions to lower the overall

energy consumption. In this list of the opportunities, FTTH with Passive Optical Networks (PONs) infrastructures can be a solution that, in the wired world, conciliate the requirements of the end user, offering highest data rates, with the will of governments assuring lowest energy consumption.

The SARDANA network, see Figure 45, transparently merges Time Domain Multiplexing (TDM) single-fiber passive tree sections with a main Wavelength Domain

Multiplexing (WDM) double-fiber ring by means of passive Remote Nodes (RN), as shown in Figure 45. The 100km WDM ring transports 32 wavelengths for > 1000 users, for a TDM tree splitting ratio of I: 32 and only I wavelength per TDM tree. Network protection and traffic balancing properties are provided by the ring configuration and the resilient design of the RNs, guarantying always a connection between each RN and the Central Office (CO) even in the case of fiber cut. The WDM ring is implemented by a double-fiber to avoid main Rayleigh backscattering (RE) impairments.

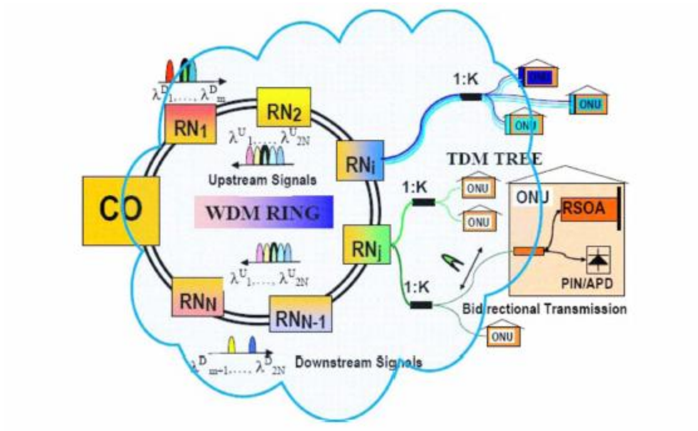


Figure 45 – A long reach broadband passive infrastructure (EU FP7 SARDANA Project)

Bidirectional propagation takes place at the single-fiber TDM trees. The wavelength transparency of the ring and Optical Network Units (ONUs), and the wavelength add/drop feature of the RNs enables sharing of the same network infrastructure, until the RNs or even up to the ONT/ONU, by several operators and allows users to select the operator by easily exchangeable filters at the ONU. This way, SARDANA offers a possible solution for implementing multi-operability in the physical layer, by simply allocating a set of wavelength DownstreamiUpstream channels to each operator.

The WDM/TDM overlay in the SARDANA network eases the migration process from legacy PON solutions, such as standard Gigabit Ethernet Passive Optical Networks (GIEPON), and next-generation lOG versions.

At the same time, SARDANA aims to reduce the complexity of the network infrastructure by implementing a fully passive (no power supply) plant from the CO to the end user premises, with several RNs interconnecting the WDM ring with the TDM trees. This means a zero power consuming plant that focalize the hot spots only in the CO and at the end user premises where are present low cost devices.

Conclusions

As we reported in the previous sections, optical technologies can be a real solution to both lower the power consumption impact and to deliver the real broadband to the end user. Furthermore, the diffusion of passive plants (PON) and the intelligent distribution of the central offices (CO) on the territory becomes crucial to deliver flexible and scalable networks reducing at the same time the carbon footprint.

8.4.2. Energy efficient Long-reach passive optical network (LR-PON)

(Giorgio Tosi Beleffi/ISCOM)

Long-reach passive optical network (LR-PON) is the last proposed member of the PON family as a more cost effective solution. It extends the reach from the traditional 20 km range to 100 km and beyond by exploiting optical amplification and WDM technologies. Providing extended geographical coverage, LR-PON is able to consolidate a number of central offices (COs), thereby merging the metro and access segments, simplifying the network infrastructure, and reducing the number of network elements.

We evaluate the power efficiency of several long-reach optical access options by concentrating on the amount of broadcast traffic and uplink limitation in the central office.

The reach extension can be achieved using either optoelectronic repeaters (OEO) or optical amplifiers (doped fiber amplifier - DFAs or semiconductor optical amplifier - SOAs). The considered optical access network options are shown in Figure 45 and main parameters used in Table 6.

Long-reach network		GPON	EPON	WDM PON	10G-EPON	SARDANA (1)	SARDANA (2)	P-t-P 1GE	P-t-P 10GE
Reach extender option		DFA	DFA	DFA	DFA	ROPA	ROPA	OEO	SOA
Max. net data rate per port [Gbit/s]	DS	2,3	1	1	10	10	10	1	10
	US	1	1	1	10	2,3	2,3	1	10
CO-equip. Power* [W]		126.26	123.87	95.78	173.87	309.66	126.17	115.36	226.49
CPE power [W]		9.69	9.38	12.69	25.89	66.88	26.62	10.49	21.28

*The additional power consumption of reach extenders is included in the power consumption of CO equipment.

Table 6 – Main parameters used in the model of optical access networks

In the case of the SARDANA network, we considered two cases. The first one (SARDANA 1) refers to the existing test bed in which values of power consumption are real measured values of the devices that are deployed in the test bed. The power consumption of the test bed equipment is not optimized in terms of power consumption as it would be in some degree done in commercial equipment. In the second case (SARDANA 2), we assume that network elements are implemented using market-ready components, i.e., components which can provide required performance and are optimized for deployment in the field. Such components would provide remarkably lower power consumption.

PON can naturally support broadcast and multicast services by sending only a single data stream to all users. This property of PON options is addressed by introducing the broadcast factor, B, which represents the percentage of the downstream data rate used for broadcast services.

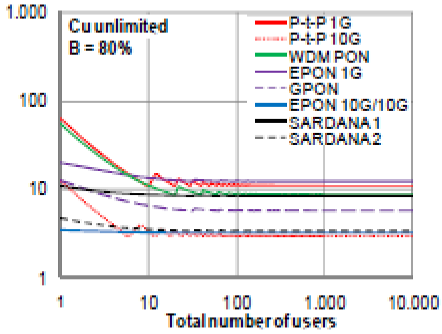


Figure 46 – Power consumption per Gbit/s and per user [W/(Gbit/s)] of the considered optical access options

Conclusions

As it can be seen from Figure 46, bandwidth limitation of CO strongly affects the 10 Gbit/s access technologies, especially P-t-P ones. However, if we would not have any uplink bandwidth limitation, 10 Gbit/s P-t-P Ethernet would provide the lowest power per Gbit/s. Passive optical networks are the most efficient when a large percentage of the DS traffic is broadcast traffic, as it would be the case when distributing many HDTV channels. On the other hand, if there is mostly pear-to-pear traffic in the network, the power per Gbit/s of PONs increases significantly. The SARDANA network, if realized using market-ready components, has the potential to provide very high power efficiency in both cases of limited and unlimited uplink as well as for broadcast and pear-to-pear traffic.

Generated WP Papers:

[1] G. Tosi Beleffi, D. Forin, A. L. J. Teixeira, E. Leitgeb, G. Incerti, S. Di Bartolo, V. Carrozzo “Broadband future access networks with low energy consumption impact” Proc. CSNDSP 2010, 21-23 July 2010, New Castle, UK.

[2] A. Lovrić, S. Aleksić, J. A. Lazaro, G. M. Tosi Beleffi, V. Polo, and J. Prat, “Influence of Broadcast Traffic on Energy Efficiency of Long-Reach SARDANA Access Network”, OFC Los Angeles, March 2011.

Relevant papers shared from other WPs or previously published on the topic:

[6] A. Baptista, N. B. Pavlović, P. André, D. Forin, G. Tosi Beleffi, J. A. Lázaro, J. Prat, and A. Teixeira, "Improved remote node configuration for passive ring-tree architectures", IEEE ECOC 2008, Bruxelles, September 2008.

[7] G. Incerti, F. Incerti, F. Di Vicenzo, D. Forin, G. Tosi Beleffi, F. Curti, A. Teixeira, J. Prat, "Remote Pumping and Signalling in a Passive Optical Network Scenario", ICTON 08 Proceedings, Vol. 1, No. 1, pp. 312-315, Athens, July 2008.

[8] F. Di Vincenzo, G. Cincotti, G. M. Tosi Beleffi, D. M. Forin, F. Curti, A. Teixeira, "Remote inline all optical signalling and monitoring in passive optical network scenarios by means of erbium doped fiber amplifier pump modulation", Conference on Laser and Electrooptics (CLEO) and Quantum Electronics and Laser Science Conference (QELS), San Jose, California, May 2008.

M. Tobia, S. Taccheo, K. Ennser, D. Forin, G. Tosi-Beleffi, M. Guglielminucci, F. Curti, A. Teixeira, "Implementation of in line first-order PMD monitoring in high-bit-rate links based on supercontinuum generation in normal dispersion regime", IEEE/LEOS CLEO EUROPE 2007, Conference, June 2007.

8.5. JA-5 ANNEX - Packet monitoring based on nonlinear optical preprocessing and filtering

This joint activity was incorporated in JA2.

8.6. JA-6 ANNEX - Impact of physical layer impairments on control plane schemes and proposals for optical circuit and packet switched networks

Summary of the current activities results

This JA initialized this year, and a great cooperation between partners was observed.

It was studied the impact of different network designs on the control plane behavior and the network performance of Optical Circuit Switched (OCS) networks. Some efforts on a network architecture based on the Multiprotocol Label Switching Transport Profile (MPLS-TP) standard were realized. A study of different cross-layer control plane network design algorithms and a study of the impact of different planning strategies on the network cost, and on the control plane implementation were performed too.

It was experimentally tested the impact of different regenerator placement strategies under dynamical provisioning in translucent GMPLS WSON networks.

Tree joint papers were submitted, from which, two were for journals and one for conference. Furthermore, six papers were submitted, but they are on review, from which, three were for journals and three for conferences.

Two informal meetings were organized during ICTON 2010 and ECOC 2010 International Conferences and two mobility actions were performed.

8.6.1. Scenario based on a MPLS-TP Carrier Ethernet (CE) translucent network

(Domenico Siracusa / PoliMi)

Objectives

The main goal of this activity is to carry out a design (occur offline) of the scenario shown on Figure 47, taking into account Physical Layer Impairments (PLIs).

The activity is based on a research of possible solution and algorithms that will minimize the Capital Expenditure (CAPEX) of the network intended as the cost of the resources that must be deployed.

Both routing constraint (establishing of all requested EVCs) and physical layer impairment constraint (intelligibility of the signal at the receivers) must be satisfied.

Introduction

The scenario is based on a MPLS-TP Carrier Ethernet (CE) translucent network.

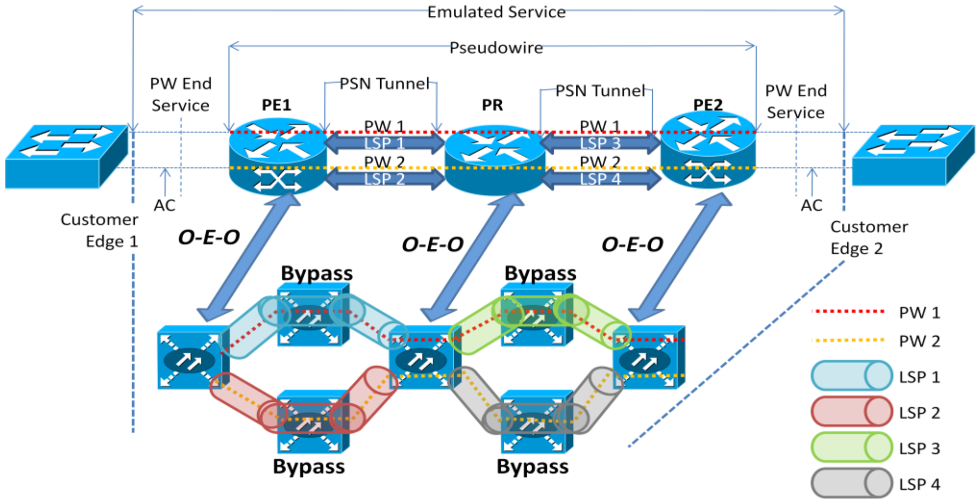


Figure 47 – Scenario based on a MPLS-TP Carrier Ethernet (CE) translucent network

Some considerations on the scenario:

- Ethernet frames are transparently carried by the optical layer (e.g, Optical Transport Network (OTN));

- Provider Edge (PE) routers are able to perform operations on the Ethernet Pseudowires while Provider Routers (PRs) are only able to work at MPLS tunnel layer;
- Ethernet Virtual Connections (EVCs) can be established between PE while PRs are not able to 'open' the already established tunnel between Ethernet source and destination.

8.6.2. Experimental Study and Assessment of the Link Distance Impact in an OSNR-Based IRWA Algorithm in GMPLS-Enabled Translucent WSON Networks

(Ricardo Martínez, Raul Muñoz, Ramon Casellas / CTTC)

Introduction

In this work is studied the impact of the fiber link distance when dynamically provisioning connections within a GMPLS-enabled translucent WSON. In particular, two link-cost strategies, namely, uniform and distance-based are compared extending previous works focused on validating a devised OSNR-based IRWA algorithm. In the uniform strategy, the metric for all the links having available wavelengths is fixed and set to 1 regardless of their physical link distance. In the distance-based, however, the link cost is set to the fiber length expressed in km.

The goal of the impairment-aware routing and wavelength assignment algorithms (IRWA) is twofold: first, to compute routes that perform optimally at the network layer; secondly, to fulfil the stringent needs on adequate optical signal quality at the receiver in terms of the optical signal noise ratio (OSNR), the Q factor, etc. In this work, we focus on IRWA algorithms to compute feasible lightpaths according to the OSNR.

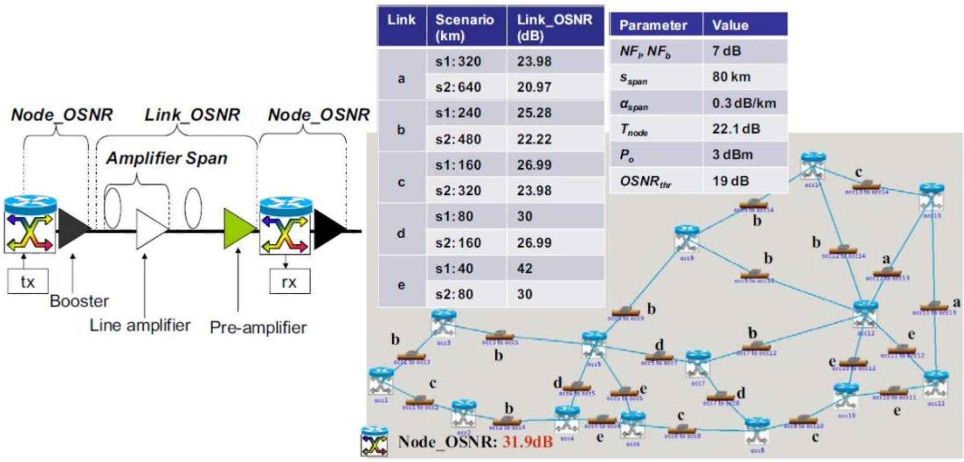
The aim of this work is to evaluate the performance of these link cost strategies when, given a network topology, their link distances change. The connection blocking probability is compared numerically, experimentally obtained within the ADRENALINE testbed®. For the sake of completeness, several scenarios with different number of 3R regenerators are evaluated for the considered network topology.

Approach on the physical impairments: End-to-End OSNR computation

In transparent/translucent WSON, the longer the path an optical signal is transported on, the more amplifiers are needed to compensate the power loss due to the fiber loss and attenuations. The increased number of amplifier makes the Amplifier Spontaneous Emission (ASE) a significant impairment factor to the signal quality. The OSNR is used to capture the impact of the ASE noise. We used a strategy to estimate the OSNR of a given transparent segment traversing l links, each allocating a different number of amplifier spans. Next, the computed OSNR ($\mathrm{OSNR}_{\mathrm{total}}$) is compared to a threshold ($\mathrm{OSNR}_{\mathrm{thr}}$) to decide whether an available 3R regenerator needs to be allocated at an intermediate node to improve the signal quality. The estimated $\mathrm{OSNR}_{\mathrm{total}}$ is

$$\boldsymbol{OSNR_{total}} = \mathbf{1} \Big/ \left(\sum_j \mathbf{1}/\boldsymbol{Link_{OSNR_j}} + \sum_j \mathbf{1}/\boldsymbol{Node_{OSNR_j}} \right) \qquad \mathbf{(9)}$$

where the $\mathrm{Link}_{\mathrm{OSNR_j}}$ and the $\mathrm{Node}_{\mathrm{OSNR_j}}$ are the OSNR for the j^{th} link and node, respectively. Both the $\mathrm{Node}_{\mathrm{OSNR_j}}$ and $\mathrm{Link}_{\mathrm{OSNR_j}}$ (see Figure 48a) are computed off-line as follows:



Link	Scenario (km)	Link_OSNR (dB)
a	s1:320	23.98
	s2:640	20.97
b	s1:240	25.28
	s2:480	22.22
c	s1:160	26.99
	s2:320	23.98
d	s1:80	30
	s2:160	26.99
e	s1:40	42
	s2:80	30

Parameter	Value
NF_l, NF_b	7 dB
s_{span}	80 km
α_{span}	0.3 dB/km
T_{node}	22.1 dB
P_o	3 dBm
$OSNR_{thr}$	19 dB

Figure 48 – a) OSNR computation; (b) Network topology: link distance (km), OSNR (dB) and physical parameters.

The $Node_{OSNR_j}$ is computed in dB using the following expression,

$$\boldsymbol{Node_{OSNR_j} = -T_{node} + h\nu\Delta\nu + P_o - NF_b} \tag{10}$$

where T_{node} is the node attenuation (dB), P_o is the optical power (dBm), $h\nu\Delta\nu$ is the quantum noise (dB), and NF_b is the noise figure of a booster (dB). Similarly, the Link_OSNR of a link formed by N spans N_{span} is

$$\boldsymbol{Link_{OSNR_j} = -T_{span} + h\nu\Delta\nu + P_o - NF_l - 10logN_{span}} \tag{11}$$

where T_{span} is the span attenuation and NF_l is the noise figure of the line and pre-amplifiers (dB). For the computation of the N_{span}, the fiber link (L) and the maximum span lengths (s_{span}) expressed in km are needed. The N_{span} is $\lceil L/s_{span} \rceil$ (i.e., upper integer). Thus, the T_{span} is computed using:

$$\boldsymbol{T_{span} = {}^{L}/_{N_{span}}\, \alpha_{span}} \tag{12}$$

where the α_{span} is the cable attenuation (dB/km).

In addition to the ASE noise, other accumulated impairments such the Polarization Mode

Dispersion (PMD) and the Chromatic Dispersion (CD) along with non-linearities may impact on the signal quality of the transparent segments. These impairments are integrated into the constraint model as OSNR penalties provided that the signal degradation caused by them is kept within acceptable ranges. For instance, the total accumulated PMD must be below a maximum tolerated pulse broadening (i.e., 10 ps at 10 Gbps). This value depends on the bit rate, the fiber PMD parameter, and the transparent segment length (km). Assuming the same low PMD parameter (e.g.,$0.1\ \mathrm{ps}/\sqrt{\mathrm{km}}$) for all the links and a transmission rate of 10Gbps, the maximum length of a transparent segment should not exceed 10000 km. In this work, the worst network scenario (i.e., links with the largest distances) has a maximum transmission distance of approx. 2300 km. Thus, the transmission of the transparent segments is not constrained by the PMD.

With regard to the CD, we assume that this is compensated on a per-link basis using dispersion compensation fibers. That is, the chromatic compensation map is known. Nevertheless, due to some uncertainties in the chromatic dispersion map knowledge, the CD compensation may not be optimal. This causes accumulation of residual CD along the lightpaths. In our constraint model, the residual CD may be managed as an OSNR penalty. In the OSNR-based constraint approach, the threshold OSNR level is determined by:

$$\boldsymbol{OSNR_{thr} \geq OSNR_{min} + OSNR_{margin}} \qquad \textbf{(13)}$$

where the $\mathrm{OSNR_{min}}$ determines de OSNR tolerance of the receiver, and the $\mathrm{OSNR_{margin}}$ stands for the OSNR penalties due to the maximum acceptable PMD, residual CD, and nonlinearities. These OSNR penalties are configured by the operators according to the bit rate, modulation format, etc. of the transmitted signal. Note that this approximation may lead to overestimation/underestimation of the real impact of the physical impairments. Finally, one of the main reasons to block LSPs (i.e., lightpath in GMPLS) in dynamic WSON is due to the WCC. To relax this problem the IRWA algorithm operates with full wavelength information. Thus, it is able to compute both a spatial (nodes and links) and spectral routes (wavelengths) fulfilling the WCC. In translucent WSON, if the entire route does not meet the WCC, 3R regenerators are allocated at intermediate nodes.

IRWA algorithm: Link cost strategies

The IRWA algorithm uses a link- and a node-cost model function to compute routes satisfying both the WCC and the adequate optical signal quality while minimizing the amount of used network resources (i.e., wavelengths and regenerators). Two link-cost strategies were proposed and evaluated, namely, the uniform and the distance-based. In the former, all the network links with usable wavelengths are set to a fixed link cost of 1. This allows balancing the network load though the overall links and, thus, attaining an efficient utilization of all the wavelengths. Additionally, the WCC is well addressed avoiding the exhaustion of particular links. However, this link cost strategy does not penalize the use of long fiber links with higher optical signal degradations than the short links, which become its main shortcoming. Thus, the distance-based approach was considered where each link cost is set to its fiber length (km). By doing so, the IRWA algorithm is able to compute routes achieving the highest optical signal quality. That is, the computed LSPs are routed through the shortest distance routes. This, in general, leads to attain the highest OSNR. Conversely to the uniform strategy, in the distance-based approach, it is very likely that the shortest distance links are exhausted. This makes the WCC more difficult to be satisfied. The goal of the present work is to conduct a similar study but using a network scenario with both longer fiber lengths and larger number of placed regenerators.

Experimental performance evaluation

The connection blocking has been evaluated within the GMPLS-based control plane emulator of the CTTC ADRENALINE testbed. The network topology is formed by 22 links and 14 nodes (N) (see Figure 48b). Each bidirectional link supports ten wavelength channels. We consider five different link distances (i.e., links a-e) and two scenarios for the same network topology, namely, s1 and s2 having short and medium fiber link distances, respectively. According to the fiber link distance in each scenario, the expression (11) is used to compute the corresponding $\mathrm{Link}_{\mathrm{OSNR}}$ value. Regardless of the scenario, the $\mathrm{Node}_{\mathrm{OSNR}}$ is computed using (10). The main assumptions for the evaluation are: the LSP-arrival process is Poisson and the holding time follows a negative exponential distribution (average holding time 240 s). Each data point is obtained requesting 104 LSPs. Each wavelength operates at 10 Gbps, which does require an $\mathrm{OSNR}_{\mathrm{thr}}$ of 19 dB. Each node places 0 (transparent), and 1 –

4 3R regenerators per (translucent) node. The link cost is set to: uniform (C1) or the distance-based (Ckm).

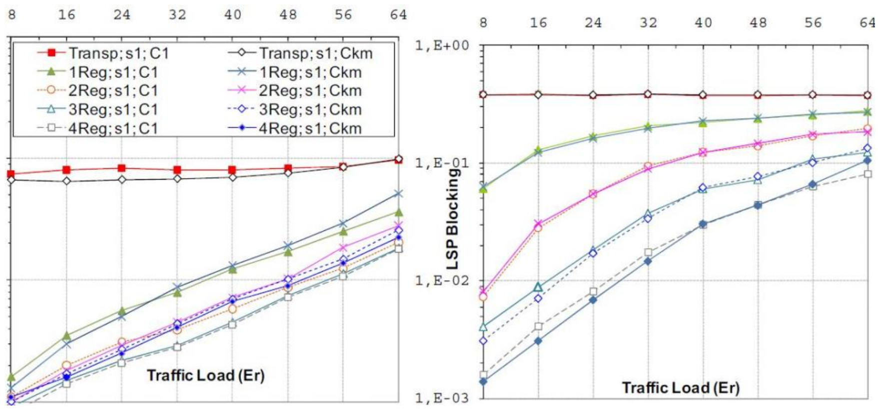


Figure 49 – Connection blocking probability: scenario a) s1; b) s2

Figure 49 plots the LSP blocking versus the network traffic load (Er) for the scenario s1 considering both the C1 and the Ckm link cost strategies. For the sake of clarification, a LSP is blocked when the IRWA fails to satisfy either the WCC or the adequate optical signal quality. Additionally, the signaling mechanism may also block an LSP if resource contention among different LSPs being set up occurs. We observe that, in general, within the transparent networks (i.e., no 3R regeneration), the utilization of distance-based scheme lowers the LSP blocking with respect to the uniform strategy (up to 19%). This is due to the fact that the former aims at computing paths having the shortest distance in km. Thereby, these computed LSPs have the highest OSNR at the receiver. This relaxes the signal quality restriction which is the main constraint in the transparent WSON. When a pool of 3R regenerators is added at each translucent (translucent) node, with 1-4 regenerators per node, the LSP blocking is significantly reduced. Indeed, using 3R regenerators allows, on one hand, regenerating the signal when needed, and on the other hand, reducing the blocking due to the WCC. If a low number of 3R regenerators is placed (i.e., 1 – 2 per node), the blocking performance attained by either strategy are pretty similar. However, as the traffic grows, the uniform strategy appreciably lowers the blocking up to 29.4% and 27% at 64 Er for 1 and 2 Reg, respectively. In this regard, the benefit of applying the distance-based strategy is that allows the IRWA algorithm to better address the optical signal quality constraint by selecting the shortest links (i.e., higher $\text{Link}_{\text{OSNR}}$ values). Nevertheless, this may lead to exhaust such links as the traffic load increases. Thereby, the WCC becomes the main reason to block LSPs. Conversely, the uniform scheme allows lowering the blocking, compared to the distance-based approach, as the traffic load grows. The reason is that the uniform link cost aims at balancing the LSP establishment among all the links. Thus, it avoids exhausting particular (shortest) links, which in turn favours to fulfill the WCC. If more regenerators are placed in the nodes (i.e., 3-4), similar performance for all the traffic loads is attained, i.e., the uniform strategy performs the best.

Figure 49 (b) plots the LSP blocking versus the traffic load for the scenario s2. Recall that in s2 the link distances are larger than in s1 (i.e., the network links have lower $Link_{OSNR}$). Therefore, the optical signal quality constraint in s2 is harder to meet. In the transparent s2, the LSP blocking attained by either the uniform and the distance-based strategies perform very similarly (above 37% for all the traffic loads). Regardless of the employed link cost strategy, such a high blocking is due to the restriction on the optical signal quality which causes that 68 out of the 182 potential connections are always unfeasible. However, as in s1, placing 3R regenerators improves connection blocking. When 1 – 2 regenerators are placed per node, the blocking reduction ranges between 47% and 84% at high and low traffic loads, respectively. We observe, however, that no performance difference exists between using either link cost strategy. Indeed, since the LSP establishment is severely constrained by the optical signal quality, the impact in the blocking attained by each strategy is barely appreciated. In other words, the set of feasible paths is considerably limited by the optical signal quality constraint. Therefore, both strategies tend to compute the same routes for a given LSP request. However, if more 3R regenerators are placed (i.e., 3-4 per node), at the low traffic load the LSP blocking performed by the distance-based scheme slightly lowers the one achieved by the uniform scheme (up to 24.4% at 8 Er in 3Reg). The reason is that, as said, the distance-based mainly addresses the optical signal quality constraint while minimizing the 3R regenerator usage. Hence, the transparent segments constituting the LSPs present the highest OSNR. This efficient regenerator utilization leads to better address/accommodate the future LSP requests (i.e., reduces the connection blocking). Obviously, as the traffic load is increased, such a blocking gain achieved by the distance-based strategy tends to disappear. Specifically, for the 4 Reg, the best performance is attained by the uniform strategy. Again, the reason is that the uniform scheme provides balancing the traffic load through the entire network resources which eases satisfying the WCC.

Conclusions

The impact of two link cost strategies (uniform and distance-based) in an OSNR-based IRWA algorithm has been evaluated when dynamically provisioning LSPs in a translucent WSON. To this end, for the same network topology in terms of nodes and links, two scenarios with short and medium fiber link distances are taken into account (s1 and s2, respectively). Additionally, different number of 3R regenerators was placed at each network node. The evaluation is carried out within the ADRENALINE testbed with regard to the connection blocking probability. In general, in network scenarios where the optical signal quality constraint represents the hardest restriction (i.e., s2), the impact of using either link cost strategy is barely appreciated. Conversely, in networks where the fiber link distance is relatively short (i.e., s1), the impact of each link cost strategy depends on the traffic load. For low traffic load, the distance-based attains the lower connection blocking due to its more efficient use of the regenerator resources. However, at high traffic loads, since the uniform scheme balances the traffic load through the entire network, the WCC is better addressed avoiding the (shortest) link exhaustion. Finally, in both scenarios, the larger the number of placed 3R regenerators, the less constraining the optical signal quality is. Therefore, the best performance (i.e., lower LSP blocking) is attained by the uniform strategy.

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8.6.3. Offline problem of Routing and Wavelength Assignment (RWA) and Regenerator Placement (RP) in translucent networks

(P. Pavon-Marino, Belen Garcia-Manrubia Ramon Aparicio-Pardo / UPCT, D. Careglio, M. Klinkowski / UPC)

We investigate the offline problem of Routing and Wavelength Assignment (RWA) and Regenerator Placement (RP) in translucent networks. Given a network topology, an estimation of the traffic demands, the objective is to minimize the cost of the regeneration equipment used, and to avoid the lightpath blocking. We formulate an optimal ILP model of the problem, to the best of the authors' knowledge, for the first time in the literature. Its simplicity allows us to test it for small and medium size networks. Despite of this merit, the problem is NP-hard. For larger problem instances we propose two heuristic methods: Lightpath Segmentation and 3-Step method. The latter guarantees that no lightpath blocking is produced by signal degradation. We also provide a lower bound for the regenerator equipment cost. The performance and the scalability of our proposals are then investigated by carrying out extensive tests, considering different network topologies, number of wavelengths per fiber, traffic load conditions and network link lengths. Results reveal that the solutions obtained by the heuristic algorithms are optimal or close-to-optimal and require low computation times. In addition, the results help to capture the trends in the regenerator equipment cost in different network instances.

In our tests, three traffic loads are considered: low, medium and high ($\rho \in \{0.4, 0.7, 1\}$). The maximum lightpath demand matrix, T^{MAX} is associated to load ρ =1 and it is guaranteed that the lightpaths in T^{MAX} can be fully carried by the network with a 0% of lightpath blocking if a sufficient number of regenerators are used. We are also interested in studying the effects of the network link lengths on the regenerator equipment cost planned. We repeat the tests for four distance factors in the network: $\{\beta^1, \beta^2, \beta^3, \beta^4\}$, where $\beta^1 = \beta^{MIN}$, $\beta^4 = \beta^{MAX}$, and we obtain β^2 and β^3 as intermediate points between the values of β^1 and β^4. After multiplying the length of all the links of the network by β^{MAX}, the longest link has a Q factor value just equal to the acceptable detection threshold (17 dB). After multiplying the length of all the links of the network by β^{MIN}, the shortest path between every pair of nodes with the worse (lowest) Q factor still has a Q factor Q = 17 dB. Note that higher β multipliers could be associated either to continental long-haul networks, or to smaller networks with e.g.

shorter reach transmission technologies.

		No. Regenerators (%)				Time (s)	
β	ρ	3-Step	LS	LERP (%Block.)	LB	LS	LERP
	0.4	0.0	0.0	0.0 (0.0)	0.0	3.7	23.4
1	0.7	0.0	0.0	0.0 (0.0)	0.0	4.8	43.2
	1	0.0	0.0	0.0 (0.0)	0.0	7.4	61.0
	0.4	0.0	0.0	0.0 (0.0)	0.0	4.9	23.4
2	0.7	0.0	0.0	0.0 (0.0)	0.0	5.9	43.0
	1	0.0	0.0	0.0 (0.0)	0.0	8.2	61.0
	0.4	5.6	5.6	2.2 (3.5)	5.6	11.3	23.5
3	0.7	8.5	8.5	7.4 (2.4)	8.5	15.7	43.1
	1	7.0	7.0	6.1 (1.8)	7.0	18.0	60.8
	0.4	18.4	18.4	10.5 (8.8)	18.4	12.4	23.5
4	0.7	29.1	29.1	31.1 (7.6)	29.1	27.0	43.2
	1	24.7	24.7	26.3 (6.3)	24.7	60.0	61.0

Table 7 – Regenerator equipment cost and execution time of the algorithms.

In Table 7 we provide the information related to the regenerator equipment cost and the execution time of the algorithms for NOBEL-EU network, and $W = 80$ wavelengths per fiber. Given the larger number of nodes and wavelengths, it has not been possible to obtain results with the optimal ILP model. The regenerator cost is given as the average number of regenerators that a carried lightpath needs (in %). That is, the total number of regenerators planned divided by the carried demand volume. The lightpath blocking information is not provided for the 3-Step, and LS algorithms since it is 0 for all of them. The column LB provides a lower bound to the regenerator cost. It corresponds to the number of regenerators needed if each of the lightpaths was carried alone in the network using the path with the smallest Q factor, that is, with the lowest number of semi-lightpaths traversed. Moreover, Table 7 displays the execution time observed in each of the tests performed for all the algorithms but the 3-Step heuristic. The execution times for the 3-Step algorithm are not shown since they were below of 1 second in all the tests.

8.6.4. Joint work between CTTC, UPC, UPCT, AIT and PoliMi concerning to the J.A6: Impact of physical layer impairments on control plane and proposals for optical circuit and packet switched networks.

(R. Muñoz, R. Casellas, R. Martinez / CTTC; S. Spadaro, J. Perello, D. Careglio / UPC; P. Pavon-Mariño, B. García-Manrubia / UPCT; I. Tomkos, M. Angelou, S. Azodolmolky / AIT; D. Siracusa, G. Maier, A. Pattavina / PoliMi)

Introduction

The main objective of this joint activity is to investigate the impact of physical layer impairments on control plane schemes for transparent/translucent infrastructures that are suggested or can be considered for both circuit switched and packet switched optical networks.

Two main works are defined. The first one dedicated to the problem of regenerator placement and allocation where both simulation and experimental evaluation are carried. The outcome of this study is reported in two joint papers [3][5]. The second one dedicated to the design of a Carrier Ethernet-based multi-layer network defining a reference node architecture and providing heuristic algorithms to optimize resources jointly at the MPLS-TP and at the optical layer, while taking physical impairments into account. The outcome of this study is reported in a joint paper [4].

Two mobility actions are also been carried out. The outcomes of such actions are reported in the relative joint papers [1][2][6].

Regenerator placement and allocation strategies [UPCT, CTTC, UPC]

In translucent Wavelength Switched Optical Networks (WSONs), there is the problem of the regenerator placement (RP) and the regenerator allocation (RA), which refers to planning and operational phase respectively. A common approach is to apply firstly a RP algorithm to sparsely and strategically place the regenerators throughout the network using a static set of connections (i.e., a given static/forecasted traffic demands), and afterwards a RA algorithm assigns the already placed regenerators to the incoming dynamic connection requests under the constraint of acceptable optical signal quality. RP is an offline problem and aims at reducing the number of regenerators that is the network cost; in contrast, RA is an online problem whose goal is to minimize the utilization of the regenerators, and thus, minimize the connection blocking. Both problems are usually addressed together with the Routing and

Wavelength Assignment (RWA) problem in its offline and online version respectively.

In this work we focus on two issues. We firstly provided a set of RWA/RP methods to sparsely but strategically placed regenerators in the network. Afterwards, we experimentally study the impact of the RP phase when subject to dynamic provisioning in a translucent GMPLS WSON. Particularly, we apply a common RA algorithm and compare the different RP algorithms.

- RWA/RP problem

In this part we investigate the offline problem of Routing and Wavelength Assignment (RWA) and Regenerator Placement (RP) in translucent networks, minimizing the lightpath blocking and regenerator equipment cost. We address two variants of the problem, which correspond to two different types of Quality of Transmission (QoT) estimators, called Linear and Non-Linear. In a Non-Linear QoT, non-linear impairments like crosstalk or cross-phase modulation which account for the interferences from neighboring lightpaths in the network are explicitly computed. Then, the QoT estimated for a lightpath depends on the routes of other lightpaths in the network. In the Linear QoT the effects of the non-linear impairments are over-estimated and accumulated to the rest of the impairments in the QoT calculation. As a result, the QoT estimation of a lightpath solely depends on its route.

For the linear case, we formulate an optimal ILP model of the problem. Its simplicity allowed us to test it for small and medium size networks. Also, we proposed two heuristic methods, namely LS and 3-Step, and a tight lower bound for the regenerator equipment cost. For the non-linear QoT case, we proposed a new heuristic called IRP. Both the IRP and 3-Step algorithms have been designed to guarantee that no lightpath blocking is produced by signal degradation. This is a relevant difference with respect to previous proposals.

- RWA/RP results

The performance and the scalability of our proposals are then investigated by carrying out extensive tests. An extensive battery of tests has been conducted. The traffic load in the tests is normalized to fairly assess the ability of the algorithms for minimizing the regeneration cost, without producing any signal-regeneration related to lightpath blocking. The results show that the LS and 3-Step algorithms provide optimal or close-to-optimal solutions in all these tests. They outperform previous algorithms, both in the quality of the solution found and the algorithm execution time. Consequently, both algorithms can be used to efficiently solve the Linear RWA-RP problem (e.g. selecting the best solution provided by both schemes). For solving the Non-linear RWA-RP problem, we present the IRP heuristic. This heuristic is able to provide a zero signal regenerator blocking. It outperforms in both lightpath blocking and regenerator equipment cost the previous proposals in the literature tested. Table 8 shows an example of results. In the example, the test has been conducted for 8 and 16 wavelengths using Internet2 topology. In the linear case, our regenerator placement methods are compared with the LERP [1] method. In the non-linear case, our regenerator placement IRP method is compared with the one proposed in [2]. The regenerator cost is given as the average number of regenerators that a carried lightpath needs (in %): i.e. the total number of regenerators planned divided by the carried demand volume.

	Linear								**Non-linear**			
W	**ILP**		**3-step**		**LS**		**LERP [1]**		**IRP**		**[2]**	
8	7.6	0.0	7.6	0.0	7.6	0.0	4.0	3.8	11.5	0.0	24.0	4.0
16	8.5	0.0	11.4	0.0	8.5	0.0	13.5	0.0	25.0	0.0	2.2	55.5

Table 8 – Percentage of regenerators placed in the network and blocking probability

Summarizing the comparison for the linear case, the LS and 3-Step algorithms provide very similar solutions in all the occasions, very close to the ILP optimal solutions obtaining always a 0% of blocking. On the contrary, the LERP algorithm needs a higher number of regenerators and/or incurs in lightpath blocking. For the non-linear case, results show that IRP outperforms [2] by eliminating the lightpath blocking, in all circumstances. In the occasions in which the algorithm [2] produces better solutions in regeneration cost, the lightpath blocking is in general quite high.

- Experiments

In this part we focus on experimentally study the impact of the RP phase when subject to dynamic provisioning in a translucent GMPLS WSON. Particularly, we apply a common RA algorithm and compare different RP algorithms. In our case, we study and implement two algorithms based on network topology: Nodal Degree First (NDF) and Centered Node First

(CNF); and one algorithm which uses traffic prediction: LERP; two algorithms proposed by us: ILP and LS.

Once the RP problem is solved, a RWA algorithm together with the RA dynamically computes the route for each incoming connection (Label Switched Path – LSP - in the GMPLS context) and assigns regenerators when required. To this end, we rely on the online Optical Signal Noise Ratio (OSNR)-based path computation for translucent WSON presented in [3].

The performance evaluation is carried out within the ADRENALINE testbed at CTTC's Lab, focusing on the LSP blocking as the metric. The LERP, ILP and LS strategies require less regenerators (28) with respect to the NDF and CNF schemes. Nevertheless, they attain a blocking performance significantly (at low traffic loads) better than the NDF scheme. The blocking differences among these three RP strategies are almost negligible. In light of the above, one may state that more sophisticated RP strategies such as LERP, ILP and LS yield a better trade-off between the network cost (due to the regenerators) and the service provisioning performance (the connection blocking).

- Summary

In this part of JA we have proposed a set of RWA/RP methods and success in experimentally test and compare them with state-of-the-art solutions. Future works will focus on improving the RWA/RP algorithms to better match with the RWA/RA method.

Multi-layer design of Carrier Ethernet-based multilayer network [PoliMi, UPC]

- Objectives

Since its definition by Metro Ethernet Forum (MEF), Carrier Ethernet (CE) service is becoming more and more important for service providers and network operators. The recently-developed MPLS-TP technology can be adopted to efficiently support CE over the Optical Transport Network (OTN). In order to reduce energy consumption and complexity, OTN relies on optical bypass at switching nodes. This makes optical signals subject to the physical-layer impairments.

In this work we design a MPLS-TP based CE over OTN network by taking into account issues both at the electronic layer and at the optical layer. The proposed CE network is translucent in the sense that not all optical signals are processed at the electronic layer (optical by-pass is possible) nor all optical nodes are equipped with electrical regenerators (all-optical switching is possible). To this purpose, this article presents and discusses the framework of the CE network and the architecture of the CE node with its functionalities. Afterwards, we propose two different multi-layer planning procedures of the reference network. They adopt a top-down and a bottom-up approach respectively. The LSP optimization with PLI verification (LP) starts manipulating LSPs at electronic layer to optimize resources utilization and then deals with PLIs at the optical layer. The PLI optimization with LSPs re-routing (PL) starts optimizing regenerators placement at optical layer and then tries to decrease the allocated resources manipulating LSPs at electronic layer. The variables are the resources that must be deployed to deliver the traffic from sources to destinations: converters, interfaces, regenerators, wavelengths. They represent the Capital Expenditure (CAPEX), so then the final goal is the optimal design in terms of cost of a multi-layer CE-based MPLS-TP/OTN network.

We finally show results of the application of these design algorithms on case-study networks.

- Results

Our numerical results have been obtained on typical national wide network. It is divided into different metro-area domains referred usually as access domains which are connected to the client networks. Direct connection between access domains is avoided. Each access domain can be connected to the rest of access domains through a transit backbone domain by means of at least one transit node. We consider four different configurations called A, B, C and D according to different values assigned to the geographical distance between the nodes of the network, the requested bandwidths for intra-domain and for inter-domain Ethernet Virtual Connections (EVCs).

Table 9 shows an example of results. MSI refers to the MPLS-TP Switch Interfaces (interface needed both for a source node and for a node performing grooming), while the column “bypass” refers to the number of bypass nodes, i.e. those nodes not performing any electronic processing.

Conf.	Method	MSI	Regenerators	Wavelengths	Bypass
A	LP	106	0	34	5
	PL	94	13	104	6
B	LP	100	0	35	6
	PL	112	20	97	2
C	LP	92	4	98	11
	PL	84	18	106	7
D	LP	98	36	96	6
	PL	84	40	107	2

Table 9 – Results of LP and PL methods

We can summarize the analysis of results presented in this section as follows. The LP procedure outperforms PL in most cases and for most design parameters particularly when grooming is possible. The grooming is exploited by PL1; the effectiveness of the two procedures tends to diverge when network topology is very symmetrical, EVC traffic matrix is uniform and the requested bandwidth per EVC is small compared to the interface capacity.

- Summary

This work deal with the problem of designing an MPLS-TP based Carrier Ethernet network over a translucent optical network, in which regenerators are placed to compensate the PLI affecting the lightpaths. Two different heuristic procedures to jointly optimize the network at the MPLS-TP and OTN layers, given a set of EVCs (with variable guaranteed bandwidth) to be set up have been proposed. By an example we show that LSP optimization with PLI verification (LP) provides better results than PLI optimization with LSP rerouting (PL), especially when grooming of paths is possible.

Mobility actions

Two mobility actions have been carried out during this year.

1. Impact of physical layer impairments on control plane schemes and proposals for optical circuit and packet switched networks [AIT, UPC]

   Siamak Azodolmolky, researcher at AIT, has been hosted at UPC from 29/01/2010 to 05/02/2010. The main focus of this mobility action was on benchmarking study to assess and compare different control plane approaches with techno-economic considerations. This study compiled the possible approaches for control plane deployment in optical networks and practical and techno-economic aspects of each approach have been extracted and investigated. The direct outcome of this mobility action is reported in a joint paper [6]. At the same time, the mobility actions gave us the possibility to complete two more joint papers [1][2].

2. Impact of physical layer impairments on Carrier Ethernet control plane schemes [PoliMi, UPC]

   Domenico Siracusa, PhD student at PoliMI, has been hosted at UPC from 24/03/2010 to 06/09/2010. The mobility action took place inside the WP 27 (JA 6) and covered some aspects related to the WP 11 (JA 3). The planned activity was to investigate control plane schemes of a Carrier Ethernet (CE) network taking into account the impact of physical layer impairments. The first part of the activity has been focused on studying and deepening the knowledge of the various CE standards in order to clarify the context in which the work should take place. In the discussions that followed fresh ideas emerged for the design of a Multiprotocol Label Switching - Transport Profile (MPLS-TP) based Carrier Ethernet Network. In particular, the electronic layer (main expertise of PoliMi) and the physical layer (main expertise of UPC) have been considered in order to adopt a multi-layer approach. The final outcome of this mobility action is the definition of the considered CE network architecture, the definition of the network node and its interfaces and the study of new control plane cross-layer algorithms to design the network. The outcome of this study is reported in a joint paper [4].

Meeting attendance

Salvatore Spadaro attended the WP27 meeting held in Torino during the ECOC conference (Monday September 20).

Conclusions

This JA achieved interesting results in the field of impairment consideration in optical networks. At the same time, it opens possible further improvements which will be addressed in the near future among the researcher groups involved in the JA.

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Publications list

[1] S. Azodolmolky, M. Klinkowski, Y. Pointurier, M. Angelou, D. Careglio, J. Solé-Pareta, I. Tomkos, "A novel offline physical layer impairments aware RWA algorithm with dedicated path protection consideration", IEEE/OSA Journal of Lightwave Technology, vol. 28, no. 20, pp. 3029-3040, October 2010.

[2] S. Azodolmolky, Y. Pointurier, M. Angelou, D. Careglio, J. Solé-Pareta, I. Tomkos, "A novel impairment aware RWA algorithm with consideration for QoT estimation inaccuracy", IEEE/OSA Journal of Optical Communications and Networking, under review.

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[5] R. Martinez, R. Casellas, R. Muñoz, B. Garcia-Munrubia, P. Pavón-Mariño, M. Klinkowski, D. Careglio, "Experimental study on the impact of regenerator placement strategies when dynamically provisioning in translucent GMPLS WSON networks", OSA Optical Fiber Communication Conference and Exposition (OSA OFC/NOFEC 2011), under review.

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D. Colle, M. Pickavet, I. Tomkos, "Techno-economic analysis of a dynamic impairment-aware optical network", OSA Optical Fiber Communication Conference and Exposition (OSA OFC/NOFEC 2011), under review.

WP Papers (submitted but not yet accepted):

[1] Garcia-Manrubia, P. Pavon-Marino, R. Aparicio-Pardo, M. Klinkowski and D. Careglio, "Offline impairment-aware RWA and regenerator placement in translucent optical networks", under review in Journal of Lightwave Technology.

[2] S. Azodolmolky, Y. Pointurier, M. Angelou, D. Careglio, J. Solé-Pareta, I. Tomkos, "A novel impairment aware RWA algorithm with consideration for QoT estimation inaccuracy", IEEE/OSA Journal of Optical Communications and Networking, under review.

[3] B. Garcia-Munrubia, P. Pavón-Mariño, R. Aparicio-Pardo, M. Klinkowski, D. Careglio, "Offline impairment-aware RWA and regenerator placement in translucent optical networks", IEEE/OSA Journal of Lightwave Technology, under review.

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[5] R. Martinez, R. Casellas, R. Muñoz, B. Garcia-Munrubia, P. Pavón-Mariño, M. Klinkowski, D. Careglio, "Experimental study on the impact of regenerator placement strategies when dynamically provisioning in translucent GMPLS WSON networks", OSA Optical Fiber Communication Conference and Exposition (OSA OFC/NOFEC 2011), under review.

[6] D. Staessens, M. Angelou, M. De Groote, S. Azodolmolky, D. Klonidis, S. Verbrugge, D. Colle, M. Pickavet, I. Tomkos, "Techno-economic analysis of a dynamic impairment-aware optical network", OSA Optical Fiber Communication Conference and Exposition (OSA OFC/NOFEC 2011), under review.

Generated WP Papers:

[1] S. Azodolmolky, M. Klinkowski, Y. Pointurier, M. Angelou, D. Careglio, J. Solé-Pareta, I. Tomkos, "A novel offline physical layer impairments aware RWA algorithm with dedicated path protection consideration", IEEE/OSA Journal of Lightwave Technology, vol. 28, no. 20, pp. 3029-3040, October 2010.

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