SEVENTH FRAMEWORK PROGRAMME

Report on Y1 activities and new integration strategy

FP7-ICT-216863/UCL/R/PU/D13.1

Project Number: FP7-ICT-2007-1 216863

Project Title: Building the Future Optical Network in Europe (BONE)

Contractual Date of Deliverable: 30/11/08

Actual Date of Delivery: 25/12/08

Workpackage contributing to the Deliverable: WP13 : WP-VCE Access

Nature of the Deliverable R(Report)

Dissemination level of Deliverable PU(Public)

Editors: John Mitchell/UCL

Abstract:

The deliverable reports on the activities and plans for integration and network in the Virtual Centre of Excellence on Access. It details the joint activities that have been undertaken in the first year of the project highlighting the research achievements. It also outlines the areas of active research currently being undertaken by partners within the VCE which will be integrated in the second year of the project. It concludes by proposing a strategy for integration, networking and collaboration between partners conducting research in the Access space.

Keyword list:

Optical Access, Radio-over-fiber, Passive Optical Networks

Disclaimer

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1. Executive Summary :

The deliverable is the first deliverable of the work package "Virtual Centre of Excellence on Access (VCE-A)", WP13. It details the joint activities that have been undertaken in the first year of the project highlighting the research achievements. It also outlines the areas of active individual research currently being undertaken by partners within the VCE which will be integrated in the second year of the project. Currently five joint activities have been identified as have critical mass across the partners. There are 1) Techno-economic analysis of optical access networks, 2) Optical Code Division Multiple Access based PONs, 3) millimeter-wave radio over fiber, 4) Quality of Service in PONs and 5) Techniques for colour-less optical network units.

We also propose strategies for integration, networking and collaboration between partners conducting research in the Access space in year 2 of the project.

2. Introduction

The Virtual Centre of Excellence on Access aims to provide a forum for exchange and consolidation of the latest research and development on access systems that use optics to provide true-broadband connections to fixed and mobile users. This encompasses a wide range of technologies including TDM-PONs, WDM-PONs, Radio-over-Fibre, Free-Space-Optics or xDSL-over-fibre. These technologies are all being to be developed and are competing in diverse scenarios. Of specific interest is the convergence of these technologies and the potential for hybrid solutions. Due to the range of expertise available within the VCE we believe was are well placed to offer leadership in this important technological area.

With this aim, specific objectives of this WP are:

- To integrate the research efforts on broadband access in Europe.
- To establish a benchmarking platform for the different optical access technologies, to provide a series of guidelines for the deployment of most promising and effective access techniques in the different scenarios in Europe.
- Provide insight into the integration of access technologies to provide operators with cost-effective evolution paths for the introduction of new services.
- Document and make available to all test-bed and platforms.
- Contribute to standards in the area, both within Europe and externally.

Section 3 begins be detailing the mechanisms that have been identified to enable integration of the research activities and expertise of the partners. It continues to present the strategy for year two of the project. Section 4 presents a summary of the structure of the VCE and the activities to date. Section 5 presents details of the joint activities that are underway or have been formed based on areas of critical mass within the workpackage. In the appendices the inventory of expertise of the partners are presented.

3. Integration Strategy

3.1 Introduction

Much integration had already been achieved in the previous e-Photon/ONe and e-Photon/ONe+ projects, and this workpackage has used the experience gained in these forums as a guide to the potential areas of integration in this activity.

The integration of the European research effort in this area is a key objective of this VCE. In the area of access it is becoming clear that no one technology will be prevalent in this area in Europe due the diverse landscape; rather a range of technologies will be required that demand complementarily and integration to achieve full cost-effectiveness. It is here that we see the coordination function of a VCE that covers the full range of technologies having the most economic impact by offer impartial and forward looking evaluations of appropriate new technologies.

3.2 Mechanisms of Integration

In the first year of the project the VCE has begun to put in place the plans to achieve this integration. As identified in the proposal document, four main areas of integration where proposed. In the next sections we identify progress towards these aims and discuss future plans.

3.2.1 Amalgamating research agendas of partners to reach a consensus on the challenges and directions of access research

Delivered at the end of month 3, Milestone M13.1 detailed the development of an inventory of expertise across the VCE. This included detailed descriptions of key resources made available to the project by partners, relevant for the development of broadband access (D13.1). The inventory descriptions as well as the summary of expertise are available on the BONE partner site (www.ict-bone.eu).

Based on the expertise inventory and the areas of interest identified within M13.1, partners were encouraged to initiate joint activities (JAs), with the expectation that all partners will become involved in at least one joint activity. To date five joint activity areas have been identified: 1) Techno-economic analysis of optical access networks, 2) Optical Code Division Multiple Access based PONs, 3) millimeter-wave radio over fiber, 4) Quality of Service in PONs and 5) Techniques for colour-less optical network units. Details of the research activities conducted to date and the research topics to be integrated within these activities are outlined in section 5, with each JA providing a description for further integration of activities and future plans.

3.2.2 Providing opportunities for the mobility of researchers to perform benchmarking activities across technologies

One of the main instruments of collaboration in the Joint Activities described above is the mobility of researchers. Details of the mobility actions completed or underway so far are given in section 4.2. Further mobilities within the JA will be encouraged.

3.2.3 Offering forums for discussion and dissemination of state-of-art research

A number of avenues are being pursued to enable discussion of the research consolidated with the VCE.

Activities to date:

- **ICT Lyon** – The VCE organised a Networking Session at the ICT 2008 meeting in Lyon in November 2008. The session, entitled "Next Generation Access Networks" attracted around 35 participants with presentations on BONE and other EU projects in the area of optical access and a discussion on the future directions for optical access research. Full details and the presentations can be found at: http://ec.europa.eu/information_society/events/cf/item-display.cfm?id=487

Future Activities

- **IET Optoelectronics Journal** –It has been agreed with the publisher of IET Optoelectronic Journal (www.ietdl.org/IET-OPT) that a ***call for papers*** will be released in January for a special issue on ***Next Generation Optical Access*** which will be specifically linked to the BONE Virtual Centre of Excellence on Access. The deadline for submission is likely to be mid 2009 with publication in mid 2010.
- **Optical Access Book** – It has been proposed that a updated volume of the success book that resulted from the access workpackage of ePhoton/ONe (Next-generation FTTH Passive Optical Networks: Research Towards Unlimited Bandwidth Access by Josep Prat) will be considered. Plans are underway to contact a publisher in early 2009.
- **Workshops** – A workshop and technical meeting is being planned for 2009. The current proposal is for a meeting to be held in London in April.

3.2.4 Influencing research strategy, both within and external to the consortium

To ensure that the research strategy of the VCE is visible to other workpackages of the project, as well as to outside parties, an advisory board was formed. The main criteria in the formation of the advisory board was select individuals involved in other interdependent workpackages with BONE, other EU funded projects in the optical access area or standard bodies working in access. The board represents, FP6 Projects ISIS and PIEMAN, FP7 project Sardana as well BT and Huawei. These last two representatives are of vital importance as the members for these companies also represent the two major standards bodies in the optical access space; **Full Service Access Network (FSAN)** group and **IEEE 802.3ah Ethernet in the First Mile Task Force.**

Within the framework of WP01 of BONE members of the VCE are currently contributing towards the generation of a Roadmap of "Optical Networking". As an initial stage of this work they are collecting some data related to access networks and the relevant state-of-the-art with the aim to identify the amount of traffic and types of services that today’s network have to accommodate and extrapolate from these future network needs.

3.3 Advisory Board

To direct the strategy of the VCE and to provide an insight into harmonization issue with other BONE workpackages and other EU funded projects, an advisory board was formed. The membership is detailed below. In brackets the affiliation they bring to the advisory board is highlighted.

- Franco Callegati DEIS-UNIBO (leader of WP11 **VCE on Network Technologies and Engineering**)
- Ioannis Tomkos AIT (WP23, **TP on Optical communication networks in support of user mobility and Networks in Motion**)
- Ton Koonen (WP16, **VCE In-building Networks**)
- Josep Prat UPC (lead erof the EU FP7 **Sardana** Project)
- Márk Csörnyei, Budapest University of Technology (FP6 Network of Excellence **ISIS**)
- Lena Wosinska, KTH
- Maurice Gagnaire, ENST
- Russell Davey, BT (leader of the EU FP6 Proejct **PIEMAN** and Chair of **the FSAN Next Generation Access (NGA) task group**)
- Frank Effenberger, HUAWEI (Member of the **IEEE 802.3ah Ethernet in the First Mile Task Force**)

4. Summary of VCE

The following member organisations have allocated manpower in VCE-A.

4.1 Membership of the VCE

Coordinator: Dr John Mitchell, UCL.

Role	Partner Number	Number Beneficiary name Beneficiary	Partner short name	Country
CO	46	University College London	UCL	UK
CR	1	Interdisciplinair Instituut voor BreedBand Technologie vzw -	IBBT	Belgium
CR	2	Vienna University of Technology	TUW	Austria
CR	4	Fraunhofer Institute for Telecommunications, Heinrich Hertz	Fraunhofer	Germany
CR	6	Universität Duisburg-Essen	UDE	Germany
CR	12	Escuela Politécnica Superior –Universidad Carlos III de Madrid	UC3M	Spain
CR	13	Universitat Politècnica de Catalunya	UPC	Spain
CR	14	Universidad Politécnica de Cartagena	UPCT	Spain
CR	15	Universidad Politécnica de Valencia	UPVLC	Spain
CR	17	France Telecom R&D	FT	France
CR	18	GET / E.N.S.T.	GET	France
CR	19	Research and Education Laboratory in Information Technology	AIT	Greece
CR	22	University of Athens	UOA	Greece
CR	26	Coritel	CORITEL	Italy
CR	27	Fondazione Ugo Bordoni	FUB	Italy
CR	28	Superior Institue of Communication and Information Technologies	ISCOM	Italy
CR	29	Politecnico di Milano	POLIMI	Italy
CR	30	Politecnico di Torino	POLITO	Italy
CR	33	University of Modena and Reggio Emilia	UNIMORE	Italy
CR	36	Eindhoven Univ. of Technology	TUE	Netherlands
CR	37	Instituto de Telecomunicacoes	IT	Portugal
CR	38	AGH University of Science and Technology	AGH	Poland
CR	41	Kungliga Tekniska Högskolan	KTH	Sweden
CR	43	Universita degli Studi Roma Tre	UNIROMA3	Italy
CR	44	Optoelectronics Research Centre - University of Southampton	ORC	UK
CR	45	University of Cambridge	UCAM	UK
CR	47	University of Essex	UESSEX	UK
CR	48	University of Wales Swansea	USWAN	UK
CR	49	Ericsson Limited	Ericsson	UK

4.2 Mobility Actions

1) *Security in OCDMA based networks*
   Valentina Sacchieri, PhD student at UniRoma3, hosted by IT from 21/01/2008 to 31/07/2008
   Status: **Approved. Completed**

2) *Performance evaluation of an optical transparent access tier*
   Bas Huiszoon, PhD Researcher at TUE, hosted by UAM from 01/03/2008 to 10/07/2008
   Status:

3) *Upstream Transmission in WDM PONs at 10Gbps Using Low Bandwidth RSOAs Assisted with Optical Filtering and Electronic Equalization*
   Mireia Omella, Phd student at UPC, hosted by AIT from 01/04/2008 to 10/04/2008
   Status: **Approved Completed**

4) *Optical CDMA*
   Izzat Darwazeh, Professor at UCL, hosted by IT from 22/10/2008 to 25/10/2008
   Status: **Approved. Completed**

5) Optical CDMA
   Miguel Pimenta (PhD Student of UCL) spent two weeks at IT, Aveiro Portugal
   Status: **Approved. Completed**

6) *Photonic-ADC experimental demonstrator*
   Tiago Alves, Ph.D Student at IT, hosted by UPVLC from 14/12/2008 to 19/12/2008
   Status: **Approved. In progress**

4.3 Joint Papers

List by publication date

1. V. Sacchieri (UniRoma3), P. Teixeira (IT), A. Teixeira (IT), G. Cincotti (UniRoma3), *Enhanced OCDMA security by code scrambling*, Bone Summer School, Mons, Belgium, September 2008
2. Papagiannakis (University of Patras), M. Omella (UPC), D. Klonidis (AIT), J. Kikidis (Analog Integrated Electronic Systems S.A), A. N. Birbas (University of Patras), I. Tomkos (AIT), J. Prat (UPC), *Upstream Transmission in WDM PONs at 10Gbps Using Low Bandwidth RSOAs Assisted with Optical Filtering and Electronic Equalization*, ECOC 2008, Brussels, Belgium, September 2008.(with WP15)
3. E. Duca (UniRoma1), S. Di bartolo (ISCOM), D. Forin (ISCOM), S. Betti (UniRoma1), A. Teixeira (IT), *Modulation Effect Induced by Continuous Wavesin Semiconductor Optical Amplifiers*, ICTON 08, Vol. 1, No. 1, pp. 278-281, ATHENS, July 2008. (with WP15)
4. Teixeria (IT), A. Vieira (IT), J. Andrade (IT), A. Quinta (IT), M. Lima (IT), R. nogueira (IT), P. Andre (IT), G. Tosi-Beleffi (ISCOM), *Security Issues in Optical Networks Physical Layer*, ICTON 08 proceedings, Vol. 1, No. 1, pp. 123-126, ATHENS, July 2008.
5. G. Incerti (ISCOM), F. Incerti (UniRoma3), F. Di Vicenzo (UniRoma3), D. Forin (ISCOM), G. Tosi-Beleffi (ISCOM), F. Curti (ISCOM), A. Teixeira (IT), J. Prat (UPC), *Remote Pumping and Signalling in a Passive Optical Network Scenario*, ICTON 08 Proceedings, Vol. 1, No. 1, pp. 312-315, ATHENS, July 2008.
6. V. Sacchieri (UniRoma3), P. Teixeira (IT), A. Teixeira (IT), G. Cincotti (UniRoma3), *Secure OCDMA transmission using data pattern scrambling*, International Conference on Optical Transparent Networks (ICTON), Athens, Greece, June 2008.
7. V. Sacchieri (UniRoma3), P. Teixeira (IT), A. Teixeira (IT), G. Cincotti (UniRoma3), *A Novel Scrambling Technique Using OCDMA Encoders*, Symposium on Enabling Optical Networks (SEON 2008), Porto Portugal, June 2008.
8. F. Matera (FUB), L. Rea (FUB), S. Pompei (FUB), A. Valenti (FUB), C. Zema (CORITEL), M. Settembre (CORITEL), *"qualità of Service Control based on Virtual Private Network Services in a Wide Area Gigabit Ethernet Optical Test Bed"*, Fiber and Integrated Optics, Vol. 27, No. 4, pp. 301-306, Amsterdam, June 2008.(with WP11)
9. F. Matera (FUB), S. Pompei (FUB), A. Valenti (FUB), C. Zema (CORITEL), M. Settembre (CORITEL), *Qualità of Service Control in Access Networks Based on Virtual Private LAN Services in a Wide Area Gigabit Ethernet Optical Test Bed*, ICTON 2008, Athens June 22-26 2008, Vol. 4, No. 1, pp. 291-293, Athens, June 2008. (with WP11)
10. F. Di Vincenzo (UniRoma3), G. Cincotti (UniRoma3), G. M. Tosi Beleffi (ISCOM), D. M. Forin (ISCOM), F. Curti (ISCOM), A. Teixeira (IT), *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.
11. M. Casoni, "A Simulation Study of the IPACT protocol for Ethernet Passive Optical Networks", Proc. of 10th Anniversary International Conference on Transparent Optical Networks ICTON 2008, June 22-26, 2008, Athens (Greece).

12.

To be published

1. E. Zouganeli (TELENOR), K. Bugge (TELENOR), S. Andres (TID), J. Fernandez (TID), A. Elizondo (TID), *Drivers for Broadband in Europe*, Broadband Access Networks, Springer,
2. J. A. Lázaro (UPC), F. Bonada (UPC), V. Polo (UPC), A. Teixeira (IT), J. Prat (UPC), *Extended Black Box Model for Fiber Length Variation of Erbium-Doped Fiber Amplifiers*, Photonics Technology Letters, (with WP15)

5. Current Joint Activities

5.1 Joint Activity - Techno-economic analysis of access networks

Some complementary topics related to the techno-economic analysis of optical access networks are under investigation within this JA, based on a cooperative effort from the participants.

5.1.1 Future Activities

AIT is going to improve the model to include costs for the OLT and to be able to predict costs for two different topologies and technologies than the aforementioned. Study's expansion in order to include WDM PON also will be done.

The second phase of FUB studies will be about broadband state of the art in Italy, distinguishing the different data speeds available on the entire national area. This information will be able to indicate what kind of infrastructure market support is needed to develop Next Generation Network, and which are the areas where to intervene first.

IBBT is further evaluating FTTH rollouts and two topics that are now studied are the sensitivity of uncertain input parameters and the effect of competition.

Firstly there are several parameters in a techno-economic model for which it is uncertain whether the values are realistic or not. Adoption parameters, CapEx and OpEx costs and the service tariffs are the most important ones. By performing a sensitivity analysis, it is possible to estimate their influence. In a first step, a basic sensitivity analysis can be done by linearly varying one parameter at a time. In a second step, Monte Carlo simulations can be used to determine a general forecast of the outcome.

Secondly the viability of an FTTH project will be largely depending on the take rate and thus on the market situation and especially on the competition with other operators. IBBT proposed an approach toward modelling the competition for the customers. A study that is now performed focuses on a case, in which a municipality rolls out FTTH in direct competition with an existing network operator upgrading its infrastructure. An economic model is implemented for both operators and game theory is used for optimizing the strategies of both operators. Static games can be used for deducing trends, and multi-stage games allow obtaining more information.

One of the planned activities for further research includes the optimization between FTTH and wireless coverage. Wireless networks can be a cost-efficient intermediate step before reaching every household with fibre access. For this topic, cooperation between IBBT and KTH is proposed.

5.1.2 Strategy for Integration

To make the JA "***Techno-economic analysis of optical access networks***" successful the partners plan some integration activities. It includes collaboration between partners on decided issues in the framework of this JA as well as mobilities between partners to intensify integration between them.

One of the planned activities for joint work includes the optimization between FTTH and wireless coverage. For this topic, cooperation between IBBT and KTH is proposed.

The next activity is related to analysis of protection schemes for ***optical access networks.*** To study this topic, joint collaboration between AGH and KTH is decided. To intensify the work on this topic also mobility between KTH and AGH is planned in the beginning of the 2009.

To integrate the partners working in this JA joint meetings are also planned during technical WP13 meetings.

5.1.3 Qualitative and quantitative CAPEX and OPEX study of PONs

Passive optical networks (PONs) combined with the various technologies of time-division multiplexing (TDM), wavelength division multiplexing (WDM), or hybrid WDM/TDM, are considered as the promising solutions to overcome the bottleneck of broadband access. Meanwhile, fault management within the network becomes more significant due to the increasing demand for reliable service delivery. On the other hand, access network providers need to keep capital and operational expenditures (CAPEX and OPEX) low in order to be able to offer economical solutions for the customers. Improving network reliability performance by adding redundant components and systems is expensive and thus, not always very suitable for cost-sensitive access networks. In addition, to cope with the increasing demand for broadband services in a cost-efficient way, a smooth migration from TDM-PON to hybrid WDM/TDM PON is envisaged for near-future deployment.

Therefore, in joint AGH-KTH work the evolution of protection schemes for PONs has been reviewed and reliability and cost of some representative protection architectures for hybrid WDM/TDM PON has been studied. In our study we considered four types of PON protection architectures: type A, B, C and D as proposed in [1]. Apart of standard methods some new protection architectures have been analysed. One of them was a novel 1:1 dedicated link protection architecture proposed in [2], denoted here by N1. In [3] a new ring-based time-shared PON with self-healing function to prevent the fiber-fault occurring has been proposed; this architecture is referred to as N2 in our study. The authors of [4] propose architecture with automatic-protection-switching (APS) mechanism against distribution fiber breaks in PONs. This configuration (N3) emulates a local area network (LAN) over the existing PON while facilitating the switching of signal transmissions to a predetermined protection path in an event of a distribution fiber break. The protection against feeder fiber breaks in the PON can also be carried out in addition to N3. By interconnecting two OLTs at the central office and remote nodes (RNs), a protection switching can be performed [5]. This protection scheme is denoted by N4.

According to the derived Reliability Block Diagrams (RBDs) we obtained asymptotic unavailability and mean downtime per year (MTD) for the considered PON protection schemes. In Table 1we show our results for two cases, i.e. first the ONU power supply is not taken into account and secondly the ONU power supply is included.

Table 1 Reliability performance

	Without ONU power supply		With ONU power supply	
Protection scheme	Unavailability	MDT [min/year]	Unavailability	MDT [min/year]
unprotected	$2{,}08 \cdot 10^{-4}$	109,3	$2{,}59 \cdot 10^{-4}$	135,9
A	$7{,}27 \cdot 10^{-5}$	38,2	$1{,}23 \cdot 10^{-4}$	64,8
B	$7{,}10 \cdot 10^{-5}$	37,3	$1{,}22 \cdot 10^{-4}$	63,9
C	$4{,}33 \cdot 10^{-8}$	0,02	$5{,}06 \cdot 10^{-5}$	26,60
D_1	$2{,}39 \cdot 10^{-8}$	0,01	$5{,}06 \cdot 10^{-5}$	26,59
D_2	$7{,}07 \cdot 10^{-5}$	37,2	$1{,}21 \cdot 10^{-4}$	63,7
N_1	$3{,}99 \cdot 10^{-6}$	2,1	$5{,}46 \cdot 10^{-5}$	28,7
N_2	$2{,}67 \cdot 10^{-6}$	1,4	$5{,}32 \cdot 10^{-5}$	28,0
N_3	$1{,}41 \cdot 10^{-4}$	73,9	$1{,}91 \cdot 10^{-4}$	100,5
N_4	$5{,}07 \cdot 10^{-6}$	2,67	$5{,}56 \cdot 10^{-5}$	29,2

After the reliability analysis the cost efficiency of considered architectures in relation to the reliability performance has been compared. The results for total cost and the cost per subscriber for considered protection schemes are shown inTable 2. We assumed a number of users equal to 16, i.e., N=16.

Table 2 : Cost of considered protection architectures

Protection scheme	Total cost ($)		Cost per subscriber ($)	
	burying 250/km	burying 7000/km	burying 250/km	burying 7000/km
unprotected	32025	639525	2001,6	39970
A	34700	709513	2168,8	44344
B	33650	708650	2103,1	44291
C	62450	1277450	3903,1	79841
D_1	62550	1277550	3909,4	79847
D_2	35300	710300	2206,3	44394
D_1 - 8 users	49250	994250	3950,0	79888

D_2 – 8 users			2206,3	44394
N_1	40240	823240	2515,0	51453
N_2	24138	260388	1508,6	16274
N_3	54625	1201475	3414,1	75092
N_4	57200	2392200	3575,0	149513

In order to get a more complete techno-economic analysis of optical access networks we have extended CAPEX study with:

- other architectures of fiber access networks such as Point-to-Point (P2P) and Active Optical Networks (AON),
- CAPEX of different fiber access network solutions considering component cost decrease in time.

5.1.4 *Economical issues related to fiber development*

AIT team has been working on economical issues related to fibre development. Analysed eeconomical considerations are key when decisions on fiber introduction have to be made. The costs of digging and ducting are the major cost items in access networks, outweighing by far the costs of the transmission medium and the line terminating equipment. Civil works typically take the majority of fiber to the home (FTTH) first installed network costs, while the fiber cable and the optical components take only a small part of them. The remainder is taken by other hardware, installation activities, and other services. Hence, in green-field situations, the costs of introducing FTTH may not differ much from, e.g., twisted copper pair or coaxial cable access solutions. Moreover, the costs of fiber-optic line-terminating transceivers are coming down rapidly. FTTH's operational costs may be lower, as it needs less active equipment in the field which needs maintenance. A fiber link can basically handle any kind of access traffic, so installing fiber is insurance for the future (future-proof, or forecast-tolerant, investment).

The study performed presents the different topologies used, the standardization and theoretical advantages and disadvantages of two of the most commonly deployed architectures.

Subsequently the equipment used for the deployment, as well as the planning on a more pragmatic level for two different networks (EP2P-GPON), next the model used and the economic results.

After that some case studies are being examined and a qualitative analysis is performed on different networks, when examined in combination with the different needs of diverse areas. The conclusions relate mainly with the cost of the outside plant of the networks.

5.1.5 *Digital Divide problem and solution*

The first step has been to discover the Digital Divide areas to establish a way to intervene. We define Digital Divide (DD) areas some areas in which there is no way to have broadband.

There are several ways in which it is possible to have broadband; the most common is xDSL system, in particular ADSL and ASDL2+, but other solutions are possible as for example wireless ones. For an instance, in Italy we observe an increase of HSPA (High Speed Packet Access) traffic from 4 PBytes (December 2006) to 10 PBytes (December 2008). Another important radio solution is WiMAX, many TELCO operators in fact bought the permission to sell broadband by using this technology. Anyway all these radio solutions will not probably be employed in DD areas, because of these ones don't generate revenues for the operators. Due to these considerations we focused on wired solutions with the task to discover which areas (and why) are affected by DD.

There are several reasons, and the first step we investigate on these.

The first one is very simple: there is no DSLAM in the Central Office (CO), because of the operator did not retain fruitful the co-location of this kind of equipment. The solution could be represented by a government incentive to put the DSLAM in the CO.

The second one is an infrastructure problem related to the lack of fiber connection between the backbone and the CO. The TLC infrastructure, planned for voice traffic, involved very small bit rates that did not require fiber connections but just copper cables (using for example ATM circuits) between Central Office and Backbone Areas. A possible solution is a government intervention in all these areas left out of operator business plans. These areas in fact are called "low ROI[1] market" and no operator is disposed to invest money.

The third reason is a physical one. We know that xDSL techniques can be employed by the end users if they stay in a short distance from the central office, and this physical phenomenon is more relevant if the xDSL generation grows; for example an ADSL user has to stay within 5 km from the central office while ADSL2+ user has to stay within 2 km. A possible solution is to create new central office near the users (unrealistic), or employing radio solutions. Also in these cases a government incentive is possible, but only if these areas are considered in low ROI market.

The fourth reason is bit more complicated, and it does not depend by economic issues or by the distance covered by the twisted pair. In order to cover new territories that were not present during the original planning, the TELCO operators adopted different solutions, and one of these is the Multiplexer solution. A typical case is when a new building was manufactured near another one already existing. To bring phone services, two ways are possible: the first one is to connect the new user to the CO with new twisted pairs, the second one is to link new user to the existing twisted pair (already used by old user) and translated the phone bandwidth around a new carrier. This way a FDM (Frequency Division Multiplexing) technique is implemented by using a Multiplexer device and saving a complete new twisted pair deployment. Such a technique allows operators to save copper but it doesn't allow to provide ADSL connection to new users because of bandwidth occupancy. The real problem is that this solution is present also in high people density areas, especially in Italy when there are many little and ancient cities in which this approach has been indispensable.

In Italy there are 10400 central offices, a very large number with respect to other Europe countries; this permits a mean distance between the users and central offices very small: 1.2 Km. Besides the quality of twisted pair is very good. These favourable conditions allow Italian people to exploit xDSL solution, anyway about 3600 CO are not connected with the

[1] Return of Investment

fiber to the backbone. To solve connection problems a government society, INFRATEL, was created with the aim to deploy infrastructures in low ROI market district. We foresee that next year the 99% of the Italians could have broadband. To make up for the lack of fiber in several districts some temporary solutions have been already implemented, for example the ADSL Lite. This provides a DSLAM collocated in central office, but the available bandwidth to end users is dimensioned on the backbone-central office link capacity. The main result is that, since the backbone in fiber connected, the user could have a "broadband" of about 640 Kbit/s.

5.1.6 Study of GPON and EPON in logical layer (Layer 2)

GPON and EPON are two most common TDM PON solutions. Their popularity is different depending on the considered region, i.e. in Europe and USA GPON is dominating while in Asia EPON is more popular. One of their primary differences is the design of layer 2 protocol defined by ITU-T and IEEE, respectively. Therefore, the corresponding features, such as bandwidth efficiency and hardware complexity, are influenced by different protocols. We have studied bandwidth allocation in EPON and GPON. We also investigated the impact of logical layers in GPON and EPON as well as next generation TDM PON on efficiency of bandwidth allocation.

5.1.7 Analysis of WONDER architecture

WONDER (see [6], [7]), is an architecture based on a folded bus topology being used as PON; this architecture offers several properties such as fault resilience and efficient local traffic support, which could be also desirable in a PON. The study aim to evaluate the WONDER architecture as a suitable architecture for a PON environment

WONDER was conceived in the context of an Italian research project aimed at finding an effective solution for bridging the gap between future access networks and backbone ones.

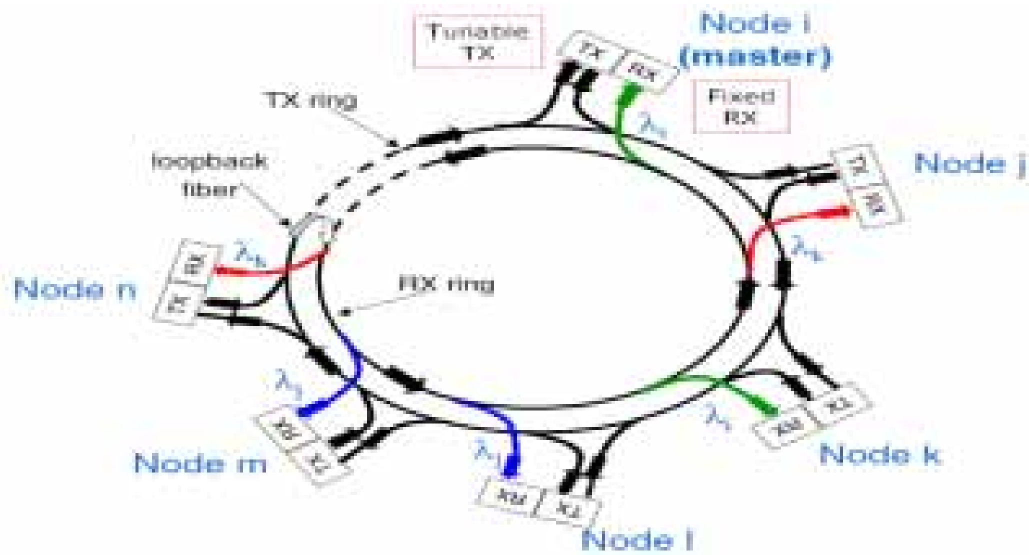


Figure 1: WONDER PON architecture

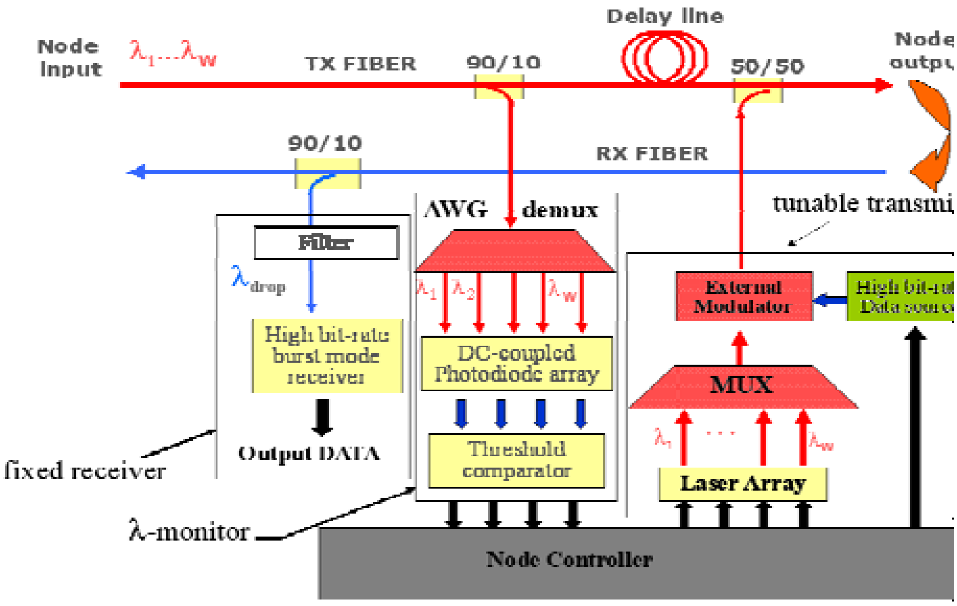


Figure 2: WONDER ONU structure

WONDER comprises N nodes connected to two counter-rotating WDM fiber rings. Each ring conveys W wavelengths, (N>W), and it is used in a peculiar way: one ring is used for transmission only, while the other ring is used for reception only. Transmission wavelengths are switched to the reception ring at a folding point between the two rings, as shown in Figure 1. Transmitted packets cross the transmission ring until they reach the folding point, where they are switched to the reception ring and received during the second ring traversal; thus, the architecture behaves as a folded bus network.

The network is synchronous and time-slotted. During a time slot, at most one packet can be transmitted by a node in one of the W available slots (one slot for each wavelength channel). Each node is equipped with a fixed Burst Mode Receiver (BMR), tuned to λ_{drop} as shown in Figure 2; given that N>W, receivers can be allocated to the WDM channels in a way that equalizes the traffic across WDM channels (see [8]). To provide full connectivity between nodes, each node is equipped with a fast tunable transmitter, which is tuned to the receiver's destination wavelength, establishing a single hop connection lasting one time slot. The channel resource sharing is therefore achieved according to a TDMA scheme. Access decisions are locally processed at access interfaces (called Optical Network Units (ONUs) in PONs), based on a channel inspection capability called λ-monitor (Figure 2) to avoid collisions, i.e., access to an already used slot.

A major issue in comparing WONDER with PONs based on tree topologies is power losses between access points. To improve WONDER scalability in number of ONUs, power losses along the ring should be reduced. This can be obtained by grouping ONUs in sets (see Fig. 3) to reduce the number of couplers the optical signal has to pass through. We call this solution Grouped WONDER (GW). If this configuration is adopted, the carrier sense line has to be decoupled from the transmission line to avoid any possible signal interference, and a suitable delay line has to be used to keep slot alignment.

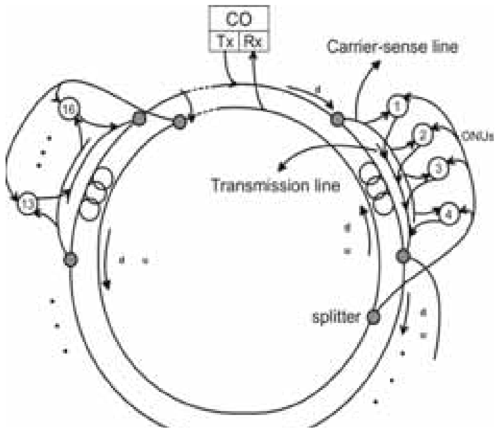


Figure 3: Grouped WONDER (GW) architecture

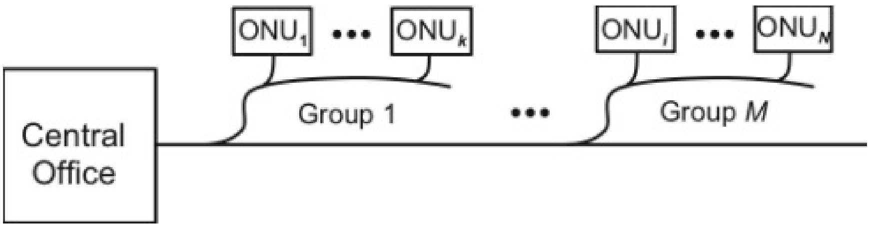


Figure 4: Grouped Bus (GB) architecture

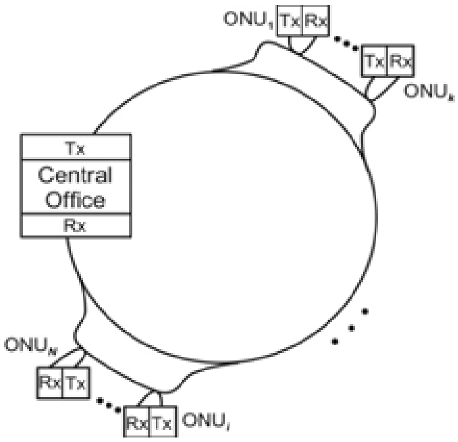


Figure 5: Grouped Ring (GR) architecture

Current PON solutions are implemented over different physical topologies, such as buses and rings [9]. In both cases, ONUs can be grouped reducing the power budget limitations as in the GW architecture. The Grouped Bus (GB) and the Grouped Ring (GR) architectures are shown in Figures 4 and 5 respectively as examples of these extensions.

Concerning performance characteristics of these architectures, we considered a test case with all ONUs uniformly distributed along a circle of radius r=20km (where CO is at the beginning of the fibers and acting as an optical line terminal – OLT). We compared their delay performance with a traditional tree (where all ONUs are at the same distance from CO, which is in the center). The different quantities considered in performance analysis were:

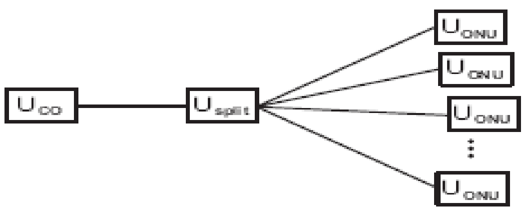
D	*worst case trip delay*	*N*	*number of ONUs*
T_c	*processing time to run the dynamic bandwidth allocation (DBA) algorithm at the OLT*	*r*	*ONU – OLT distance*
d_i	*trip delay between* ONU_i *and OLT*	$\overline{D}$	*average trip delay*
P_d	*light propagation delay, equal to 5 µs/Km*		

Table 3 Worst and average delay for different PON architectures

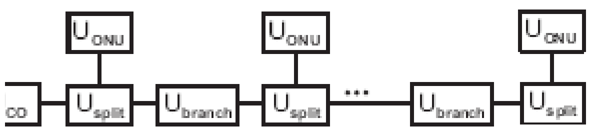
Architecture	Worst Delay [ms]		Average Delay [ms]	
	N=16	N=32	N=16	N=32
Tree	0.2+Tc	0.2+Tc	0.2+Tc	0.2+Tc
Bus	1.1+Tc	1.2+Tc	0.628+Tc	0.628+Tc
Ring	0.591+Tc	0.609+Tc	0.589+Tc	0.608+Tc
WONDER	1.1	1.2	0.5544	0.592

Table 3 shows WONDER as the only architecture in which the delay is not dependent on the computation time required at the CO since a distributed access scheme is implemented. The average WONDER trip delay is similar to the bus and the ring values. The tree architecture shows the lowest values for the worst and average delay among the architectures depending on Tc , which is not easy to estimate. In the considered setup, WONDER shows better performance when Tc > 0.39 ms.

From the reliability point of view, PoliTo analyzed reliability properties of the different PON architectures; considering different system modules or functions as reliability blocks, we can derive the steady-state unavailability of series and parallel blocks [10]. Blocks can be splitters, group branches, ONUs and CO. WONDER reliability can be improved by means of a fault recovery mechanism (from which the rings can be folded in the case of failures by using 2 optical switches controlled by a folding element controller);



(a) Tree RBD



(b) Bus RBD

Figure 6 : Reliability Block Diagrams (RBD) [11], [9]for tree and bus architectures

Table 4: Unavailability and expected downtime for different PONs (N=16)

Architecture	Unavailability (U)	Expected downtime [min/yr.]
Bus/Ring	2.40*10-4	126.08
Unprotected tree	7.56*10-5	39.72
WONDER	2.81*10-5	14.76

The power budget in PON architectures is defined as the optical power that can be lost by optical signals along the path between the CO and the ONUs. It is one of the biggest PON limiting factors and deeply affects network scalability. The power budget of the tree architecture is dominated by the splitter/combiner located between the CO and the ONUs, while the power budget of the bus and the WONDER architectures is dominated by the couplers used to attach each ONU to the shared medium. We performed a numerical analysis considering the insertion loss (IL) of optical components; also the optimum ONUs group disposition for power requirements was considered and compared with non-grouped versions of the architectures.

Figure 7 shows power budget computation for the considered architectures. Dashed lines represent the power budget lower bound in GPON and EPON standard [12], [13]. The tree architecture shows the best behavior, while the WONDER architecture shows the worst one. Grouped architectures show a better behavior with respect to the original WONDER, bus and ring architectures.

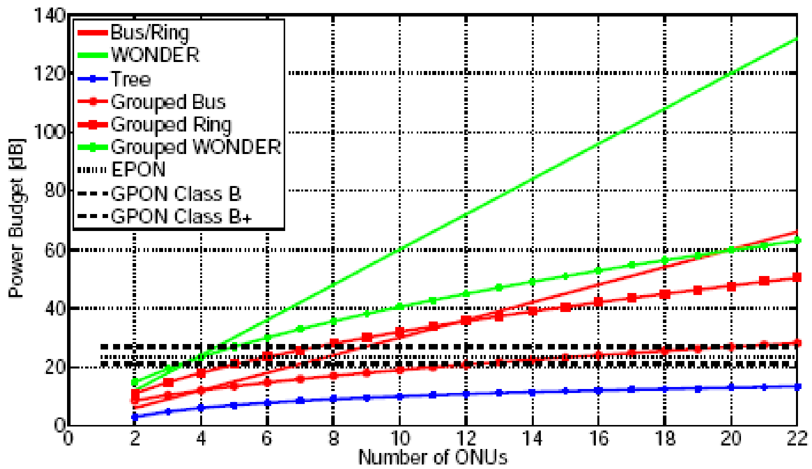


Figure 7: Power Budget performance

As a summary, PoliTo showed how WONDER can be employed as a PON. It allows communication between ONUs without CO involvement, an important feature for supporting efficiently P2P applications. Besides, it shows interesting fault recovery properties, as it exhibits lower unavailability than all unprotected architectures. The main drawback of the WONDER architecture is represented by its scalability in number of ONUs due to its power budget. However, this limitation can be overcome by grouping nodes in sets, as in the Grouped WONDER (GW) architecture.

5.1.8 *Outcome of the joint and individual research activity:*

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5.1.9 *Techno- economic analysis of FTTH networks*

Two techno-economic topics in the field of fibre-to-the-home (FTTH) networks are studied by IBBT:

- A detailed view on FTTH deployment costs, including both capital expenditures (CapEx) and operational expenditures (OpEx).
- The economic impact of a fibre-to-the home (FTTH) rollout by a local community.

The first topic deals with an approach for getting a clear estimate of all expenses for an FTTH rollout. Deploying a new FTTH network in a region involves a tremendous work and cost. Literature mentions a typical 1500 Euros per home connected in highly residential regions and much more in lower residential regions [14]. It is clear that large savings are possible on such a huge cost and thus a detailed modelling is required to make the best upfront decisions. We focus on the most important expenses first and, in subsequent steps, gradually zoom in to get a balanced and more detailed view on the total cost. We start with decomposing the total cost according to the different lifecycle stages: planning, deployment, service migration and the up and running operations. We complement this model with a high level view of the expenses in each of those steps, methods and tools for calculation and the most important parameters or risks. We further increase the level of detail by gradually zooming into those parts, which are either most important or most unknown (i.e. highest risk).

The second topic is inspired by the fact that, today, a lot of telecom operators are hesitating to invest heavily in infrastructure for rolling out FTTH. They first want to pay off their previous broadband investments and are uncertain about new local loop unbundling (LLU) regulation for fibre networks. Consequently, a lot of them prefer to extend their existing infrastructure to higher bandwidths (by means of VDSL or DOCSIS 3.0). Since a few years, a new trend is ongoing in which other players, such as municipalities, power utilities and housing companies, are investing more and more in the physical infrastructure of new FTTH networks [15,16] (e.g. in the Netherlands (Almere, Amsterdam), Sweden (Västerås), Iceland (Reykjavik), France (Pau), etc). We have made an investment analysis for an FTTH rollout done by a cooperation of a municipality (applied for the city of Ghent (Belgium)) with an existing network operator. Our analysis shows that such an FTTH community network can be economically viable. This is mainly due to an additional positive economic impact and a possible reduction in digging available to a municipality.

Example: cost breakdown and NPV analysis for a community network

To give an idea of the kind of obtained results, Figure 8 and Figure 9 show a cost breakdown and net present value (NPV) analysis for a municipality FTTH rollout in the city of Ghent (Belgium). The considered FTTH rollout covers the city centre with an area of ca. 20 km² counting 90,000 inhabitants (i.e. ca. 42,000 households) and 222 industrial companies. The case study is evaluated over a duration of 15 years (2008 to 2022). As network architecture, an active home run fibre network was chosen, which seems to be preferred for municipality-driven FTTH deployments [17].

Figure 8 (left) gives an overview of the division between CapEx and OpEx from the viewpoint of the operator/municipality (summed over the evaluation period of 15 years). CapEx takes the largest part, mainly due to the dominating costs for the outside plant, consisting of digging and equipment (ducts, fibre) costs. Other CapEx are related to the CO and customer side. The CO is equipped with racks containing the optical line terminals (OLTs), and besides there is equipment installed for powering, and heating, ventilating, and air conditioning (HVAC). The low percentage for the customer premises equipment (CPE) is caused by the assumption that most of the CPEs (ONUs) are paid by the customers and only in case of pre-subscriptions the operator pays for it. OpEx are split between network related (maintenance, repair, power, operational handling) and service related (service provisioning, pricing & billing, helpdesk, marketing) costs.

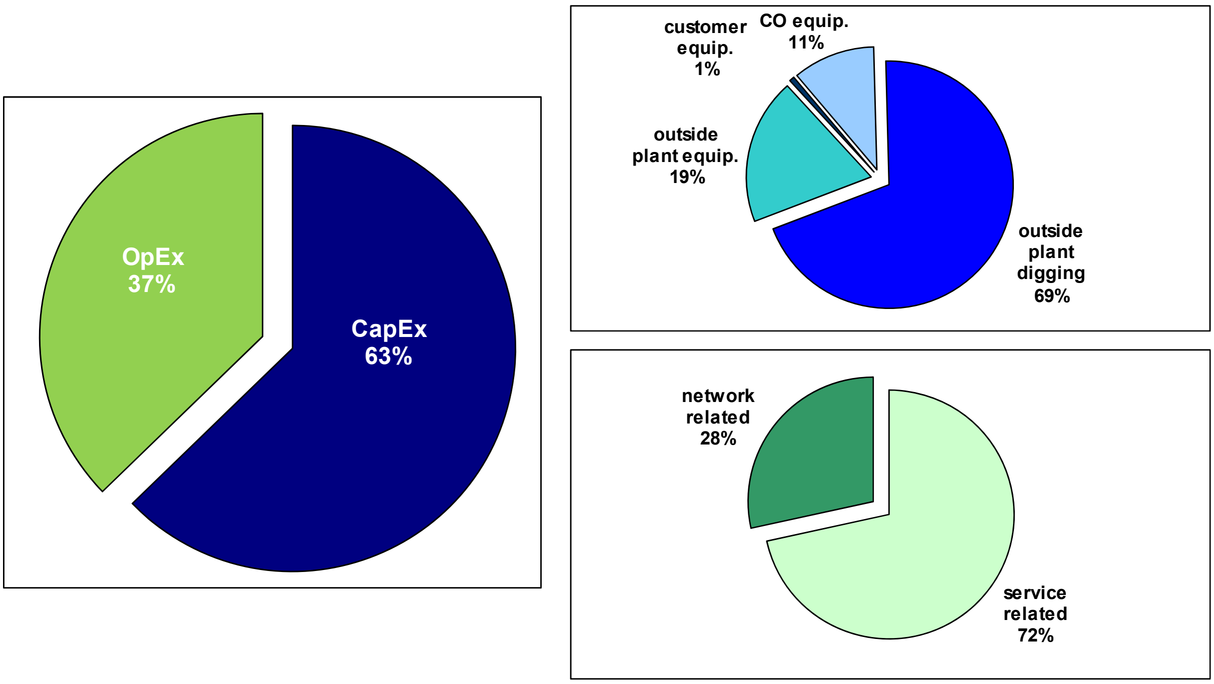

Figure 8: Division between CapEx and OpEx (left), CapEx breakdown (right, top), OpEx breakdown (right, bottom)

All cost and revenue figures are combined to calculate the net present value (NPV) of the municipality network, using a discount rate of 10%. Figure 9 shows the evolution of the NPV for three different rollout speeds, ranging from a total rollout in 6 years (i.e. by the end of 2013, fast), in 10 years (i.e. by the end of 2017, moderate) and in 15 years (i.e. by the end of 2022, slow). The same figure gives an indication of the difference between a municipality and a private operator, due to the valuation of the positive economic impact and the reduced digging costs. The moderate rollout speed, with a total rollout in 10 years, shows a reasonable initial investment cost (min. NPV of € -13.4M, in 2016), while reaching an NPV of € 5.5M in 2022. Rolling out faster results in a much higher initial investment and thus high financial risk (min. NPV of € -24.8M, for the fast rollout), and rolling out slower results in a lower final NPV because of a big loss of revenue streams in the first years (final NPV of € 1.7M, for the slow rollout).

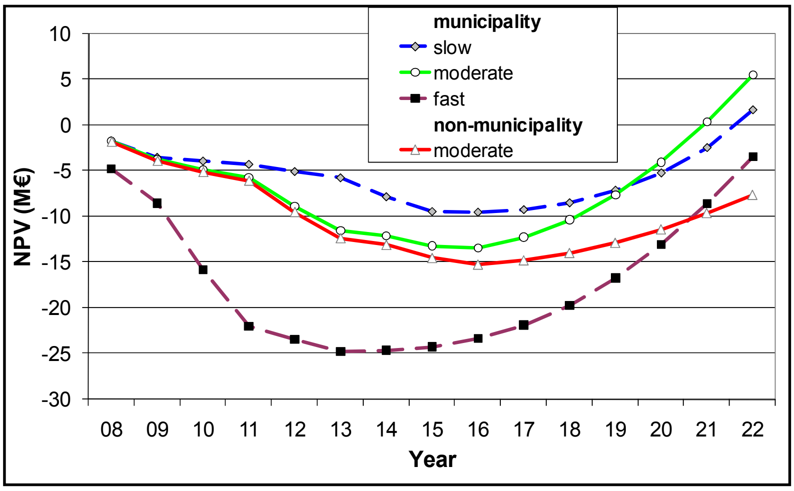

Figure 9: NPV analysis for an FTTH municipality network, considering different rollout speeds

Publications related to the above topics:

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5.2 Joint Activity - Secure OCDMA-based PONs

5.2.1 Introduction

Optical code division multiple access (OCDMA) has been recognized as a potential candidate for the next generation broadband multiple access networks, with unique features of full asynchronous transmission, low latency access, soft capacity on demand as well as optical layer security. By combining OCDMA with wavelength division multiplexing (WDM) technique, high capacity in access networks can be achieved, which in prospective can enable Gigabit-symmetric fiber-to-the-home (FTTH) systems.

Some complementary topics related to the secure OCDMA networks are under investigation within this JA, based on a cooperative effort from the participants.

5.2.2 Collaborative actions carried out

- Mobility action

Valentina Sacchieri (PhD student of UNIROMA3) spent 5 months at IT, Aveiro Portugal from 21/01/2008 to 31/07/2008

Miguel Pimenta (PhD Student of UCL) spent two weeks at IT, Aveiro Portugal

- Mutual visit

Gabriella Cincotti (UNIROMA3) spent two weeks at NICT in October 2008, to test a new encoder/decoder

Prof Izzat Darwazeh (UCL) spend 3 days at IT, Aveiro Portugal in October 2008 to test wavelength/time encoders

5.2.3 Proposed Future Activities

NICT and UNIROMA3 will perform new experiments on block-ciphering schemes by optically implement block chaining (CBC) encryption using field programmable gate array (FPGA). Complete confidentiality can be achieved by substituting line encoders with a cipher module, where each block of plaintext is XORed with the previous ciphertext block before being encrypted. Furthermore, a new multiport spectral encoder is currently under test and it will be used in standard OCDMA and quantum encryption schemes.

Spectral amplitude coding (SAC) will be one of the key research topics on secure OCDMA. The technique proposed by University of Essex is particularly attractive for its simple implementation and can be merged with the encoding scheme proposed by NICT and UniRoma3, where a single multiport spectral encoder/decoder is used. The Instituto das Telecomunicacoes Aveiro, Portugal (IT) will contribute to this activity by introducing code scramblers to enhance the system security. One of the most interesting results stemming from a collaborative research will be the comparison of the performance of SAC techniques and the

Wavelength-Hooping Time-Spreading (WHTS) encoding scheme, investigated by the University College of London (UCL), and IT.

5.2.4 Current Activities

Essex's contribution to secure OCDMA-based PONs has been the development of a novel spectral amplitude coding (SAC) technique. Particular advantages to this approach include service differentiation by varying the code weight of a particular channel using SAC techniques with codes chosen from [18,19] due to its simpler hardware realization and better transmission performance than its counterparts [18]. Other advantages of the code include unity cross-correlation which simplifies the process of multiple access interference (MAI) cancellation. Here, MAI is eliminated using direct decoding scheme where only the non-overlapping spectrum(s) of the particular code are detected. We have also performed an experimental proof-of-principle demonstration, with schematic outline shown in Figure 10. In this case, two channels of different weights were transmitted over 40 km SMF. The SMF length was chosen to show the system's tolerance to fibre impairments for the typical fibre length of access/metro networks at OC-48 (2.5 Gb/s) transmission rate. Looking to the future, we are anticipating integrating our SAC technique with networks at other partners' institutions.

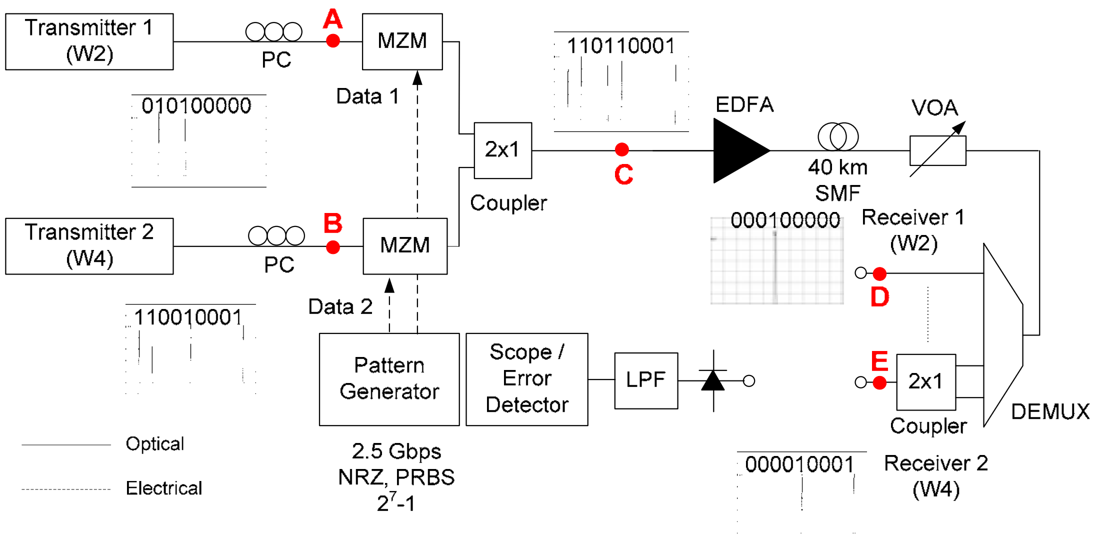


Figure 10 :Experimental setup of variable weight implementation at 2.5 Gb/s.

Uniroma3 and NICT focused their research activities on different architectures of OCDMA-based PONs, that use both bit- and block-ciphering schemes, evaluating their data confidentiality within an accurate cryptanalysis framework. A 8-user duplex asynchronous OCDMA transmission has been demonstrated for the first time in a field trial experiment of a PON system, using a fully asynchronous 10GbE interface, a single multiport encoder/decoder (E/D) at the optical line terminator (OLT) and low-cost fiber Bragg grating (FBG) E/Ds at the optical network unit (ONU) [20,21,22,23,24]. The uplink setup is shown in Figure 11.

In an OCDMA-based PON system, there are several serious security problems related to fact that all the downstream information is broadcast from the OLT to the ONUs, so that a malicious user can easily sift through data directed to another user. MAI noise protects data confidentiality, but an accurate cryptanalysis should consider only point-to-point (P2P) transmissions; in this case, on-off keying or 2-code OCDMA system result unsecure, because they can be easily attacked by power or differential detection. The security performance of a (P2P) OCDMA transmission has been carefully analyzed, considering both bit- and block-ciphering schemes and advanced eavesdropper attacks [25,26].

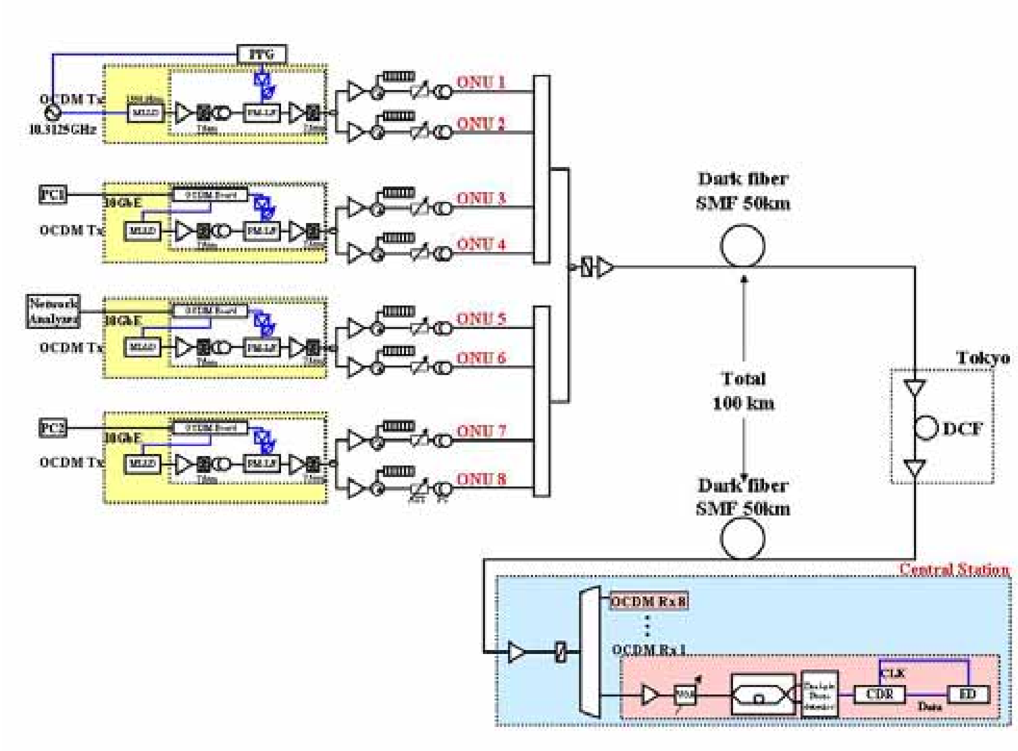


Figure 11: Experimental setup of a 8-user asynchronous 10Gb/s OCDMA PON.

Block-ciphering presents superior performances and the electronic codebook (ECB) encryption, where the message is divided into blocks that are encrypted separately, has been successfully demonstrated using 16 optical codes and a multiport E/D [27].

Bit- and block-ciphering schemes can furnish only computational confidentiality, based on the fact that an eavesdropper would require a large amount of resources and time to decode the message. Only the physical laws of nature can provide unconditional security based on the foundations of quantum mechanics. UNIROMA3 and NICT have proposed a new architecture of the Yuen's quantum encryption mechanism, using a newly developed spectral multiport E/D [28,29].

The Instituto das Telecomunicacoes Aveiro, Portugal (IT) and UNIROMA3 have performed some numerical simulations of a new code-scrambling OCDMA technique, that introduces additional degrees of freedom in the encoding system, enhancing the security [30,31,32]. A scrambled signal is fully distorted and the corresponding eye diagram is closed, so that an eavesdropper cannot sift data by standard or differential power detection. To break the security, a potential attacker should test all the code words, considering all their possible combinations. Code scrambling is also compatible with current WDM technologies.

The University of Cambridge (UCAM) team has been working in low-cost high-speed CDMA optical networks with electronic code processing. Electronic processing may provide similar benefits of OCDMA such as one wavelength used for all users, bidirectional code transmission, coding gain and networking functions, at gigachip per second rates and low cost. The Code generation is performed by electronic FIR filters. This technology makes possible low-cost and low-power code generation at very high chip rates. The FIR filter splits an input pulse across m taps (where m is the length of the code) each of which is separated by a delay of 55 ps, providing 18 Gchips codes. Experimental work was carried out in a partly populated 14 user system where two users (one as user and the other as interferer) were demonstrated using the ECDMA approach [33,34,35]. Here two Gold codes at 18.1 Gchips/s with length 7 were generated using the transversal filters and code modulated two 1.25 Gb/s data signals. The combined electrical signal modulates a DFB laser via a $LiNbO_3$ modulator and is amplified by a SOA. After 10 km of standard single-mode fibre, the detected optical signal is input to a receiver CDMA decoder, amplified by a RF amplifier and then input to a 1.25 Gb/s BERT. Error free transmission with the interferer was achieved. Simulation results show that the fully user populated system works with a good margin.

University College of London (UCL), in collaboration with the Instituto das Telecomunicacoes Aveiro, Portugal (IT), have investigated Wavelength-Hooping Time-Spreading (WHTS) OCDMA networks, which provides increased code design flexibility and better network performance when compared to one-dimensional temporal OCDMA. WHTS exploits the vast fibre-optic bandwidth more efficiently than other OCDMA systems and allows fully asynchronous operation. However, despite these advantages, multi-wavelength OCDMA systems suffer from dispersion-induced temporal skewing among wavelength channels. In fact, the detection of a given codeword is an incoherent process that relies on the temporal distance of the chips on different wavelengths. If the network induces relative temporal shifting between the wavelengths, the code pattern is distorted giving rise to errors in the receiver.

The impact of the optical fibre Group Velocity Dispersion (GVD) in multi-wavelength OCDMA systems has been addressed by several research groups. Solutions to alleviate this problem include compensation schemes based on a combination of Arrayed Waveguide Gratings (AWGs) and precisely configured optical delay lines and code pattern pre-skewing. However, such all-optical approaches rely on the use of optical delay lines which suffer from lack of tunability and accuracy.

Electronic post-detection processing is a potential solution that has yet to be explored. Recent advances in electronics allow the processing of OCDMA signals in the electrical domain. Considering the very high chiprates involved, it is key that a viable compensator should operate across a wide range of frequencies from near DC up to (and beyond) the chiprate. A structure with such characteristics is the electronic distributed amplifier, which may be configured as a simple multi GHz amplifier/transversal filter/compensator.

UCL has proposed a front end receiver structure based on the distributed transversal filter in order to correct the correlation peak distortion resulting from temporal skewing among wavelength channels. This allows not only tunability of compensation parameters but also tunability across different code words, thereby resulting in a flexible, adaptable and efficient solution.

The structure of the proposed Optical CDMA receiver is shown in Figure 12. The Optical CDMA signal is decoded in the optical domain using traditional methods (for example, an array of Fibre Bragg Gratings) after which it is received with a photodetector. The block diagram of the GVD compensator is shown in Figure 13 and its temporal response is described by the Equation 1. The electrical GVD compensator is effectively a front-end transversal filter.

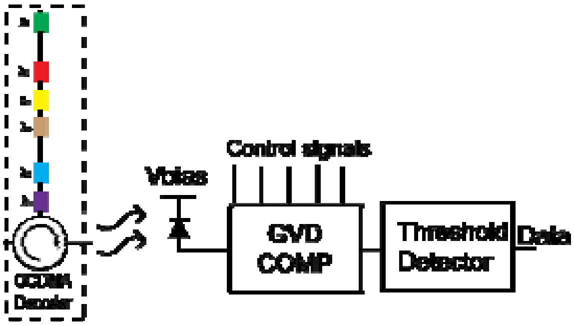


Figure 12: Block diagram of the proposed OCDM receiver

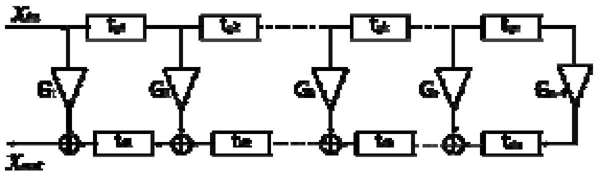


Figure 13: Distributed transversal filter block diagram

$$x_{out}(t) = \sum_{k=1}^{n+1} G_k x_{in}(t - \sum_{i=0}^{k-1}(t_{dk} + t_{gk})) \qquad (1)$$

An experimental demonstration of time skewing compensation in Fibre Bragg Grating based OCDMA networks, with an electronic fractionally-spaced transversal filter was implemented in the Instituto das Telecomunicacoes in Aveiro, Portugal.

Main Features

- 20 Gchips/s
- Three simultaneous users
- Five wavelengths with 200 GHz spacing.
- **Modified Wavelength Hoping "Mendez" Codes [JLT, Nov 2004]:**
  - **Four** active chips
  - **Five** wavelengths (1548.20 to 1554.50 nm)
  - **Eight** time slots (transmission at 20/8 = 2.5 GBit/s)

Codes

For verification purposes, a set of optical orthogonal codewords were designed based on codes proposed by Antonio Mendez [36]. The following codewords have zero auto-correlation and normalized cross-correlation equal to one:

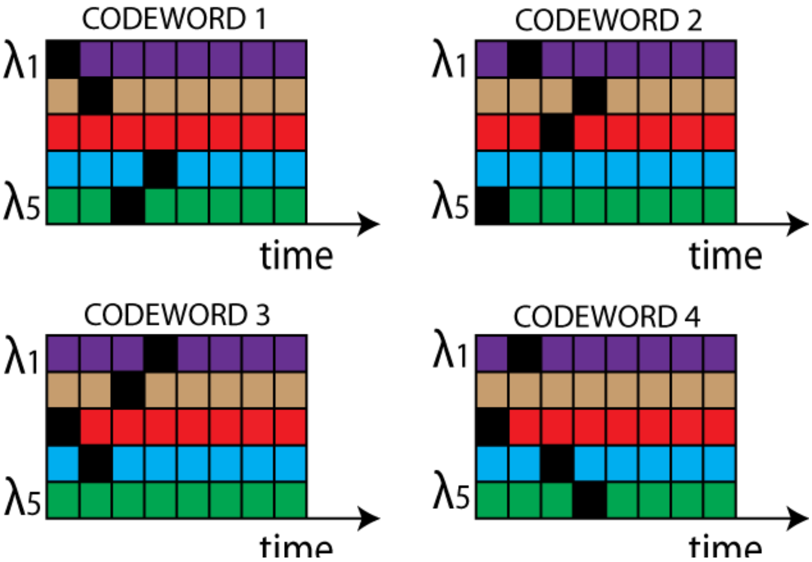


Figure 14: Wavlength Time Codes

Fibre Bragg Grating Array fabrication

The Fibre Bragg Grating Array is user specific and the round-trip propagation time between adjacent FBGs is T_{Chip}. For 20 Gchip/s the distance between two consecutive FBGs to achieve one chip delay is:

$$d = \frac{c.T_{chip}}{2.\eta_g} = \frac{3 \times 10^8 \times 50 \times 10^{-12}}{2 \times 1.447} = 5.183\ mm$$

η_g is the effective group index of the fibre (η_g is 1.447 for the photosensitive fibre used in the FBG array fabrication). The figure bellow shows the user 1 codeword and the correspondent encoding FBG array:

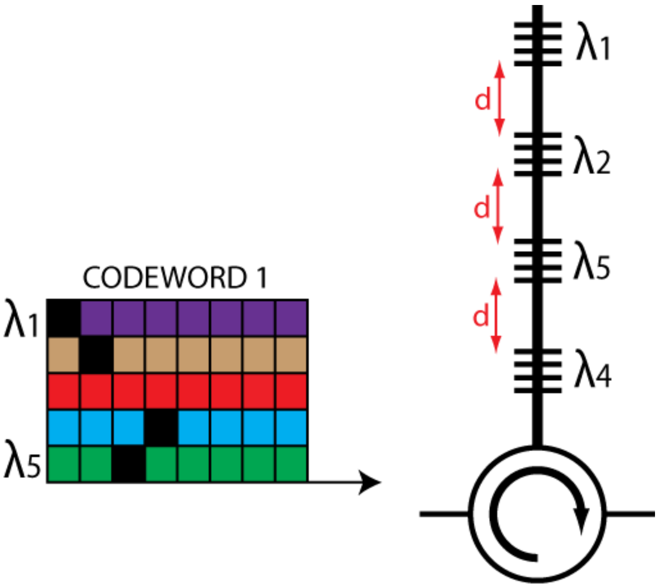


Figure 15: Generation of codeword using fibre bragg gratings

Experimental Setup Description

The following figure shows the proof-of-concept prototype. The system comprises five continuous wave lasers with central wavelengths separated by 200 GHz (1548.20 to 1554.50 nm). The pulses are obtained with a Mach-Zehnder modulator after which the light is divided in a 3:1 coupler. The codeword for each user is generated by a FBG array similar to the one described in the previous section. After that, another 3:1 coupler is used to add the three users. The transmission medium is a 40 km Single Mode Fibre (SMF) followed by a 5 km Dispersion Compensation Fibre (DCF). The receiver module comprises a 30 GHz receiver and a trans-impedance amplifier. The 5-stage distributed transversal filter is intended to compensate for residual dispersion. The results are analysed with an optical oscilloscope.

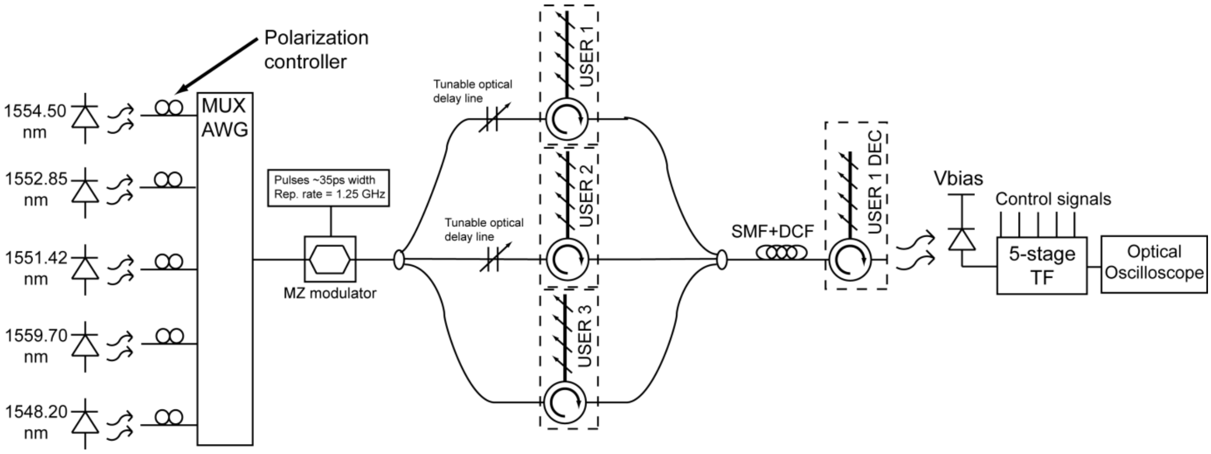
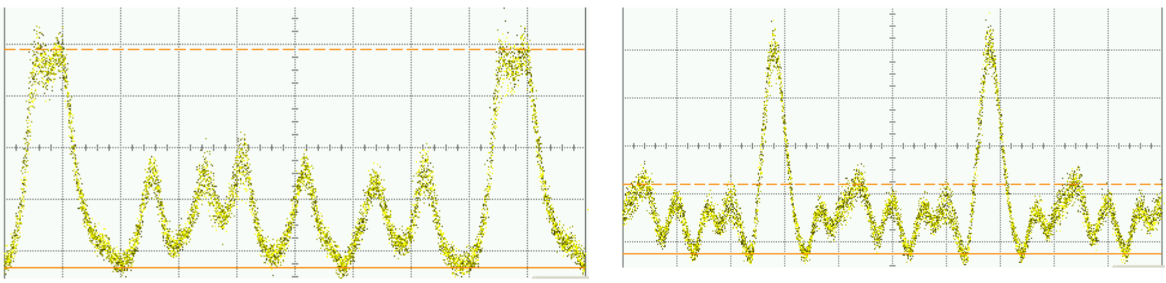


Figure 16: Experimental Set-up of wavelength time coding demonstration

Results

To quantitatively measure the system improvement, we introduce the parameter auto-correlation intensity peak to the maximum cross-correlation level ratio (P/C ratio). The following figures show the oscilloscope outputs; the first image first the case where no compensation is applied and, in the second, the coefficients of the transversal filter are tuned to maximize the P/C ratio. In this scenario an improvement in the P/C ratio from 2.03 to 3.02 is achieved.



Time: 100 ps/div; P/C ratio = 2.03 Time: 200 ps/div; P/C ratio = 3.02

Figure 17: Experimental Results

5.2.5 References

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5.3 Joint Activity – Millimeter Wave Radio Over Fibre

5.3.1 Introduction

Five joint activities looking at mm-wave RoF technologies have been performed between University of Essex, UPVLC, Instituto de Telecommunicacoes, Politecnico di Torino, UC3M and DUE as part of the BONE WP13. These are listed as follows:

5.3.2 Outcome of the joint research activity:

Some measurements and models previously described have been developed and a paper is under development.

5.3.3 Future Activities

UPVLC will keep the work in the framework of the BONE network in the RoF area: An extension of the UWB-WiMAX RoF coexistence work will be performed in 2009 considered a FTTH scenario where the signal is optically feed to a complex radio office environment where UWB and WiMAX are operating in presence of other wireless technologies. IR-UWB optical generation techniques for ultra-high speed transmission will be investigated in 2009.

UC3M and DUE will perform new experiments on GI-POF fibers at 850nm.

5.3.4 UPVLC collaboration with University of Essex (UPVLC-UoE) on RoF UWB evaluation on external/direct and SSMF/MMF simulation evaluation

The performance of a UWB-on-fibre point-to-point link is analyzed in this collaboration for two electrical/optical conversion scenarios (external Mach-Zehnder or direct VCSEL modulation) and the two optical media (SSMF or MMF) in order to provide a quantitative example.

Table 5. UWB radio-over-fibre parameter for analysis

PIN params.	*value*	*MZ-EOM params.*	*value*
Responsitivity	0.7 A/W	E/O BW	20 GHz
Thermal noise	10 pA/√Hz	V_π DC	5 V
VCSEL params.	*value*	V_π RF	5.5 V
Core radius	2×10^{-6} m	Insertion losses	6 dB
Active region thickness	0.3×10^{-6} m	Thermal freq shift	-10^{-12} df/dJ
Confinement factor	0.03	Extinction ratio	35 dB

The target is to evaluate the maximum reach transmitting UWB radio on fibre at the maximum bitrate defined in the ECMA-368 standard, i.e. 480 Mbit/s.The UWB signal is centered at 6 GHz and comprises 128 carriers QPSK modulated, at 4.125 MHz carrier spacing, with an overall bandwidth of 528 MHz. The optical link configuration is shown inFigure 18. The MZ-EOM employed is a chirp-free Lithium-Niobate x-cut modulator. The modulation index has been optimized in every configuration analyzed to maximize UWB reach. Table 5 summarizes the device parameters employed in the analysis.

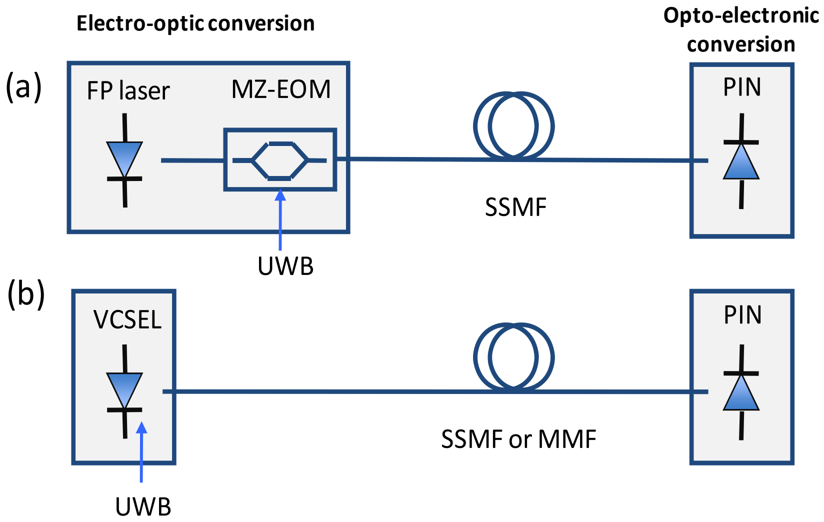

Figure 18. UWB radio-over-fibre optical link analysis configuration: (a) Mach-Zehnder external modulation. (B) VCSEL direct modulation

The performance of UWB transmission is given by the error vector magnitude (EVM). EVM limit is translated to a signal to noise ratio of 20 dB. Figure 19 shows the SNR obtained when transmitting the UWB signal on SSMF/MMF optical media for the direct modulation and external modulation cases.

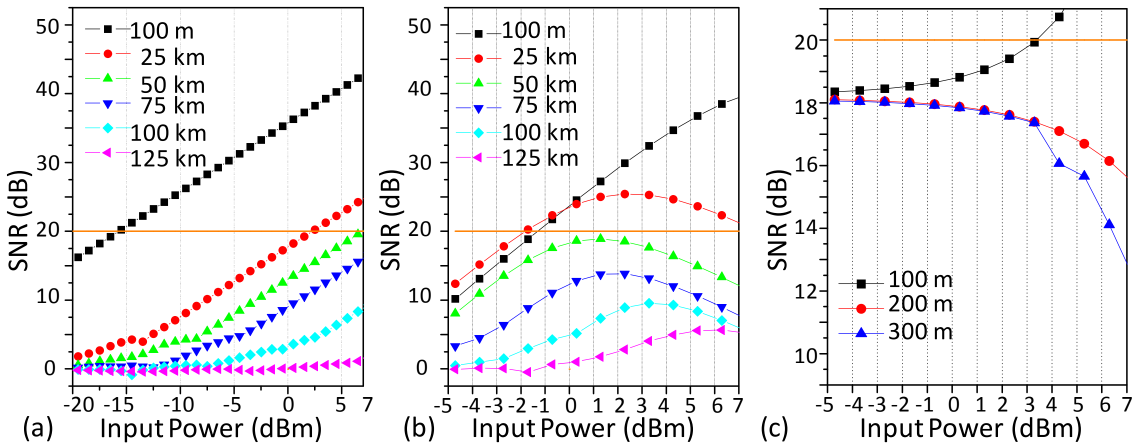

Figure 19. UWB on fibre performance for (a) External modulation on SSMF, (b) Direct modulation on SSMF, and (c) direct modulation on MMF. Horizontal lines indicate the SNR threshold

The results shown in Figure 19 indicate that external modulation on SSMF give a maximum reach of 50 km, with 7 dBm optical power launched in the fibre. If MMF is employed as optical transmission media, the maximum reach is 100 m for 3 dBm optical power.

The results of this collaboration have been reported in the following paper:

- Roberto Llorente, Manoj P. Thakur, Maria Morant, Stuart D. Walker, Javier Marti, “Performance comparison of radio-over-fibre UWB distribution in SSMF and MMF optical media”, ECOC 2008, Belgium, September 2008.

5.3.5 UPVLC collaboration with Instituto de Telecomunicacoes (UPVLC-IT) on IR-UWB and OFDM-UWB comparison in Radio-over-Fibre applications

It is the interest of UPVLC and IT to evaluate which of the two mainstreams UWB technologies, OFDM-UWB and IR-UWB exhibits better performance when distributed through a RoF link. Experiments and simulation work have been done at UPVLC labs in collaboration with IT addressing UWB distribution on a point-to-point architecture in-house and also in fibre-to-the-home links.

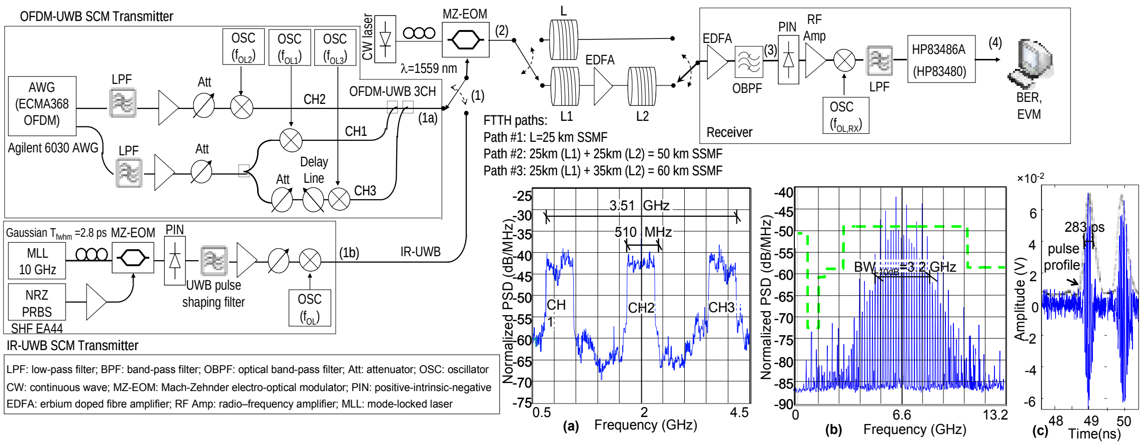

Figure 20. UWB-on-FTTH demonstration set-up. Both IR-UWB and OFDM-UWB exhibit bit-rate of 1.25 Gbit/s. Three FTTH paths with reach from 25 km to 60 km considered. The receiver emulates the UWB channel extractor at access node. Insets: (a) OFDM-UWB electrical spectrum at point (1a) of transmitter; (b) IR-UWB RF spectrum, and (c) Electrical IR-UWB signal and pulse profile at point (1b)

The UWB signal degradation due to the fibre transmission impairments experienced in the FTTH link has been experimentally analysed.. The compared performance of IR-UWB and OFDM-UWB in UWB-on-fibre has been investigated with the set-up shown in Figure 20 This figure shows a central node (head-end) which generates UWB signals transporting uncompressed A/V HD content. These signals are distributed through the FTTH network to a number of subscribers. At the subscriber premises, the received UWB signals are photo-detected, filtered, amplified and radiated to broadcast the HD content to an UWB-enabled TV-set or computer. This technique benefits from the high bit-rate capabilities of UWB, supporting bitrates up to 1 Gbit/s at a few meters range.

The BER achieved by OFDM-UWB and IR-UWB is shown in Figure 21 for all the fibre paths between 25 km and 60 km and back-to-back versus the received power. These experimental results demonstrate the feasible distribution of 1.25 Gbit/s UWB signals achieving BER<10^{-9} operation at 50 km with both IR-UWB and OFDM-UWB implementations. Figure 21 shows that the IR-UWB technique exhibits performance degradation in comparison with OFDM-UWB. This is due to the different modulation schemes. OFDM-UWB channels are generated independently and up-converted to generate a SCM group. The IR-UWB signal does not follow this channelization, and to provide a bit rate of 1.25 Gbit/s, a single IR-UWB signal with 3.2 GHz bandwidth @-10 dB was generated. IR-UWB suffers from the non-perfect operation of up- and down-converting mixers over such wide bandwidth. Figure 21 also shows that OFDM-UWB degrades quickly with fibre length due to the carrier suppression effect originated from the SSMF chromatic dispersion.

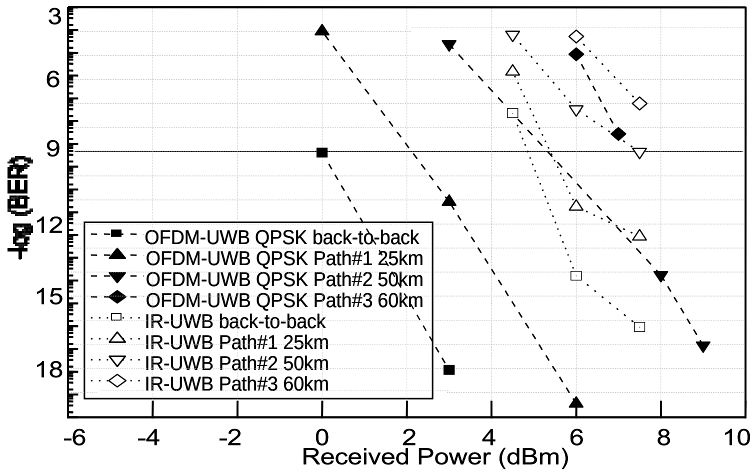

Figure 21. Comparison of UWB implementations at 1.25 Gbit/s for the three FTTH SSMF paths. Dotted lines: OFDM-UWB three channels SCM group (QPSK per carrier); dashed lines: IR-UWB signal. OFDM-UWB signal achieves better performance at same received power for all FTTH paths

In conclusion, OFDM-UWB distribution in SSMF exhibit better performance than IR-UWB for the same launched power and bitrate. Successful UWB transmission have been demonstrated at distances up to 50 km in 3 UWB channels with QPSK per OFDM carrier configurations, and up to 70 km in 5 UWB channel distribution with a BPSK per OFDM carrier configuration

<u>The results of this collaboration have been reported in the following papers:</u>

- T. Alves, M. Morant, R. Llorente, A. Cartaxo, J. Marti, “Experimental demonstration of 1.56 Gbit/s OFDM-UWB distribution over 100 km of standard-fibre in FTTH networks”, 2008 Opto-Electronics and Communications Conference (OECC) and the Australian Conference on Optical Fibre Technology (ACOFT), Sydney, Australia, July 2008, paper TuB-3.
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5.3.6 Collaboration with Politecnico di Torino (PdT–UPVLC) in WiMAX – UWB coexistence in integrated wireless/optical networks

The work done addressed the coexistence of WiMAX and UWB, coexisting in the 3.5 GHz band, in fibre transmission and in the radio channel. It is the interest of UPVLC to study experimentally the feasibility of distribution WiMAX and UWB in coexistence, including the radio path problem of UWB radio with narrowband systems such as UMTS, GSM, GPS, etc.

WiMAX and UWB coexistence is a key issue in the indoor scenarios. WiMAX RoF applications target to improve the coverage of broadband services in distributed antenna systems (DAS) applications, where several remote antenna units are distributed around the service area. Typical transmission media in in-house installation is multi-mode fibre (MMF). Standard multiband-orthogonal frequency division multiplex (MB-OFDM) UWB, as defined in ECMA-368 and IEEE 802.16d WiMAX have been employed in this experimental analysis.

Figure 22 shows the experimental setup to evaluate the performance of MB OFDM UWB and WiMAX RoF coexistence, including the radio transmission path. This experimental work covers the signal generation, optical modulation, RoF transmission and also Radio transmission. WiMAX is generated according IEEE 802.16d standard using a 4438C Agilent vector signal generator. The WiMAX signal is centred at 3.5 GHz and comprises 256 carriers 64QAM modulated with 15.625 KHz carrier separation, giving an overall bandwidth of 3.5 MHz. On the other hand a three-channel MB-OFDM UWB signal is generated by a DV9110 UWB transceiver from Wisair, following ECMA-368 standard.

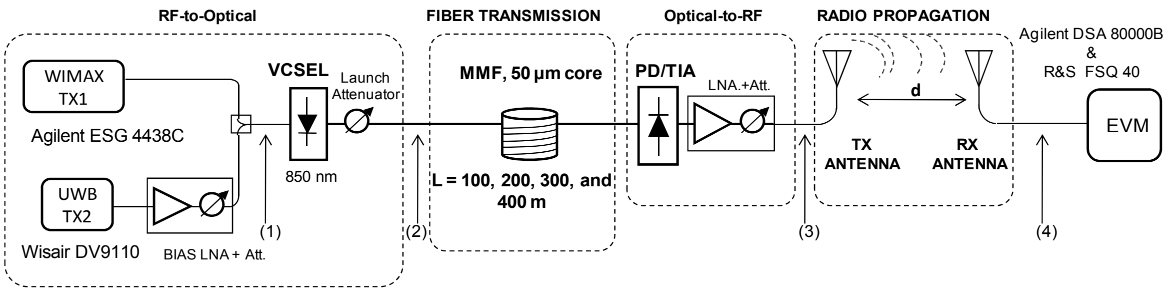

Figure 22. Experimental setup for combined performance analysis of UWB and WiMAX-on-fibre and further UWB-WiMAX wireless radio

The results shown in Figure 23 indicate that at low input powers the noise is the main cause of EVM degradation, at higher values VCSEL distortion is produced. At -9.12 dBm launched optical power it can be observed that fibre dispersion does not introduce serious degradation for the explored lengths at WiMAX frequency. In most cases, the measured EVM is below the 3.1 % limit imposed by current standards when 64 QAM modulation is employed.

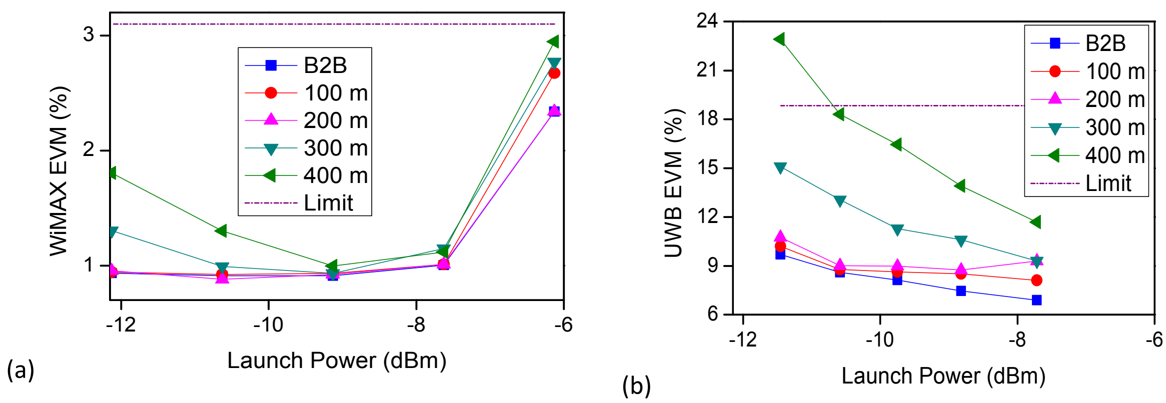

Figure 23. (a) WiMAX-over-fibre stand-alone transmission. (b) UWB-over-fibre stand-alone transmission

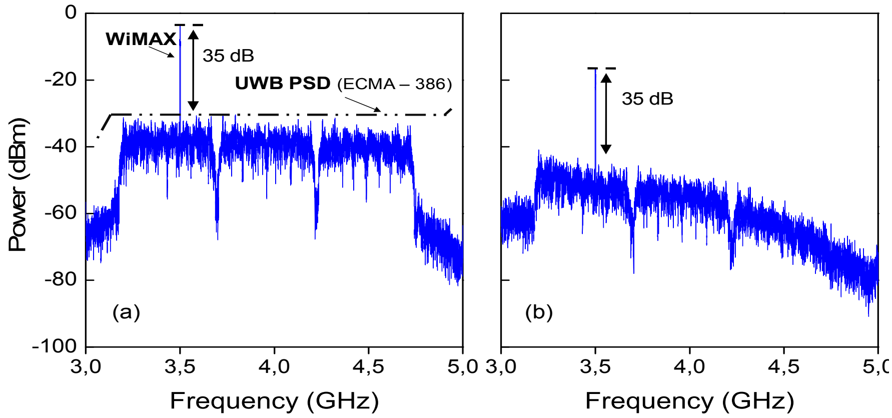

Figure 24. UWB and WIMAX coexistence: RF spectrum (a) before VCSEL, (b) after 400 m of MMF transmission (RBW: 181.068 kHz)

Figure 24 also shows both WiMAX and UWB transmission masks in current regulation. It can be observed that both wireless signals meet their regulation mask relatively. The exact spectral power levels are obtained adjusting the amplifier in the optical-RF conversion block shown in Figure 22.

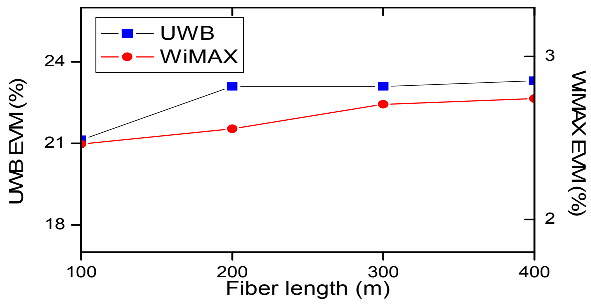

Figure 25. WiMAX and UWB in coexistence for different MMF lengths

The measurements shown in Figure 25 demonstrate that simultaneous transmission of UWB and WiMAX in RoF introduces an important degradation: MB-OFDM EVM increase from 11% with single transmission (Figure 23) to 21% when 100 m simultaneous transmission is also performed (Figure 25). WiMAX transmission is also degraded as EVM drops from 1.17 % to 2.46 %. This is due to MMF modal dispersion and limited bandwidth (3 GHz) of the receiver.

An extension of this work will be performed in 2009, considered a FTTH scenario where the signal is optically feed to a complex radio office environment where UWB and WiMAX are operating in presence of other wireless technologies, such as Wi-Fi and Bluetooth. The potential interference in this scenario comes from transmitters located inside the area under analysis at close distances.

The results of this work have been reported in the following papers:

- R. Alemany, J. Pérez, R. Llorente, V. Polo and J. Martí, "Coexistence of WiMAX 802.16d and MB-OFDM UWB in Radio over Multi-mode Fiber Indoor Systems", 2008 IEEE Topical Meeting on Microwave Photonics, MWP2008, Gold Coast, Australia, 30 Sept-3 Oct 2008.

5.3.7 Collaboration with Instituto de Telecomunicacoes (IT–UPVLC) in Spectrum sensing on hybrid wireless/optical access networks

Collaboration between UPVLC and IT is ongoing addressing the spectral monitoring of UWB signals for hybrid fibre/wireless access networks. UWB monitoring is typically performed employing bandwidth-limited filters and down-converters. The technique requires filter sweeping and frequency down-conversion, which are time-consuming when covering the whole UWB frequency band from 3.1 to 10.6 GHz. Photonic ADC (Ph-ADC) techniques can be used covering the whole UWB band. In this case, the real-time UWB spectrum measurement enables the simultaneous measurements of UWB emissions after FTTH transmission.

This is an ongoing work by the time of writing this deliverable (November-December 2008) with preliminary results reported in the following paper:

1. Marta Beltran, Roberto Llorente, and Javier Marti, "Photonic ADC technology for spectrum measurement and wireless coexistence", Walter UWB workshop, Ispra, Italia, 1-3 July 2008.

5.3.8 Temperature Dependency of Multimode Fibre Transfer Function on RoF systems

UC3M, DUE and UPVLC's contribution to RoF systems is focused on developing a model describing RoF propagation in MMF based on modal analysis and characterizing temperature dependence on those systems.

Radio-over-Fibre (RoF) technology entails the use of optical fibre links to distribute RF signals from a central location (headend) to Remote Antenna Units (RAUs). In narrowband communication systems and WLANs, RF signal processing functions such as frequency up-conversion, carrier modulation, and multiplexing, are performed at the base station and immediately fed into the antenna. RoF makes it possible to centralise the RF signal processing functions in one shared location (headend), and then to use optical fibre, which offers low signal loss (0.3 dB/km for 1550 nm, and 0.5 dB/km for 1310 nm wavelengths) to distribute the RF signals to the RAUs which are simplified significantly.

RoF techniques are going to be utilized for WLAN, UMTS or Bluetooth communications, but it can be expected that this technique will especially be very useful for the distribution of the upcoming UWB (ultra wide band) technology, particularly in combination with RFID techniques. At the transmitter side, directly-modulated lasers with bandwidths in excess of 10GHz are now readily available, its low cost and simplicity allow the direct modulation system architecture to be advantageous in many applications [37]. In other situations external modulation is preferred.

Concerning the optical fiber type, in shorter distance MMF can be used, cutting cost and with proper launching conditions broadband response can be obtained. But it is important to asses that the temperature dependence effect is not relevant in any case.

For describing RoF propagation in MMF different models have been developed based on modal propagation as in [38] by Gasulla et al. and on [39] by Yabre. We have developed those models and specially using model [37], on the schematic system shown on Figure 26, to validate temperature dependences. Those results can be seen on Figure 27

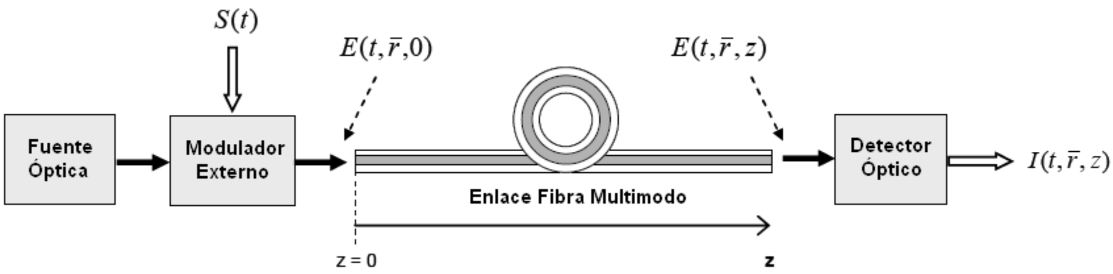

Figure 26:RoF MMF link. L=3Km, λ=1300nm

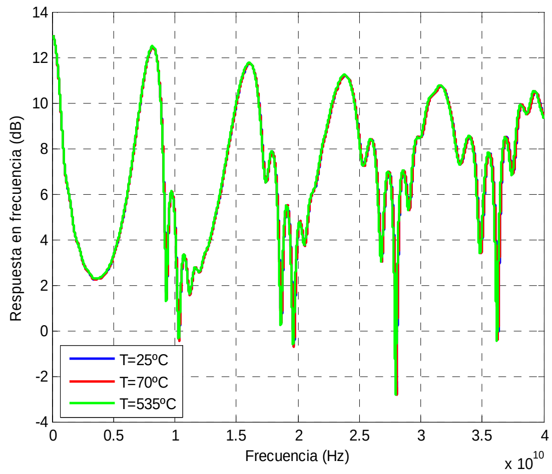

Figure 27: Simulated MMF transfer function. L=3Km, λ=1300nm

On the other hand, some measurements have been taken using the set-up described in Figure 28 MMF link has 3050m long and external modulation using a MZI interferometer is used for 1300nm carrier modulation.

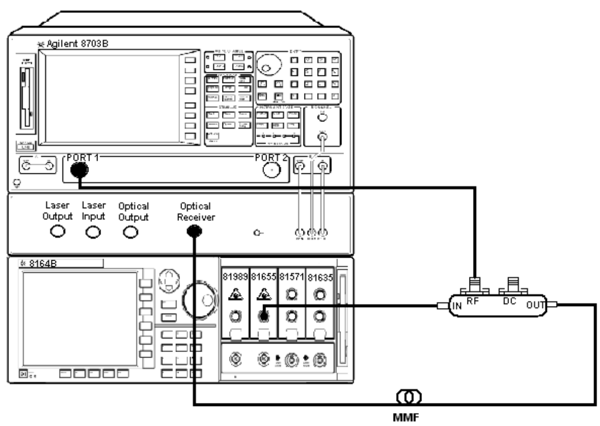

Figure 28: Experimental set-up for characterizing RoF transfer function

Preliminary results show there is no temperature dependence when considering medium values but when analysing each specific measurement it can be seen there are transfer function fluctuations which can be as high as 20 dB in the temperature range from 25ºC to 70ºC. This temperature changes has been locally applied only to the optical fiber. Some measurements on temperature dependence of Error Vector Magnitude (EVM) in RoMMF links with directly modulated laser is reported on [40].

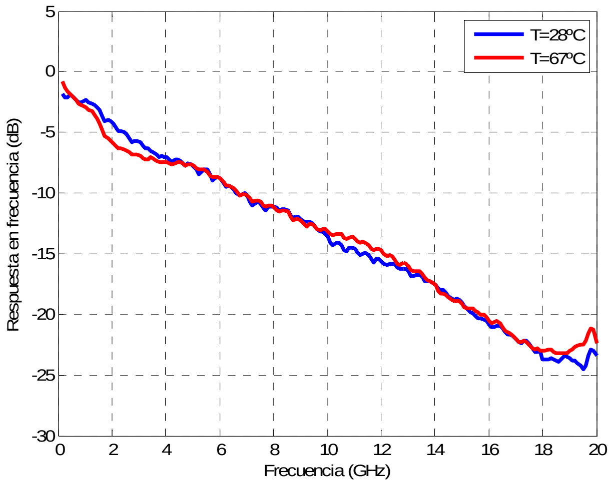

Figure 29 : ***Average of 16 MMF transfer function measurements. L=3Km, λ=1300nm***

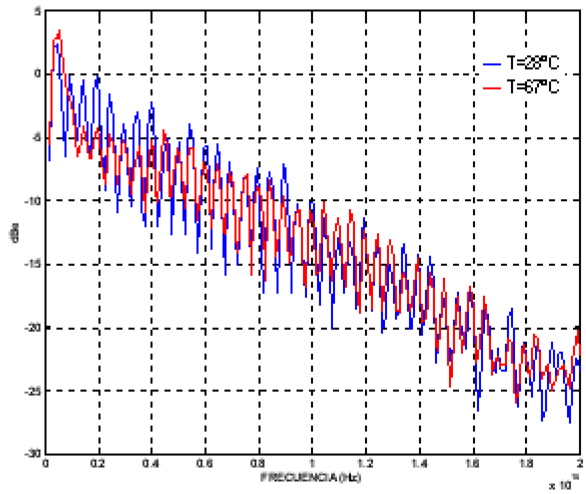

Figure 30:***Instantaneous MMF transfer function at 28 ºC and 67ºC temperatures. L=3Km, λ=1300nm***

5.3.9 References

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38 I. Gasulla and J. Capmany. "Transfer function of multimode fiber links using an electric field propagation model: Application to Radio over Fibre Systems". Optics Express, Vol. 14, No.20, pp. 9051 – 9070. 2 de Oct 2006

39 G. Yabre. "Comprehensive Theory of Dispersion in Graded-Index Optical Fibers". J. Ligthwave Technology, Vol. 18, Nº 2, pp 166 – 177. Febr 2000

40 P. Hartmann, Xin Qian, A. Wonfor, R. V. Penty and I. H White, "1-20 GHz Directly Modulated Radio over MMF Link," proc. Microwave Photonics 2005, pp. 95-98, Seoul, South Korea.

5.4 Joint Activity 5 – QoS in PONs

5.4.1 Introduction

PON will be one of the key points of improvement of Internet with optical technology. However, it has to be pointed that, even if the capacity of PON is much wider with respect to other access techniques based either on copper or on radio, in future application also current PON could be congested by the traffic required by the users. In fact Home streaming at 100 Mb/s could be necessary for services based on High Definition (HD) TV, Digital cinema and so on. Due to this fact, we believe that QoS procedure have to be introduced also at PON level, and in particular traffic priorities can be introduced at edge level following the indications where a QoS management method based on VPLS was demonstrated to guarantee the transmission of HD TV streaming in xDSL accesses. In this section we show how to extend such a method to EPON networks.

5.4.2 Proposed Future Activities

In 2009 the investigation on QoS in PON networks will consider EPON, GPON and WDM networks. First of all a comparison will be carried out about on the treatment of QoS in EPON and GPON with respect to next generation services with particular effort for IPTV and High Definition TV; in particular studies will be made on the methods to extend tagging techniques up to the ONU, to achieve an end-to-end QoS. In this context we will see how Carrier Ethernet techniques can add advantages in the management of QoS and therefore the role of Q in Q, MAC in MAC and PBT will be investigated. This investigation will be completed with the introduction of the WDM dimension.

According to the experimental facilities that are available, this JA will try to demonstrate some principles of these QoS techniques in the experimental test bed described later in 4.4.3.

To improve the QoS in upstream direction in PON this JA will try also to propose novelties in the dynamic bandwidth allocation schemes. In particular, studies will be made about new methods to manage and allocate, in an efficient way, the upstream bandwidth, with interest for:

- Algorithms to assign transmission slots to ONUs based on negotiated SLAs and dynamic information transmitted by the ONUs;
- Intra-ONU scheduling method that specifies how each ONU uses the allocated grants.

Current solutions as IPACT will be taken into account. In particular, new scheduling disciplines will be investigated to improve ONU’s bandwidth usage. Furthermore studies will be made about the integration between an Ethernet PON and OBS network. In this context, new scheduling algorithms and improvement to existing schemes will be proposed. This theoretical studies will achieved mainly by means of simulation tools as ns2.

5.4.3 End-to-End QoS improvement in EPON networks

We implemented a E-line VPLS between PE1 and PE4, and VLAN tagging from CE1 to PE1 and from PE4 to the OLT. Therefore a tunnel based on VPLS&VLAN tagging between Area 1 and the ONU2 is established permitting the QoS control with Gold class [??].

To test the impact of the network congestion, a traffic generator is included in the Test Bed for introducing background traffic of 1 Gb/s between PE4 and the OLT. We considered the downstream scenario and we sent a flux from PC1 to the user (ONU2) and we overloaded the link between PE4 and the OLT to see the impact of the traffic congestion on the services at the ONU output. In this way we take into consideration a scenario in which the ONUs require to download heavy traffics, that can induce a congestion between PE4 and the OLT with a consequent degradation manifested at the ONU output.

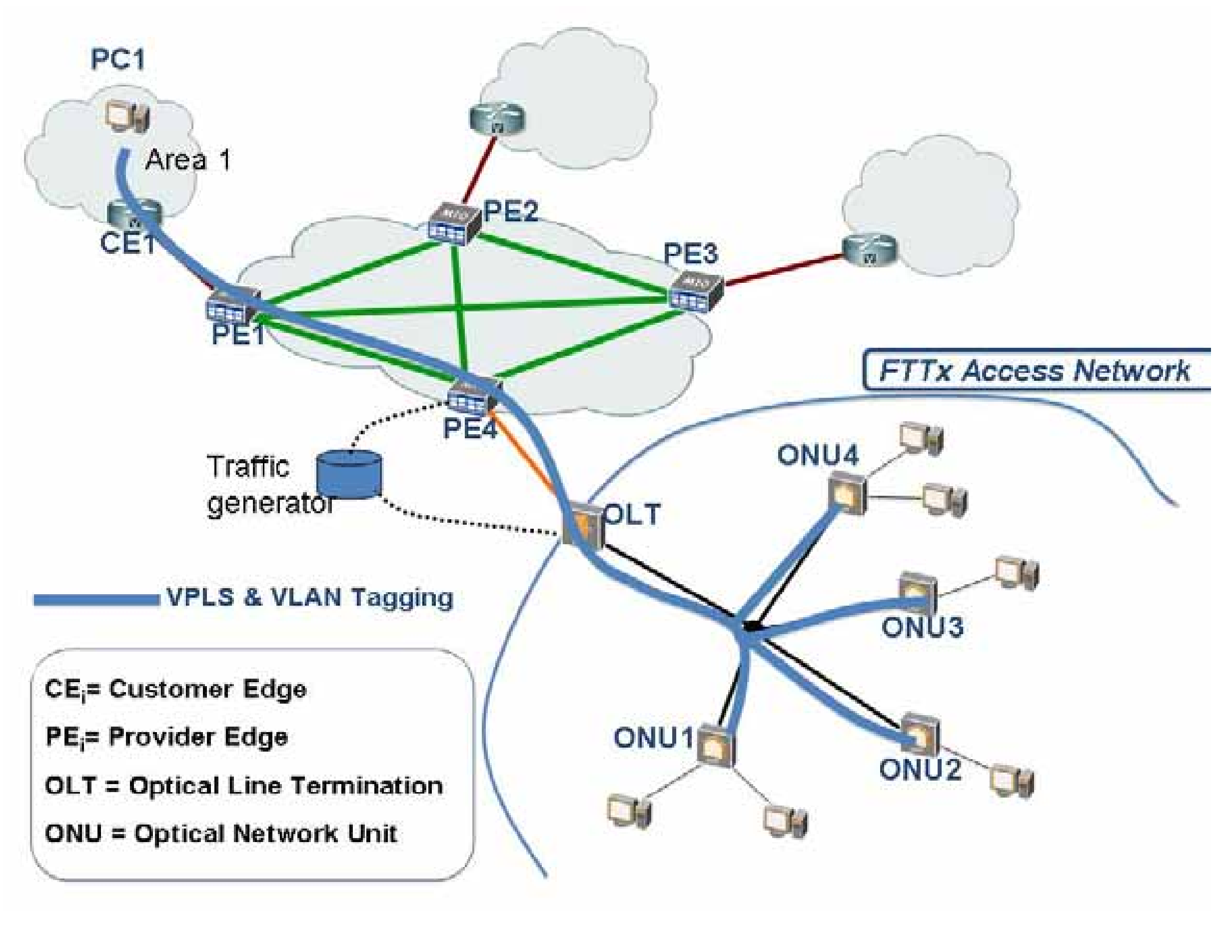


Figure 31: Test-Bed design. The routers, OLT and ONUs are optical fiber interconnected with GbE interfaces.

The advantages of our method are illustrated by the Figure 31 , that reports the effects of the congestion on throughput at the ONU2 output for 20 Mbits/s and 40 Mbits/s fluxes coming from PC1, both in the presence (QoS) and in the absence (no QoS) of VPLS&VLAN tagging Gold instance (the absence corresponds to best efforts); we indicate “congestion” the period when we introduced the background traffic of 1 Gbit/s between PE4 and the OLT. Figure 31 shows that by means of VPLS&VLAN tagging Gold we can guarantee QoS since no throughput reduction is manifested when a congestion event occurs.

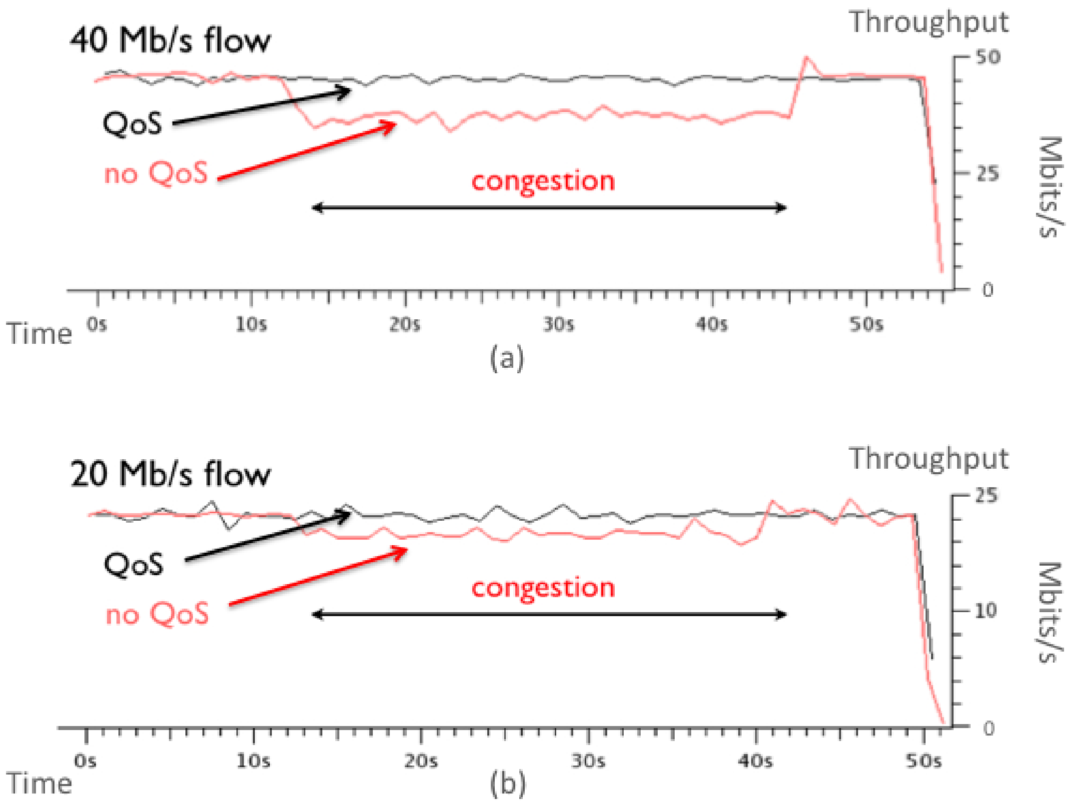


Figure 32: Throughput for 40 and 20 Mb/s fluxes at the ONU2 output.

The QoS improvement by means of VLAN tagging-VPLS Gold is more relevant for the higher bit rate and this confirms the importance of the QoS management for next generation services.

5.4.4 Performance of a Multiservice Ethernet PON

In our work, we focused on a simulation based analysis, using ns-2, of the QoS delivered to upstream traffic in EPONs, and on the efficiency of the allocation process. Our preliminary findings led us to design a simple priority based upstream traffic management policy [41]. Many mechanisms which allow a dynamic allocation of transmission opportunities have been proposed [42,43]. Those mechanisms assume that the traffic is IP based, and may be multiservice with various QoS requirements. The basic concept of a dynamic allocation of transmission opportunities relies on three features:

- a signalling mechanism that allows an ONU to describe its needs and the OLT to allocate transmission opportunities;
- a Dynamic Bandwidth Allocation (DBA) method implemented at the OLT side that computes transmission opportunities offered to each ONU based on negotiated SLAs and dynamic information transmitted by the ONUs;
- an intra-ONU scheduling that specifies how each ONU uses the allocated grants.

The IEEE 802.3ah [44] standard has specified a Multi-Point Control Protocol (MPCP) for MAC layer of EPON system. MPCP is commonly used, and solves point 1. On the other hand, there is no current agreement regarding points 2 and 3. Although some early proposals such as IPACT [45] are currently considered as benchmarks for other proposals, many issues regarding a multiservice support by EPONs of broadband traffic in the upstream direction are still open. We have considered the following traffic types.

Table 6: Traffic types

Classes	Characteristics	Requirements
T_0	Real-time CB	low delay and jitter, limited loss rate, guaranteed bandwidth
T_1	Data CB	limited delay and jitter, limited loss rate, guaranteed bandwidth
T_2	Best Effort	none

Basically, we assume that there are 2 Committed Bandwidth (CB) classes and a single Best Effort (BE) class. A major difference between CB and BE traffic is that CB traffic is characterized by a traffic profile specified in a SLA and expects its QoS requirements to be fulfilled as long as the offered traffic complies with the negotiated traffic profiles. On the other hand, there are no BE traffic profiles and BE traffic cannot request QoS commitments.

The DBA policy called DBA-TCM (Traffic Conformance Mechanism) has been proposed in [41]. It has the following characteristics:

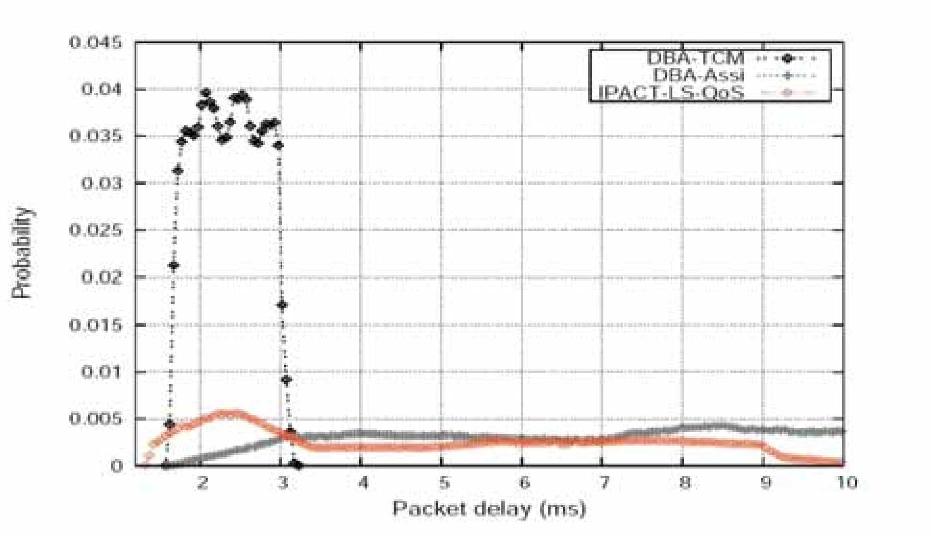
- it allows variable length polling cycles while enforcing an upper bound on the maximum polling cycle length T^{max}.
- it is priority based at the inter-ONU level, i.e. the DBA algorithm serves each class successively and attempts to satisfy all the demands from one class before allocating transmission opportunities to a lower class.
- it is priority based at the intra-ONU level, i.e. each ONU applies exactly the allocated per-class grants and frames that arrived after the previous request cannot be served within the current cycle.
- it enforces ONUs to comply with their negotiated SLAs by checking conformance of upstream Committed Bandwidth (CB) traffic: the OLT filters the demands and takes account of a virtual policing scheme when computing the amounts of grants to be sent to the ONUs.

Upstream traffic handling in PON

In this section, we first show that both the centralized computation of transmission opportunities and the intra-ONU scheduling policy should be QoS sensitive. We then analyze the efficiency of DBA-TCM, showing that BE traffic can fill the capacity of the upstream traffic while the committed QoS is delivered to CB traffic. Lastly, the impact of the polling procedure on delivered QoS is addressed.

5.4.5 Class Sensitiveness Issues

The proposed DBA-TCM is class sensitive: it serves the demands in priority order. The following scenario justifies this design choice. In this scenario, 4 ONUs send only T_0 traffic



(Average rate R_a=30 Mbps), 12 others ONUs send T_2 traffic (greedy FTP sources).

Figure 33: Impact of a class sensitive DBA on QoS for class T_0

Fig.1 represents the T_0 packet delay distribution for 3 DBAs: IPACT-LS-QoS[46], Assi[47] and our proposed DBA-TCM. It shows that the delay for DBA-TCM presents centralization with all data points condensed before 3.0 ms whereas the two others present a heavier tail. In other words, only DBA-TCM provides a very short delay for T_0 traffic, while both IPACT-LS QoS and Assi distributions present very long tails. This is easily explained: IPACT-LS QoS applies an Inter-Leaved Polling scheme in which the OLT does not have an overview of all demands from the ONUs when computing transmission opportunities. Therefore, high-priority traffic is handled by the OLT in the same manner than BE traffic, which results in a serious degradation of the QoS delivering to T_0 traffic as illustrated in Figure 33. The DBA scheme proposed by Assi experiences also a T_0 traffic QoS degradation. Indeed, in this scheme, the OLT still only focuses on how to satisfy bandwidth requests from different ONUs by fairly distributing the excessive bandwidth among highly loaded ONUs and does not provide a better service to high priority traffic.

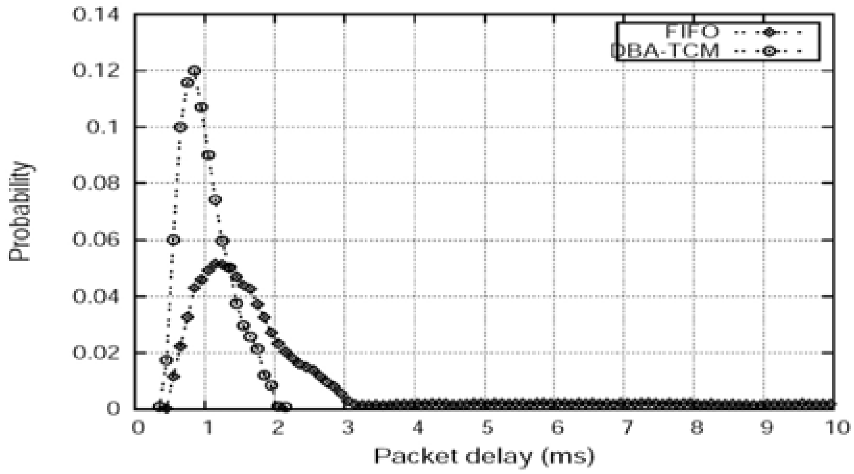


Figure 34:Impact of FIFO intra-ONU on QoS for class T_0

Taking QoS into account at the intra-ONU scheduling level is also necessary as we show now. In this scenario corresponding to Figure 34, we assume that all ONUs generate T_0 traffic (R_a=30 Mbps) plus some T_2 traffic (a Pareto source with a 5 Mbps mean rate). In the first case, the intra-ONU scheduling policy is pure FIFO, serving the packets in the order of their arrivals, whereas in the second case, the intra-ONU scheduling policy is not FIFO, but serves each traffic class as specified in the GATE messages. It may then happen that T_0 overtakes T_2 traffic. Figure 34 represents the T_0 packet delay distribution in the two cases. It clearly shows the impact of the FIFO mechanism on the QoS delivered to CB traffic: the peak is much flatter and the tail heavier. Obviously, the presence of T_2 traffic, even in small proportion, degrades the QoS delivered to the T_0 traffic.

These preliminary studies justify the design choice of treat BE and CB traffic separately both for inter-ONU scheduling and intra-ONU scheduling.

5.4.6 Analysis of upstream channel utilization

Since DBA-TCM does not limit the transmission opportunities to individual ONUs as IPACT-LS does, it can fill the upstream channel as long as enough traffic is offered by the ONUs.

This is shown in a scenario in which ONUs vary their respective activity levels: T_0 sources (R_a=18.75 Mbps) in each of 16 ONUs are active only from 0.0 s to 6.0 s and from 9.0 s to 12.0 s. Each ONU also starts a FTP session at 3.0 s. Upstream traffic is controlled by DBA-TCM.

Figure 35 represents the achieved utilization versus time. In the first 3.0 s, only T_0 traffic is carried and the system is under-loaded since the offered traffic corresponds roughly to 30% the capacity of the system. When the FTP sources are activated, the upstream channel is almost full, since FTP traffic grabs all available bandwidth (the channel is not completely full, due to the guard time overhead). Between 3.0 s and 6.0 s, the capacity used by T_0 traffic is unchanged while FTP grabs more resources between 6.0 s and 9.0 s when all T_0 sources are idle. The main point is that, as long as T_0 traffic is sent, it receives the expected throughput, whether or not FTP sources are activated. These results clearly demonstrate the efficiency of DBA-TCM in terms of ensuring high upstream channel utilization while delivering the QoS commitments to CB traffic.

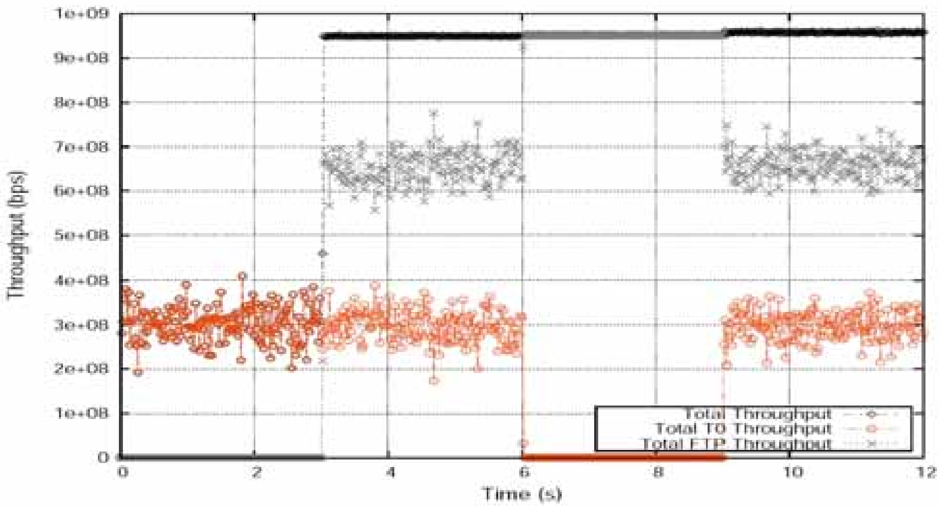


Figure 35: Upstream channel utilization using DBA-TCM

5.4.7 Impact of polling on delivered QoS

All DBA policies implement mechanisms to limit the latency of the system at high load. Indeed, it may happen that the total offered traffic, over a given period of time, exceeds the capacity offered by the PON to upstream traffic. In order to avoid a global degradation of the performance, the DBA has to ensure isolation between ONUs, i.e. offer a good latency to ONUs that do not send excess traffic. Since upstream traffic management is based on polling, the polling cycle, which in EPON is variable, should be upper-bounded.

In IPACT, as described in [46], no ONU can receive more than a given amount of resources per cycle. This automatically enforces a maximum cycle time.

As explained above, DBA-TCM also enforces an upper bound T^{max} on the cycle time. The difference with the approach in [46] is that the limit T^{max} is enforced globally and not on a per ONU basis. This is made possible by the global computation and allocation process performed by the OLT for each cycle. Let us now assess the impact of T^{max} on the latency offered to upstream traffic.

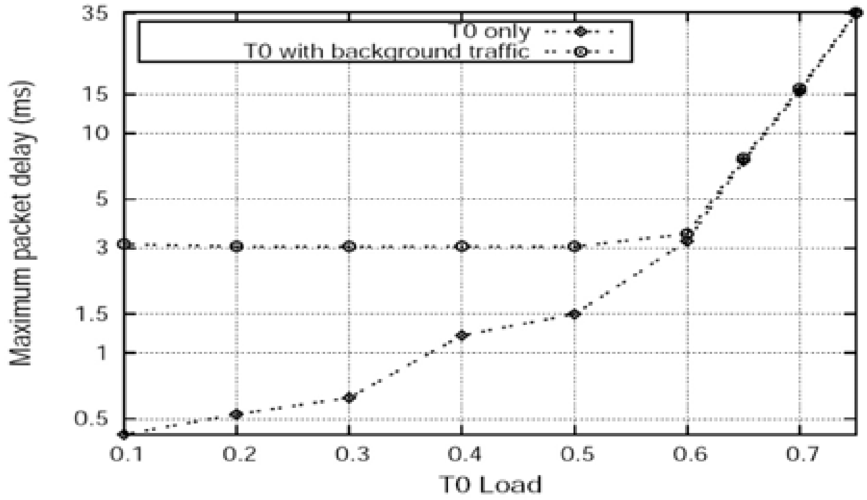


Figure 36: Impact of total T_0 load on QoS for class T_0

Two scenarios are compared. In both scenarios, ONUs send identical and balanced traffic. In the first scenario, only T_0 traffic is sent, and the total offered load varies between 100.0 Mbps and 800.0 Mbps. In the second scenario, we add an active FTP source in each ONU, which is transmitted as T_2 traffic. As in the previous cases, T^{max}=1.5 ms. Figure 36 shows an upper quantile of the T_0 packet delay versus total T_0 load in the system. This upper quantile represents, as usual, the maximum delay performance delivered to the T_0 traffic**.** We can see in Fig.4 that, as expected, the maximum T_0 packet delay increases with the offered T_0 load, and the latency is worse in the second scenario than in the first.

On the other hand, an unexpected behaviour is also observed : at low T_0 traffic load, the delay performance offered to T_0 traffic is significantly worse in the case when there is T_2 traffic, whereas when the T_0 traffic load is large enough, the delay performance offered to T_0 traffic appears not to be impacted by the presence of T_2 traffic. The limit between the two zones corresponds to a delay performance of 3 ms, i.e. twice the maximum cycle time. This (apparently) strange phenomenon is explained as follows: although T_2 traffic has less priority than T_0 traffic, it can be served as long as the cycle time due to T_0 traffic only is smaller than the maximum cycle time set to 1.5 ms. When T_2 is served, it increases the cycle time, and thus degrades the QoS offered to T_0 traffic. On the other hand, when the amount of T_0 traffic is large enough, some cycles reach the cycle time limit of 1.5 ms , with only T_0 traffic, and almost no T_2 traffic is served in those cycles. The maximum delay for T_0 traffic, when the cycle times are limited to 1.5 ms due to T_2 traffic, is then equal roughly to 3 ms since the worst case for a T_0 packet is to arrive at an ONU just after a REPORT was sent. In that case, it has to wait 2 cycles, i.e. 3 ms; this is observed on Figure 36.

In the study reported here, we have shown that DBA-TCM can be used to support a combined support of real time and interactive data services, while authorizing BE traffic to use remaining

bandwidth. To the authors' knowledge, DBA-TCM is the first proposed DBA that simultaneously offers a multiservice support and an efficient use of available resources by Best Effort traffic.

We have shown that the efficiency of DBA-TCM lies in the fact that resource allocation is performed by the OLT, which centralizes all ONUs' requests on a per cycle basis, and can then optimally distributed the available resources. This principle allows easily extending DBA-TCM e.g. by implementing some type of fair scheduling for different classes. This would allow e.g. ensuring a minimal support for Best Effort Traffic even when the amount of submitted Committed Bandwidth traffic is large. The centralized scheduling algorithm in DBA-TCM can thus be used to implement functions such as per class/per ONU conformance control and/or fair scheduling.

5.4.8 Experimental tests of Carrier Ethernet techniques

In 2008 the research group of University of Modena and Reggio Emilia (UNIMORE) has investigated the performance of optical access networks. In particular, Passive Optical Network based on the Ethernet framing has been considered in a typical tree-based topology.

Passive Optical Network (PON) is a promising technology to solve the last mile problem. Ethernet over PON (EPON) has been regulated by IEEE [48] and it has been the subject of first year activities.

In order to connect all users, not just business but also residential, point-to-point fibres from the central office should be installed. This approach comes to be too expensive since two transceivers per line should be employed. Thus, the point-to-multipoint (P2MP) topology is rather used where one single fibre is used both for down and upstream data communications. Following this, a concentrator is placed closed to a set of users with a passive coupler for connecting them. Several P2MP topologies are possible: tree, bus and ring. In this paper a bus topology will be considered. Fibre-to-the-curb (FTTC), fibre-to-the-building (FTTB) and fibre-to-the-home (FTTH) are possible ways to implement PON depending on where the fibre from the Optical Line Terminal (OLT), which is point-to-point connected to the network backbone, ends its run, at the curb, at the building or at home, respectively.

Data transmissions are full-duplex over the PON and they are on separate channels. Downstream is the flow from the core to the OLT and then to the ONUs (Optical Network Unit), close to the users, while upstream is the data flow from users to the core network. Since there is one communication channel only from OLT to the core, a user access control for upstream transmissions has to be implemented to avoid collisions.

The most common dimension in this scenario for contention resolution is the time, through Time Division Multiplexing. Downstream transmissions are broadcasted by OLT to all ONUs and data frames have a variable length up to 1500 bytes. These frames are broadcasted through a 1:N splitter, where N can be from 4 to 64 depending on the optical power available. Each frame has a label in the header which uniquely identifies the destination ONU. A ONU selectively reads incoming frames, forwarding the ones containing its identifier only. As mentioned above, upstream communications use TDM, where each ONU is assigned a time slot by OLT, in order to solve possible contentions, and two time slots are separated by a time guard interval. During each time slot more Ethernet frames may be transmitted. If N is the number of ONU, the set of N time slots is called cycle. When the ONU has the right to transmit, during its time slot, it is allowed to send all queued packets at top speed, for instance 1 Gbit/s.

As regards upstream transmissions, time division multiplexing can be used by assigning time slots either statically or dynamically. With a static or fixed bandwidth assignment the same time interval is given to all ONUs and it constant for all cycles. It often happens that this constant time slot is not fully used because, for instance, the remaining part of the slot is not enough to send the next packet, which has then to be delayed to the next time slot, consuming bandwidth. In order to increase the efficiency in bandwidth usage and to better meet the bursty nature of data traffic, an algorithm for a dynamic bandwidth assignment has to be employed. Generally speaking, such an algorithm cycle per cycle assigns a variable time slot to ONUs, short for ONUs which have fewer packets to send and longer for ONUs which are more heavily loaded. Therefore, ONUs have to inform OLT about their incoming load, e.g . the queue length, to allow for the OLT to determine the best strategy of time slot assignment.

The Interleaved Polling with Adaptive Cycle Time (IPACT) algorithm is widely known and some further results are here presented when different disciplines are adopted. This algorithm makes use of polling with OLT as master which periodically sends queries to ONUs and this generates a polling cycle. While the interested reader can go to [49] for a detailed description of IPACT, here we recall some possible scheduling disciplines which it can adopt. Let $u[i,j]$ be the transmission window assigned to ONU i in the j-th cycle and $r[i,j]$ be the requested window. Let also W_i^{max} be the maximum transmission window for the i-th ONU. For the static or fixed discipline, $u[i,j] = W_i^{max}$. For the discipline called Limited, $u[i,j]= min\{ r[i,j]; W_i^{max} \}$, which means that the requested transmission window is agreed if it does not exceed the maximum one. For the Constant Credit discipline, $u[i,j]= min\{ r[i,j]+const; W_i^{max} \}$. Here to the requested window a constant is added to take into account the estimated amount of data during the control exchanges between OLT and ONU.

We report now some numerical results on the IPACT performance for three scheduling disciplines, regarding a tree topology with 4 ONUs. They have been obtained by means of simulations performed using the ns-2 simulator vers. 2.31 [50], which is an object-oriented tool widely adopted to evaluate network performance. It is assumed a constant packet size equal to 1000 bytes and W_i^{max} = 50000 bytes. The optical link data rate between OLT and the core network is equal to 1 Gbit/s.

Figure 37 reports the average bandwidth usage for single ONU for the three strategies as a function of the offered load. It is interesting to note that for low and medium loads the fixed discipline is highly inefficient since time slots are not fully used. On the other hand, the limited discipline exploits the bandwidth at the best since the slot is always completely filled in. Figure 38 shows the bandwidth usage for the four ONUs for the Limited discipline as a function of time for medium traffic load values. It is worthwhile noting the presence of peaks above and below the value of 250 Mbit/s (the average data rate per ONU) which reflect the dynamic nature of the Limited discipline: every time a ONU has few data to send a larger time slot is assigned to more demanding ONUs.

Figure 39 reports the average queue length as a function of the average traffic load per cycle for the Limited discipline. This figure shows that for the current settings when the incoming data per cycle to a ONU exceed 49 Kbytes, the ONU cannot transmit it completely so that some data are queued and this a potential cause of instability for the queuing system.

In conclusion, the limited discipline has shown the best performance in terms of bandwidth usage. This investigation has revealed that a proper traffic analysis and possible access control has to be done to avoid the congestion in the ONUs, which may lead to instability or very high packet loss probabilities.

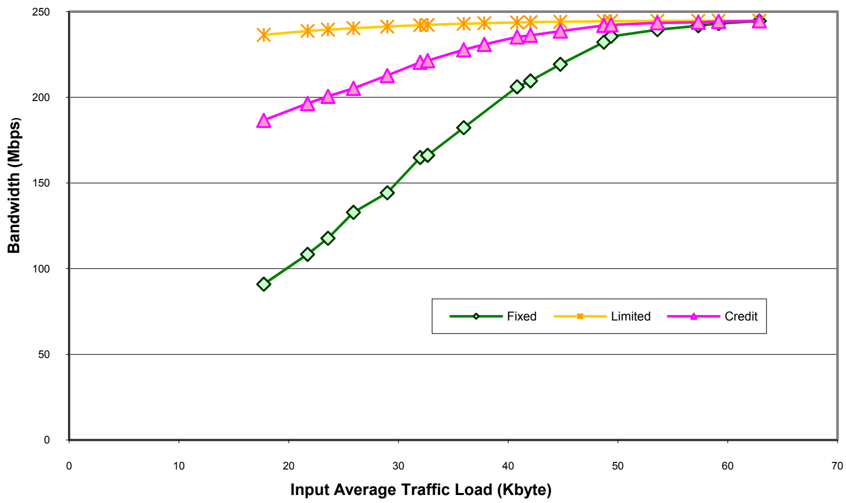


Figure 37: ***Average bandwidth usage for single ONU for the three discipline as a function of the offered load***

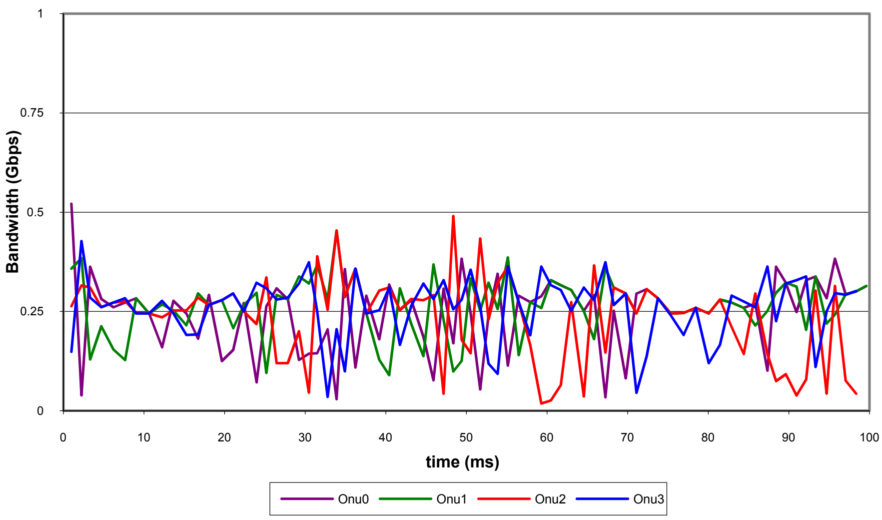


Figure 38: ***Bandwidth usage for the four ONUs for the Limited discipline as a function of time for medium traffic load values***

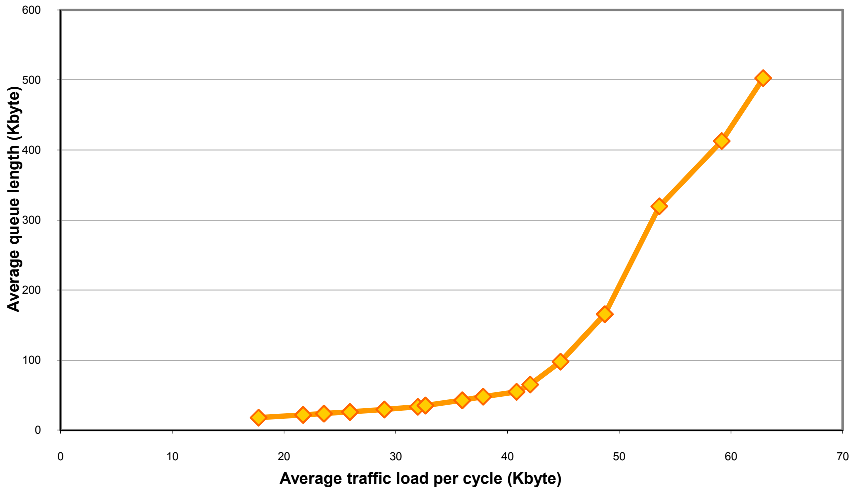


Figure 39: ***Average queue length as a function of the average traffic load per cycle for the Limited discipline.***

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5.5 Joint Activity – Techniques for Colourless ONUs

5.5.1 Introduction

The increasing demand on bandwidth and scalability in Passive Optical Networks (PONs) at limited extra cost imposes the use of cost efficient technologies in combination with the currently available resources. The use of wavelength division multiplexing (WDM) and advanced electronic processing schemes, together with simple optical solutions can be a key player towards the realization of extended reach high capacity PONs [51]

5.5.2 Proposed Future Activities

The research areas proposed demonstrate a number of potential areas for collaboration in year 2. In particular two partners are considering wavelength conversion techniques. Also of specific interest are techniques or methodologies to allow benchmarking of optical access techniques so that stakeholders can objectively compare the relative merits of the technologies. The wide variety of expertise in different architectures provides an excellent opportunity to propose a benchmarking scheme in the optical access space.

5.5.3 Upstream Transmission at 10 Gb/s Using RSOAs Optical Filtering and Electronic Equalization

The use of reflective semi-conductor optical amplifier (RSOA) at the ONU parts of the WDM-PONs is a widely adopted low-cost solution [51,52] that allows colourless operation. Although RSOA-based PON systems with 10Gb/s downstream transmission have been reported [52], symmetrical data transfer at 10Gb/s is currently limited by the speed of the commercially available RSOAs.

Here, we demonstrate 10Gbps upstream transmission up to 85Km using an RSOA with 1.5GHz electrical bandwidth at the ONU. This is achieved with: a) the implementation of offset optical filtering (similar to the technique applied for direct modulated lasers in [53]) and b) the use of decision feedback equalization (DFE) at the OLT. To the best of our knowledge this is the first time when equalization is applied in combination with RSOA generated signals.

Experimental set-up

The experimental set-up is shown in Figure 40. The ONU transmitter is an Alcatel-Thales III-V-Labs RSOA module. The maximum gain peak of the utilized RSOA is located at 1510nm. A CW signal at 1535nm is introduced from the OLT. A 10Gb/s NRZ data stream with 2^{31-1} long PRBS is applied to the RSOA through a bias-T and the RC equalizer. The combination of the RSOA and a passive pre-equalizer electrical gives as a result the increase of the original bandwidth from 1.5 to 2.5GHz at the output of the RSOA; this has been biased with 70mA DC current and modulated with a current of ±35mA. The generated signal is transmitted upstream over an uncompensated link consisted of SMF-28 fibre. We focus our study in the up-stream transmission chromatic dispersion effects, without considering Rayleigh back-scattering.

At the receiver end, first an OSNR emulator (VOA + EDFA with noise figure ~5dB) is used to alter the OSNR. Following this, a 40 GHz tuneable optical bandpass filter (BPF) with a small offset to the central CW is inserted before the PIN to interact with the chirp characteristics of the transmitted signal and reshape it. Figure 40 includes the eye diagrams of both the original signal after the RSOA and the reshaped one after optimum offset filtering when the system is connected in back-to-back configuration. The filter detuning plays a role in the detection because of the high transient chirp of the RSOA, improving the demodulation. After the receiver, an integrated electronic equalization circuit is used, consisting of a 5-stage FFE, clock/data recovery and a 2-stage DFE. The taps for each case are adjusted in terms of optimum BER. In all cases, the performance of the received signals was evaluated in terms of required OSNR for 10^{-9} BER.

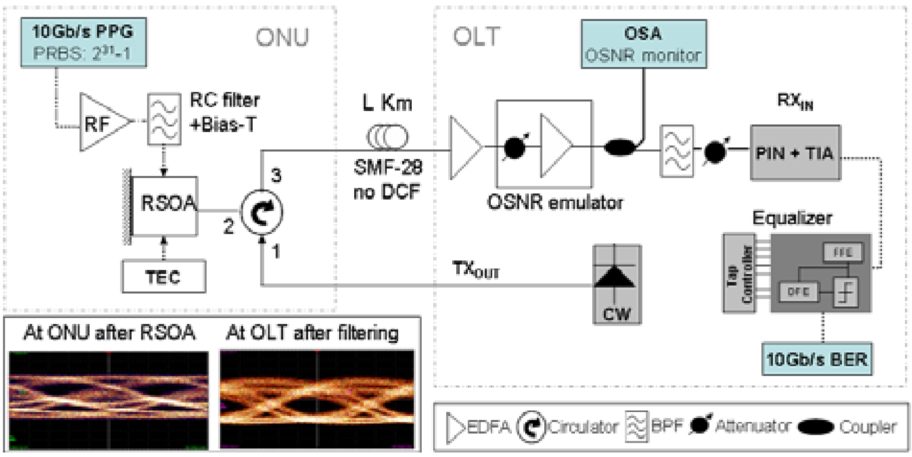


Figure 40: **Experimental set-up and eye diagrams (transmitted - after RSOA, and received - after filter)**

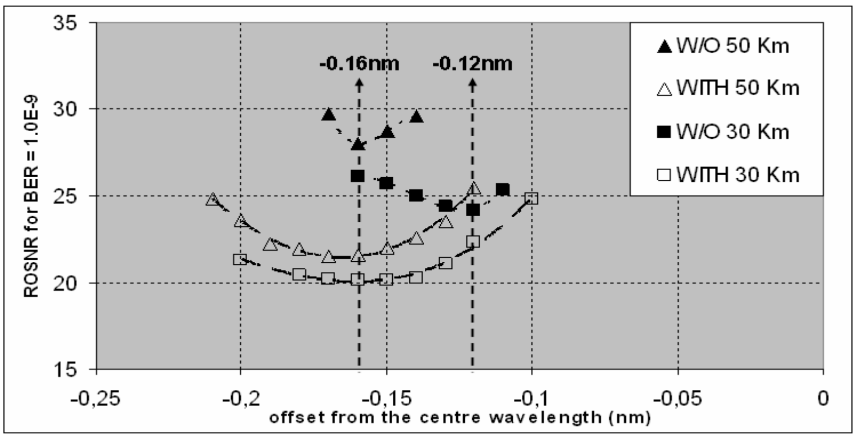


Figure 41: **Required OSNR for 10^{-9} BER at 30 & 50km for various filter offset positions with and without DFE.**

Experimental results

The initial results obtained targeted in identifying the optimum filter position with respect to the central wavelength of the transmitted signal, with and without the assistance of equalization at the receiver end. Figure 41 shows the required OSNR for 10^{-9} BER, at 30Km and 50Km, for various filter offset values with and without DFE (5,2). The input CW power to the RSOA was -10 dBm. It is observed that when no equalization is used, the optimum filter detuning value depends on the transmission length (-0.12nm for 30Km and -0.16nm for 50Km). This stems from the fact that the chirped signal properties change due to dispersion as the signal propagates various fibre distances. As offset filtering interacts with the signal's chirp, a different effect is observed for different distances. Moreover, it is shown that small filter offset variations around the optimum offset value result in significant signal degradation (or in other words accurate and stable filter tuning is required in order to assure optimum performance). However, when DFE equalization is used in combination to offset filtering at the receiver, then a) the link's distance dependency to filter offset is minimized (optimum filter offset always at 0.16nm), b) the system performance is significantly increased (in terms of OSNR performance compared to the case without DFE) and c) the signal degradation due to filter offset variations around the optimum offset value is significantly reduced, (higher tolerance in terms of filtering accuracy and stability).

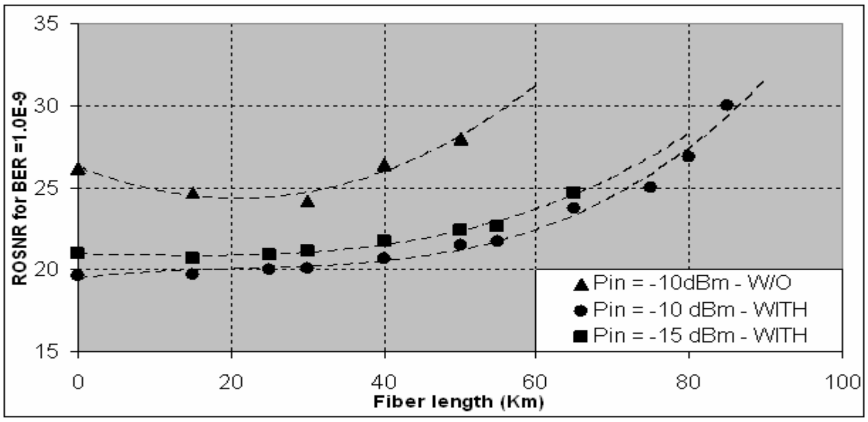


Figure 42: **Required OSNR for 10^{-9} BER vs. fibre length when optimum filter offset combined or not with DFE. P_{in} refers to RSOA input power.**

In order to examine the achievable error free transmission distance (in terms of required OSNR for 10^{-9} BER) when optimum filtering and DFE (5,2) is applied, the results shown in Figure 42 have been obtained. Here, the upper refers to the case where only optimum offset filtering is applied at the receiver end. These values have been obtained by optimizing the filter position according to the measured distance, which is a rather impractical approach. In this case, it is observed that the best performance is achieved after 30Km, which proves that the initial signal from the RSOA is pre-chirped and its interaction with the fibre chromatic dispersion and filtering effect smoothes out signal distortions around 30Km.

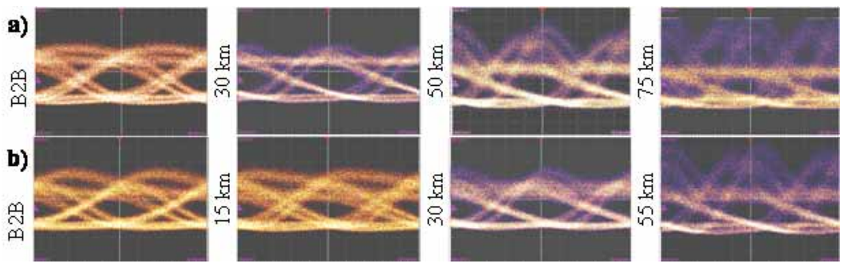


Figure 43: ***Received eye diagrams after filter for various distances and RSOA P_{IN} a)-10dBm and b)-15dBm.***

This is evident also from the eye diagrams presented in Figure 43a . The lower two curves in Figure 42 provide the results obtained when optimum offset filtering (fixed at -0.16nm) is combined with DFE(5,2). This case has been examined for two different input power levels at

RSOA, -10dBm and -15dBm, as the long achievable distance may prevent a strong CW signal to be send from the OLT to the RSOA. It is noted that without equalization, it was impossible to achieve error free (BER>10^{-9}) measurements for -15dBm RSOA input power, mainly due to the fact that the transmitted wavelength (1535nm) was set away from the maximum gain peak of the RSOA (1510nm) and therefore the power dependency is stronger. The corresponding eye diagrams are shown in Figure 43b.

These studies show that a bandwidth limited RSOA can be used for 10Gb/s upstream transmission if electronic equalization in combination with offset filtering is applied at the receiver (OLT) end. However, without equalization, strict design rules must be applied in order to maintain an accurate and stable filter position. The additional use of DFE(5,2) relaxes the system from strict design requirements and offers significant transmission improvement achieving error free transmission over 85Km or 65km depending on the input power to the RSOA (-10dBm and -15dBm respectively)

Conclusions

This work has experimentally demonstrated that despite their limited electrical bandwidth, RSOAs can be used as low cost wavelength independent sources at ONUs and allow error free 10Gb/s upstream data transfer over more than 85Km when combined with optimum filter offset and DFE at the receiver end.

5.5.4 Polarization Beamforming MIMO-based PON: 20 Gb/s Transmission over a 10 Gb/s System with Dynamic Power Allocation and Improved Reach

A low-complexity *Polarization-Multiplexing* (PolMux) based upgrade for *Time Division Multiplexed* (TDM) *Passive Optical Networks* (PON) is expected to provide significant performance improvement as this novel scheme doubles the *Downstream* (DS) throughput and further expands the network reach, while multiple access fairness and flexibility are enhanced by means of *Dynamic Power Allocation* (DPA) to all *Optical Network Units* (ONU), electronically-controlled at the *Optical Line Terminal* (OLT). Such a *Multiple Input Multiple Output (MIMO)* Polarization-Time Division Multiple Access approach retains the passivity of the optical distribution network, merely requiring, for the purpose of DS transmission, to replace the first *Optical Splitter* (OS) by a *Polarization Beam Splitter* (PBS) (PBS_{RN} in Figure 44). The proposed scheme is suitable for asymmetric PONs (e.g. 10Gb/s DS / 1.25 Gb/s US GPON) and may also be suitable for migration towards *Wavelength Division Multiplexed* (WDM) / TDM PONs [54,55].

Theoretical Model

The novel PolMux architecture suggested has been inspired by previous research [56,57] in MIMO transmission for Multi-Mode Fiber (MMF) [58]. This scheme is ported to PON systems based on Single Mode Fiber (SMF) – the rationale being that each SMF path may be considered as a 2x2 MIMO system with respect to the two orthogonal polarizations supported by SMF. This approach allows for broadcast transmission by means of Zero-Forcing Beamforming (ZFBF) MIMO, doubling the throughput under the same transmit power constraint. It further enables electronically-tunable DPA to the individual ONUs, yielding additional loss budget improvement. The scheme maintains the simplest possible receivers, while adding complexity mostly to a shared common transmitter at the OLT. Although MIMO ZFBF theory plays a key role in the conception of this PON structure, it is nevertheless possible to interpret the new architecture solely in terms of Jones matrix theory, without resorting to the advanced MIMO concepts of communication theory.

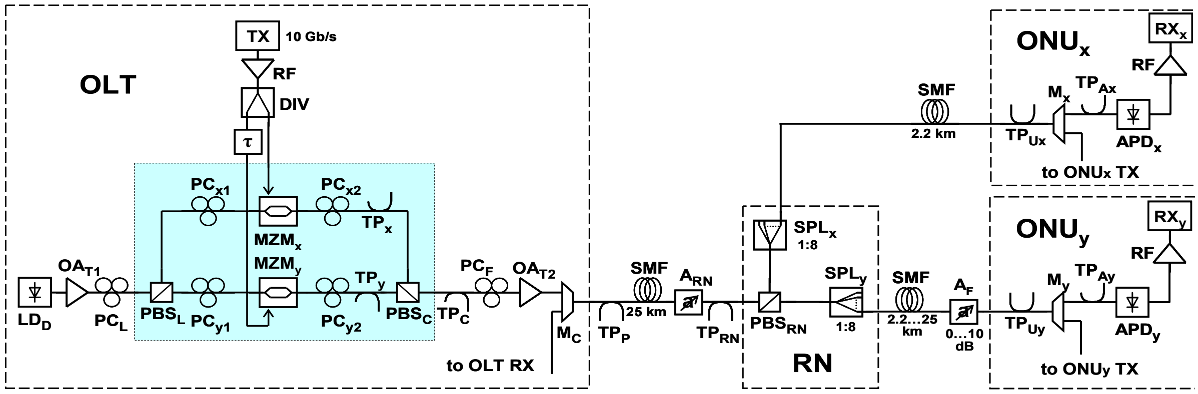


Figure 44: Schematic diagram and experimental setup of the PolMux PON. At the OLT the two orthogonal states are independently modulated (shaded box). The conventional splitter at the Remote Node is replaced by a combination of a PBS and a conventional power

In the PON structure described in Figure 44, the transmitter incorporates a polarization (pol.) modulator generating arbitrary States-Of-Polarization (SOP). The trunk fiber from the OLT is terminated at its first passive splitting point in a PBS rather than a conventional OS. Unlike a conventional TDM PON, where in each time slot the transmission is intended to a unique user, in a PolMux PON, signaling in each time slot concurrently addresses a unique pair of users (respectively connected to the x- and y- outputs of the PBS). The two users are fed by optical powers in a particular ratio, aiming to make their SNRs equal (i.e. the user with higher loss is fed proportionately more power over its polarization path). As each of the two orthogonal polarizations can be independently modulated, the total data rate is now doubled, yet without incurring a power penalty, as each pol. traverses the PBS losslessly. The virtual 3 dB loss budget advantage over each pol. (due to the PBS transparency to each of the two polarizations) is offset by the total transmitted power being divided between two polarizations, rendering the loss budget seen by each ONU identical to that of the corresponding conventional PON. This establishes the DS data rate doubling for equivalent conditions, namely topology, Bit Error Rate (BER) and total TX power. Although the scheme described applies to the DS direction, it may co-exist with a PolMux transmission in the US direction. In the proposed architecture, each of the two users detects its own tributary, unaffected by the signal to the complementary user. To this end, the PolMux transmitter launches in each symbol interval a SOP consisting of a superposition of the two vectors, each modulated independently, $s_p, p = x, y$: $\underset{\sim}{\mathbf{E}}^s = E_0(\mathbf{A}_x^{(k)} s_x + \mathbf{A}_y^{(k)} s_y)$, where s_x, s_y are the bits transmitted to the x,y-ONU respectively. The SOP vectors $\mathbf{A}_x^{(k)}, \mathbf{A}_y^{(k)}$, satisfy a Zero-Forcing Beamforming condition, nulling out interference between ONUs. E0 is a scalar gain, determined by the available transmit power.

Experimental Setup

In the experimental setup illustrated in Fig. 1, manual Polarization Controllers (PC) were used to generate the required SOP by minimization of the crosstalk between the x- and y-ONUs.

The optical power from a Laser Diode (LDD), operating at 1552.52 nm, boosted by an Erbium-Doped Fiber Amplifier (EDFA) (OAT1) is distributed by PCL between the two pol. channels in a designated ratio, applying the DPA policy for balancing the received powers at the two active ONUs. PBSL then splits the signal into orthogonal components, independently modulated via two Mach-Zehnder Modulators (MZMx, MZMy) driven by a Non-Return-To-Zero (NRZ) signal with a Pseudo-Random Bit Sequence (PRBS) of length 27-1 at a data rate of 10 Gb/s. For simplicity, the same pattern generator was used for both x- and y-signals, with a delay applied in one path to decorrelate the signals. PCx1 and PCy1 are introduced to optimize the response of the MZMs. Another set of PCs is applied at the MZMs output (PCx2, PCy2) to align the polarized signal in each path to the x- and y- axis of the following PBSC which in turn combines the two orthogonal polarizations. The signal then passes through PCF compensating for the trunk fiber polarization transformation, ensuring that the x-(y-)pol. component arrives aligned with the x-(y-) axis of the PBSRN at the Remote Node (RN). Another EDFA (OAT2) is used to keep launched power at a constant level of 12 dBm for all measurements. A WDM coupler (MC) is inserted to separate the DS/US signals.

A variable attenuator (ARN) is introduced after the trunk fiber to measure the BER in respect to the input power level at the RN. The signals are split into two groups of users, associated with the two polarizations, using PBSRN. For each group the signal is further divided by a passive OS (SPLx, SPLy) in a 1:8 ratio, altogether forming a 16 users network. While ONUx is connected to the RN through a drop fiber with a fixed length of 2.2 km, the length of the drop fiber connecting ONUy is either 2.2, 12 or 25 km. In addition to the variable drop length, a variable attenuator (AF) is added to emulate additional loss on the signal path increasing the network imbalance. Standard SMF was used for all fibers in the setup. At the ONUs, a WDM coupler (Mx/My) splits/combines the DS/US and the DS signal is detected by an Avalanche Photo Diode (APD) and fed to the electrical receiver.

A conventional TDM system (not shown in the figure) was used as a reference, implemented as similar to the PolMux system as possible. Its OLT consists of a single modulator and two EDFAs without any PC or PBS, the RN has a passive OS instead of PBSRN, and the same ONUs are used. For each of the two systems a BER curve was acquired for a specific set of conditions in the drop path (fiber length and attenuation AF) as a function of the received optical power at the RN input. In the PolMux system, the power was re-allocated between ONUx and ONUy to balance the powers at the ONUs and the launched SOP was periodically adjusted to accommodate for random drifts in the fiber birefringence.

Results and Discussion

The three curves in Figure 45(a) associated with the unbalanced network conditions (markers: ■,▲,●) show improved performance at a BER of 10-8 (10-9 could not be attained with the conventional TDM system for high imbalance) while throughput is doubled, thus experimentally proving the PolMux PON concept: PolMux outperforms TDM by 1 dB, 1.4dB, and 1.8 dB for 9.8 km, 22.8 km, and 22.8 km + 5dB loss, respectively. Notice that these are reasonable loss imbalance values between an ONU connected very close to the RN, compared to an ONU remotely placed at the maximal allowed range, utilizing the maximum power budget of a standard PON.

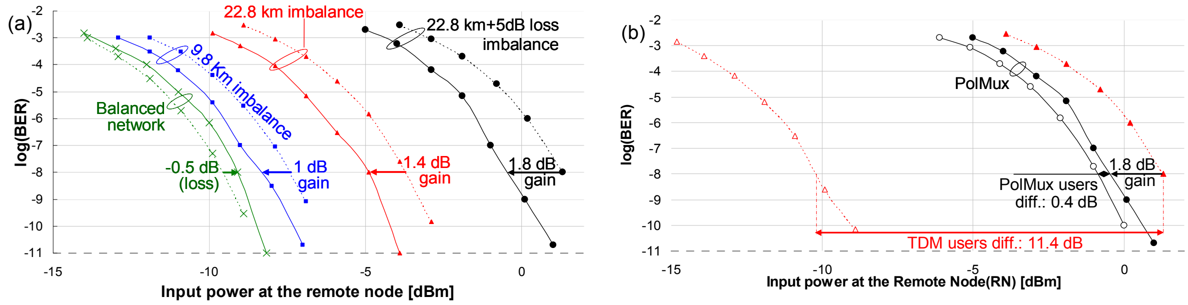


Figure 45: BER as a function of signal power at the Remote Node (RN) for Polarization Multiplexed (PolMux) PON (solid lines) compared to a reference TDM PON (dashed lines). (a) **Results of a balanced (X marker) & unbalanced networks (■,▲,● markers for 9.8 km, 22.8 km, and 22.8 km + 5dB loss imbalances, respectively)** (b) **BER for both the "weak" (filled markers) and "strong" (outlined markers) ONUs in a network with 22.8 km+5dB loss imbalance (PolMux system marked with circles, TDM**

The first pair of curves in Figure 45(a), (X markers) illustrates the exception case of a balanced network, wherein the PolMux scheme suffers a 0.5 dB loss relative to the TDM reference. This exception may be explained by the imperfect manual training, failing to optimize the receiver eye opening. An automated training procedure, performed at higher rates, is expected to achieve better results. Another reason for this penalty is the imperfection of the two PBS components (PBSC, PBSRN) used for combining/splitting the signal, namely the finite extinction ratio of orthogonal pol. states. Figure 45 (b) indicates that the DPA manages to reduce the received power differences between the two ONUs: a difference of 11.4 dB in a TDM PON was reduced down to 0.4 dB in the PolMux PON. The balancing effect of DPA action is also evident from Figure. 47, showing eye diagrams of both systems. In, the power advantage due to DPA is illustrated as a function of network imbalance for BERs of 10^{-8} and 10^{-4} (suitable with Forward Error Correction (FEC)), showing an expected monotonic increasing trend. For the case of 10 dB budget loss imbalance, the PolMux system features 1.7 dB improvement.

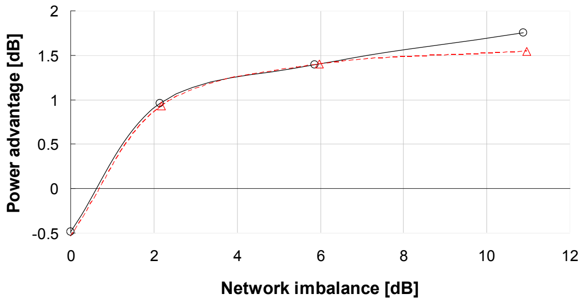


Figure 46: PolMux loss budget improvement over TDM PON reference system, as a function of loss imbalance of two ONUs, measured for a BER of 10-8 (solid line) and for 10-4 (dashed line) considering FEC.

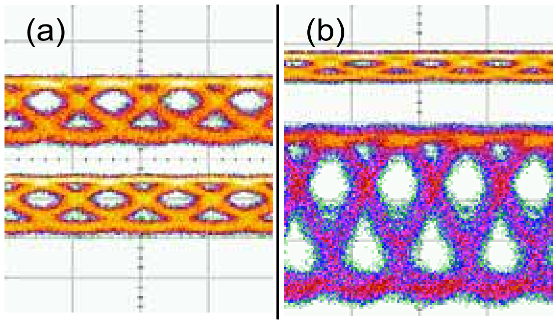


Figure 47: Eye diagrams of the "weak" (far) ONU and "strong" (close) ONU: (a) **PolMux 50 mV scale** (b) **TDM reference 100 mV scale**

Conclusion

The PolMux concept was proven to be feasible, supporting also the theoretical analysis to a good approximation. A PON with TX modulators and RX photo diodes at 10 GHz may support a total throughput of 20 Gb/s, using a single wavelength, as well as simple On Off Keying receivers. Moreover, in the practical case of unbalanced network, whereas throughput was doubled for the same transmitted power, loss budget was shown to actually increase. The adaptation of the PolMux technique for US transmission and the integration of PolMux and WDM-PON approaches are left for future work.

5.5.5 Wavelength conversion in EPON

Future PON will be upgraded with WDM transmission, furthermore according to WDM scenario evolution in the links between OLT and ONU several further channels could be located and dedicated to specific services as for example to operate as backhaul for terrestrial TV stations and for radio Base Station. In this environment AOWC could be required also in this access segments, by means of very cheap devices. In this Section we experimentally investigate also the AOWC in the EPON network by using Semiconductor Optical Amplifier, that should result quite cheap.

In particular, we propose a way to convert the downstream signal to a C-band signal and then to report it back into its usual operative band (1480-1500 nm, according to 802.3ah), based both on a SOA double XGM (Cross Gain Modulation) and a single XGM plus noise modulation. This function permits to explore WDM ePON and to realize wavelength routing granting to several service providers the physical access network sharing. Moreover it grant the possibility of treating the signal in the C-band, in which the majority of devices like lasers and DFAs work.

The experimental set-up is reported in Figure 48. The signal from the OLT (AN5116-03 ePON FiberHome) is coupled with a CW from a DFB laser, these signals enter in the first SOA (Covega 2385) where the first wavelength conversion based on a classical XGM occurs (XGM1). The OLT provides two giga Ethernet ports (EPON1 and EPON2) able to implement two different passive optical networks. The XGM1 converts the OLT wavelength from 1490 nm to 1536 nm near SOA gain peak. The converted signal is coupled with a second CW from an ECL (External Cavity Laser); these signals enter into the second SOA (Alcatel M18) performing the latter XGM (XGM2).

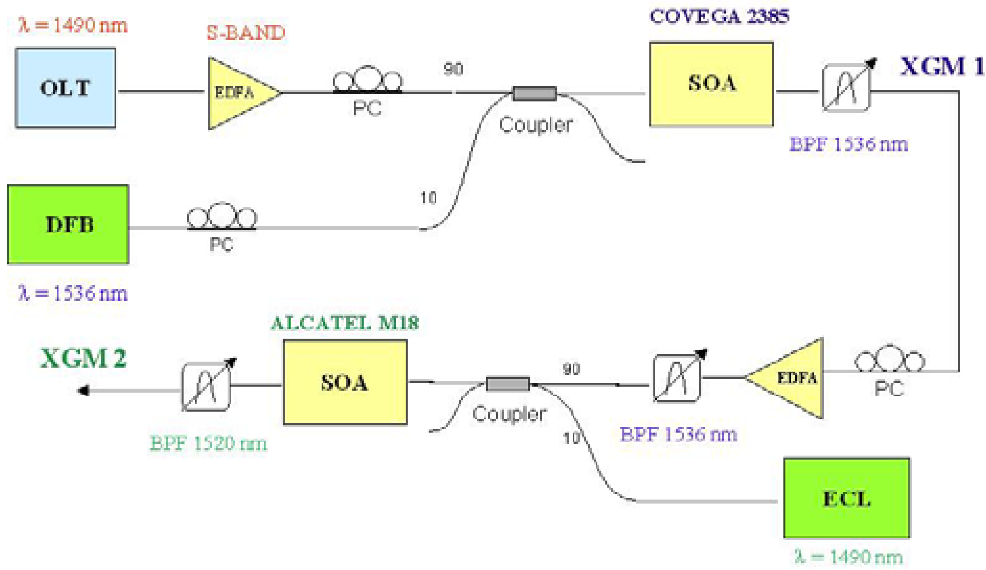


Figure 48: Experimental set-up for AOWC based on SOA

In XGM1 the signal is logically inverted, in XGM2 there is a second logical inversion that bring back the signal to its original shape (Figure 49).

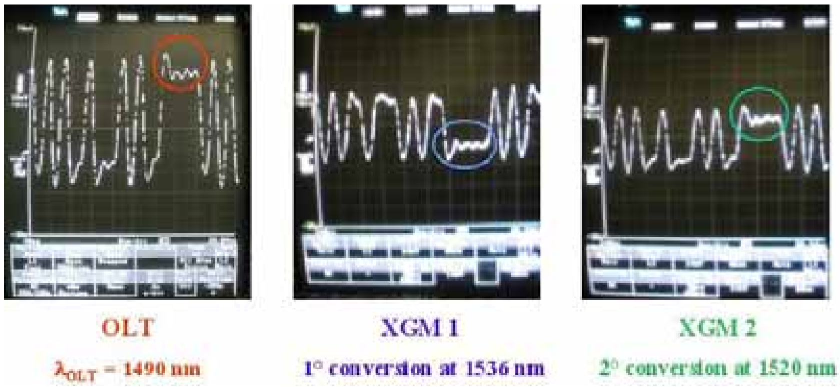


Figure 49:Signal conversions with double XGM

The results are taken using a real time oscilloscope (Tektronix DSA 602). The double XGM induces a weak signal degradation, that however does not worsen the communication between OLT and ONUs (AN5006-05 ePON FiberHome) and it does not induce throughput decreasing.

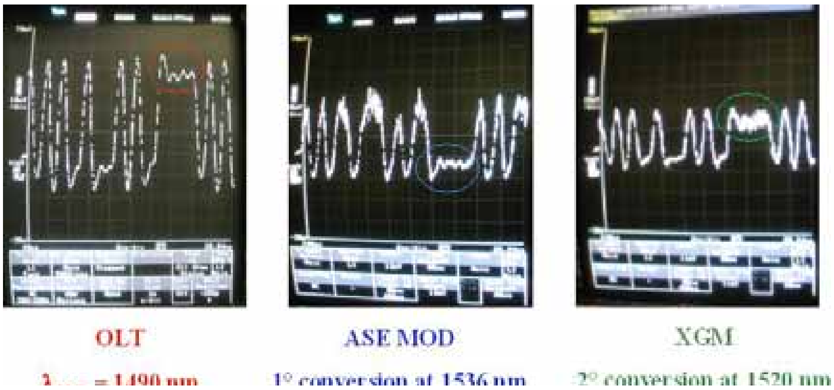


Figure 50: Signal conversions with noise modulation and single XGM

A second method that guarantees optical wavelength conversion is based on the modulation and subsequent filtering of the ASE SOA spectrum as reported in Figure 50

The noise modulation set-up is similar to the Figure 48 set-up and the difference is the absence of the DFB branch, so the amplified OLT enters into the SOA saturating its gain. The performances get worse because the signal on the converted “1s” is much noisier; however the second conversion reconverts and cleans the signal. Within the overall effect, ONUs and OLT still exchange packets but there is a bit worsening in the performances with respect to the double XGM.

Comparing Figure 49 and Figure 50 on the right we can see that the latter method induces more noise on the signal, however no relevant variation in terms of throughput was observed between two methods, even though we believe that the first method is more reliable.

5.5.6 Architecture to Integrate Multiple PONs with Long Reach DWDM Backhaul

The concept of our proposed system is shown in Figure 51. The inclusion of a wavelength converter means that drift of the transmitter wavelength has no effect on system performance as it is converted to a stable wavelength before the narrow-band filtering in the optical path. Via the wavelength conversion process, the network operator has complete control over the wavelength to which the original wavelength (pump wavelength) is converted.

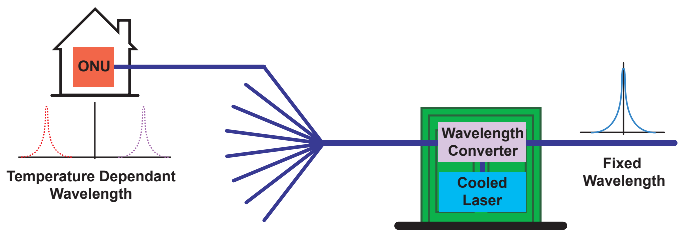


Figure 51: Conversion between temperature dependant wavelength and a DWDM wavelength

The conversion to a stable wavelength has a major advantage; a number of PONs can be grouped together over the same backhaul fiber, the data from each PON being converted to a separate wavelength. This will reduce the overall cost per customer as the utilisation and efficiency of the backhaul fiber is increased allowing the cost to be spread over a larger number of customers. Therefore, with the incorporation of a wavelength converter, a high-split, long-reach optical access network combining both access and metro networks can be created from standard PON architectures and the existing metro backhaul, as illustrated in Figure 52.

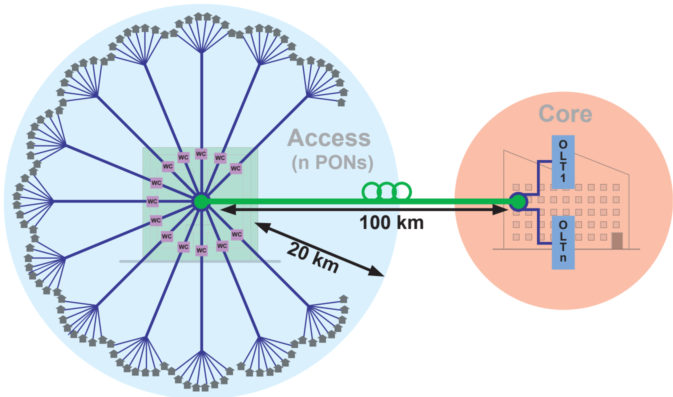


Figure 52: Formation of long reach high split combined access and metro network from existing standard PONs through the use of wavelength conversion

The experimental, upstream, dual fiber architecture of the long reach WCOAN is shown in Figure 53. The focus was on the upstream transmission as it presents the most difficulties due to the cost sensitivity of the ONU. In the distribution section, a single fiber infrastructure which follows the GPON standard was represented by a 20 km of fiber (SSMF, $\alpha = 0.25$ dB/km, Dispersion = 16 ps/nm.km) and an optical attenuator were used to represent the attenuation inherent in the optical splitter. An insertion loss of 3.5 dB per 2 way split was assumed with the additional 0.5 dB added to account for non-ideal device construction. For example, the insertion loss equivalent to a 32 way split is 17.5 dB ($32 = 2^5$; $3.5 \times 5 = 17.5$ dB). In the experiment the ONU transmitter consisted of a tunable laser with an external MZ modulator operating at 2.5 Gbit/s to simulate the possible wavelength drift of an uncooled, directly modulated ONU transmitter which would be mandated in a commercial realization. The transmitter had an output power of 2 dBm with an extinction ratio of 10 dB which complies with the GPON standard. The transmitter wavelength was 1550 nm ±10 nm, following the wavelength plan suggested previously for long reach optical access networks [59]. As in previous systems, a dual fiber backhaul would be used to avoid any wavelength overlaps between the upstream and downstream channels [60]. This may also reuse existing fiber pairs; for example those installed to provide SDH backhaul to current systems. After propagation through the PON distribution section the data signal was transferred to the probe wavelength in the XGM wavelength converter. The probe wavelength was supplied by a CW DWDM laser. Exact details of the wavelength converter will be given in the subsequent sections.

Directly after the wavelength converter was the backhaul section. The converted signal, at the probe wavelength, was wavelength multiplexed into a 100 km SSMF backhaul through an arrayed wavelength grating (AWG). A second AWG was positioned immediately after the backhaul fiber to filter each channel to the correct Optical Line Terminal (OLT). The OLT was formed of a 2.5 Gbit/s avalanche photodiode (APD) receiver with sensitivity of -31 dBm at BER = 10^{-9}. The AWGs had 20 channels with 100 GHz spacing, allowing DWDM to be implemented in the backhaul. An SOA is placed after the backhaul fiber. In this configuration the second AWG will also act as an ASE filter at the receiver. In this particular setup the wavelength converter uses an SOA pre-amplifier as in the system shown in Figure 54.

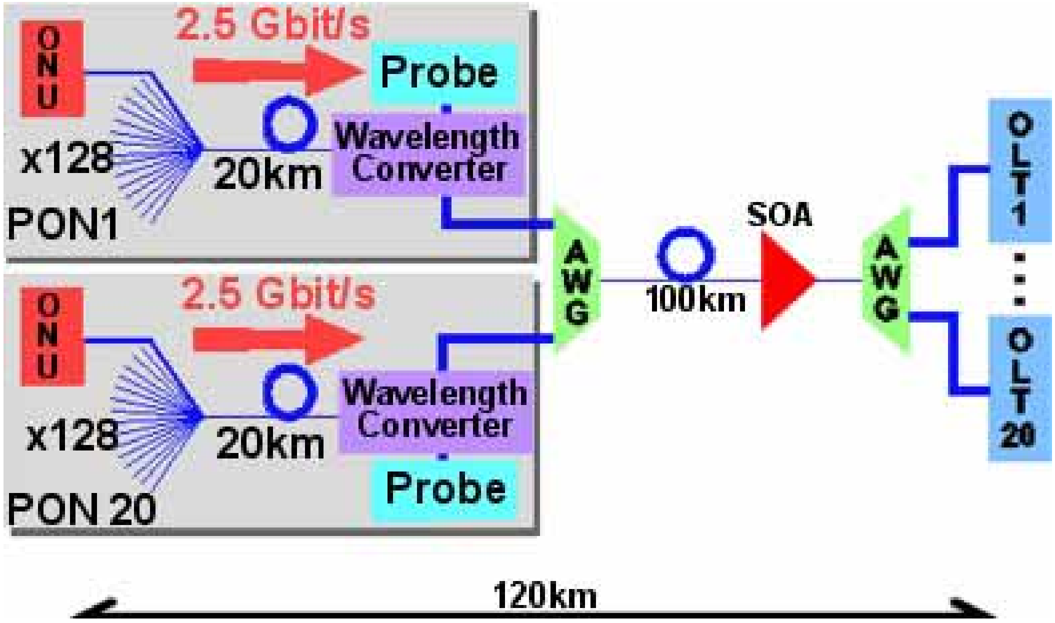


Figure 53: 128 way split architecture with optically pre-amplified receiver

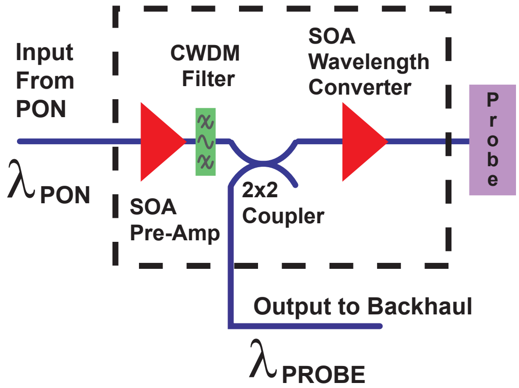


Figure 54: Wavelength converter for the 32 way split system using an SOA pre-amplifier and an SOA to provide the XGM wavelength conversion to the counter propagating probe wavelength

Experimental Results

Initially, the optimum probe power was determined to be -26 dBm when using a backhaul wavelength of 1530.04 nm. Figure 55 shows how the optimum probe power enabled the system to operate with a performance better than BER = 10^{-10} for a split ratio of 128 across a CWDM band centred at 1550 nm. The performance variation with wavelength corresponds to the wavelength dependency of the SOA. An increase to 256 way split PONs would be possible when using an EDFA pre-amplifier in the wavelength converter. However, the benefit of using two SOAs is that both devices can be integrated into the same package which creates a much more compact solution.

The dynamic range of the system is shown in Figure 56. The dynamic range of the system defines the range of pump signal power over which the target performance of BER = 10^{-10} can be maintained. Out of the three wavelengths used to simulate the CWDM band centred on 1550 nm, the minimum dynamic range of 11.6 dB was achieved for 1542 nm wavelength.

Due to the wavelength dependency of the SOAs the longer wavelengths have less gain. This enables the shorter 1542 nm wavelength to operate with a larger split size. However, higher gain means that the zero level signal will begin to saturate the wavelength converter at lower input power. Saturation of the SOA by the zeros would result in a reduced extinction ratio in the converted signal and hence reduced performance. For longer wavelengths, lower gain means that zero saturation of the SOA is limited, which leads to a larger dynamic range. At 1558 nm, it was not possible to measure the dynamic range due to power limitations i.e. it was not possible to achieve the signal power required for the zero level SOA saturation, indicating that it was in excess of 15dB.

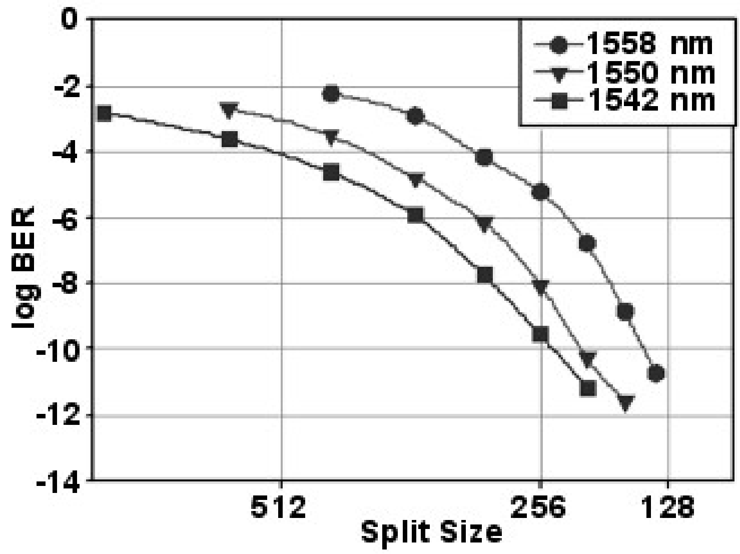


Figure 55 Performance of the amplified backhaul system showing that a split size of 128 is achievable when the ONU wavelength varies over CWDM channel centred at 1550 nm

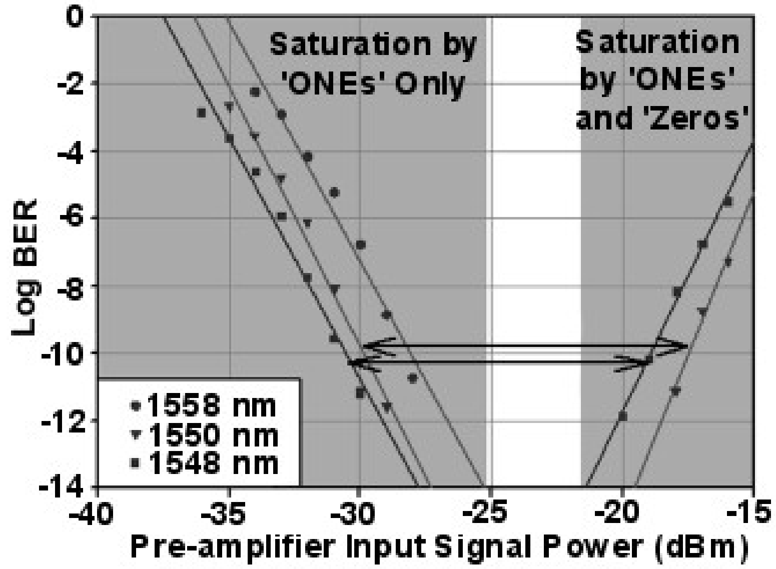


Figure 56 Dynamic range of the network measured for distribution wavelengths which span a CWDM channel. Shaded areas indicate where the wavelength converter is saturated by 'ones only' (left) and 'ones and zeros' (right).

The wavelength drift of the ONU transmitter across a CWDM band centred at 1550 nm, was simulated by using three test wavelengths, 1542, 1550 and 1558 nm. An attenuator placed prior to the receiver was used to adjust the received optical power in 1 dB steps. The optimum probe powers were determined to be -9 dBm and -7.5 dBm for the 1535.04 nm and 1520.25 nm probe wavelengths respectively. The difference between the two optimum probe powers can be attributed to the wavelength dependency of the SOA devices used. The peak gain of the SOA devices used was at 1480 nm. Hence, the small signal gain of the device increased as the wavelength decreases. Therefore, at 1520.25 nm the device had a higher gain and required more power from the pump/probe combination so that the device could be saturated ensuring successful wavelength conversion through the XGM process.

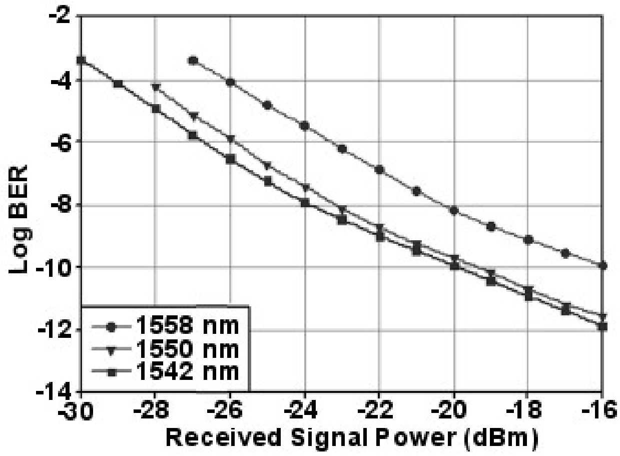


Figure 57: System performance against received power when converting the distribution wavelengths to a backhaul wavelength of 1535.04 nm

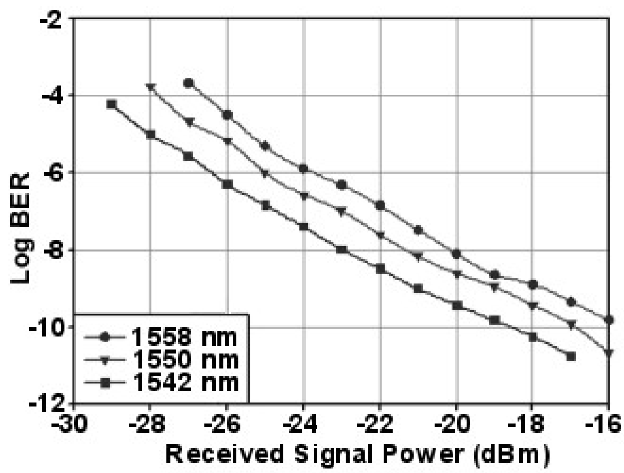


Figure 58: System performance when converting the distribution section wavelengths to a backhaul wavelength of 1520.25 nm

The main conclusion taken from the system performance results at the two extremes of backhaul wavelengths, given in Figure 57 and Figure 58 was that the target BER of 10^{-10} was achievable with wavelength drift across a CWDM band across backhaul wavelengths from

1520.25 nm to 1535.04 nm. Subtle differences between the system performance at the ONU test wavelengths for each backhaul wavelength do exist. These differences can be attributed to the choice of probe wavelength. For the 1535.04 nm case, Figure 57 shows that at probe powers close to the optimum power the performance of the 1542 and 1550 nm wavelengths is very similar, which is also reflected in Figure 57. In Figure 58 the performance of all three wavelengths are evenly spaced. Therefore, it can be concluded that the differences in performance at wavelengths in the ONU transmitter CWDM band can be controlled through the choice of probe power.

The results of the wavelength drift in the distribution section against received power were similar for both backhaul wavelengths. Figure 57 and Figure 58 show that the target performance of BER = 10^{-10} was achieved across the 1520.25 nm to 1535.04 nm wavelength band chosen for the DWDM upstream backhaul wavelengths.

5.5.7 Joint Project for establishing the reliability of Fibre Bragg Gratings in FTTH networks and comparing it against new quasi periodic structures.

Partners: Ericsson and FPMS.

Timescale: June 2008 - end 2009

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

The reliability of the entire communications network and services is dependent on the reliability of each device used in that network. Even though redundant transmission systems allow higher reliability, the maintenance costs can be minimized if reliable components are used. Investigations carried out on optical devices and modules indicate that they have failure mechanisms that are accelerated by both temperature and moisture. In many of the proposed applications, the devices will be located in environments that are subject to both high temperature and potentially high humidities. Information about the accelerating effect of both temperature and humidity is therefore essential to ensure that the devices are fit-for-purpose and for characterizing the service access problem at the network side.

Reliability in Design and new technologies in optical communications is essential as businesses and consumers expect uninterrupted service and fault free operation. This will enable the network services to fulfil the level of connectivity needed by applications. Costs associated with the failure of optical components can be significant. The relative costs of correcting field failures and redesigning are significantly higher than the initial cost of design of the optical component. There is also an additional need to integrate full electronic controls into the earlier designs of simple optical components. Increased complexity and capability, leads to increased failure modes. This report reviews the reliability testing that was undertaken on Fiber Bragg Gratings (FBG) Filter for FTTH networks and for Dense Wavelength Division Multiplexer (DWDM), channel spacing at 50GHz and 100GHz.

Reliability testing on current Fibre Bragg Gratings

The FBGs available were tested for qualification and reliability required by Telcordia GR-1209 CORE demonstrating the performance, reliability and integrity of the device. The tests that have been completed so far are:

- Temperature humidity cycling,
- High temperature storage testing,
- Thermal Shock test,
- Low temperature storage.

Further tests are yet to be done and these include Temperature cycling, water immersion test, Vibration, Side Pull, Cable Retention and Impact test. Electrical and optical performance tests were conducted prior to and after each reliability test. The change in product performance resulting from the environmental exposure was measured and compared with the established acceptance criteria.

Optical Measurement Set up and Test Results

The optical performance measurement during the tests are measured by Agilent DWDM system with 81640A tunable laser module, 81634B power sensor module, return loss module and polarization controller.

5.5.8 High Temperature Storage Test (Damp Heat)

1. Testing criteria	Temperature	85 deg C
	Humidity	85 %
	Duration	1000 Hours
2.Measurement	Measure centre wavelength position after 168, 500, 1000 hours	
3. Acceptance level	Centre wavelength drift < 0.05nm	

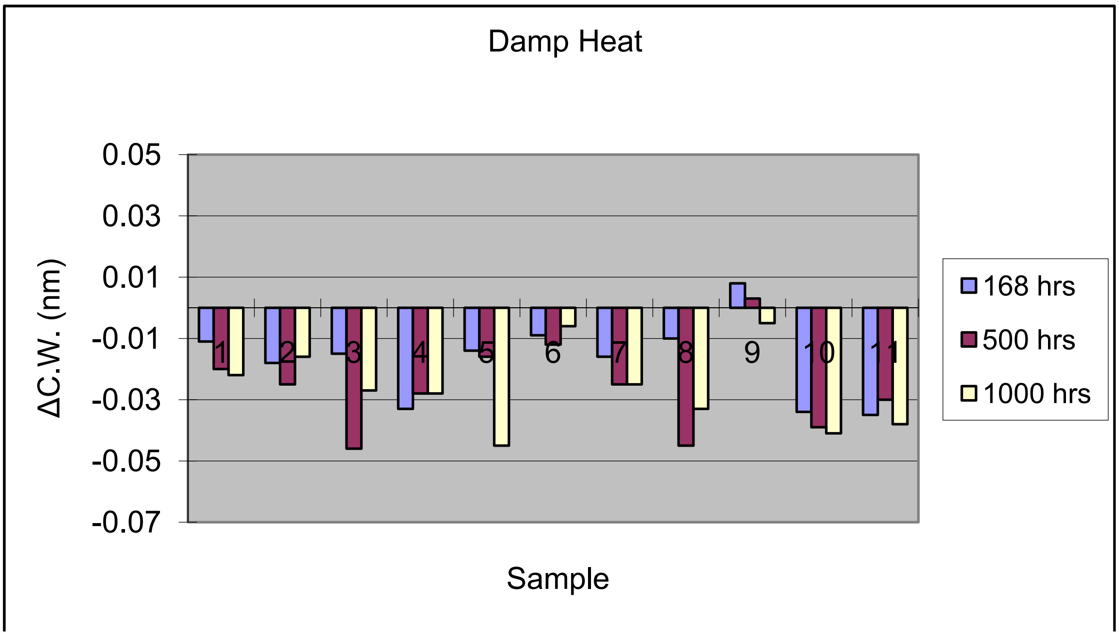


Figure 59: Result of Damp Heat test

5.5.9 Temperature-Humidity Cycling

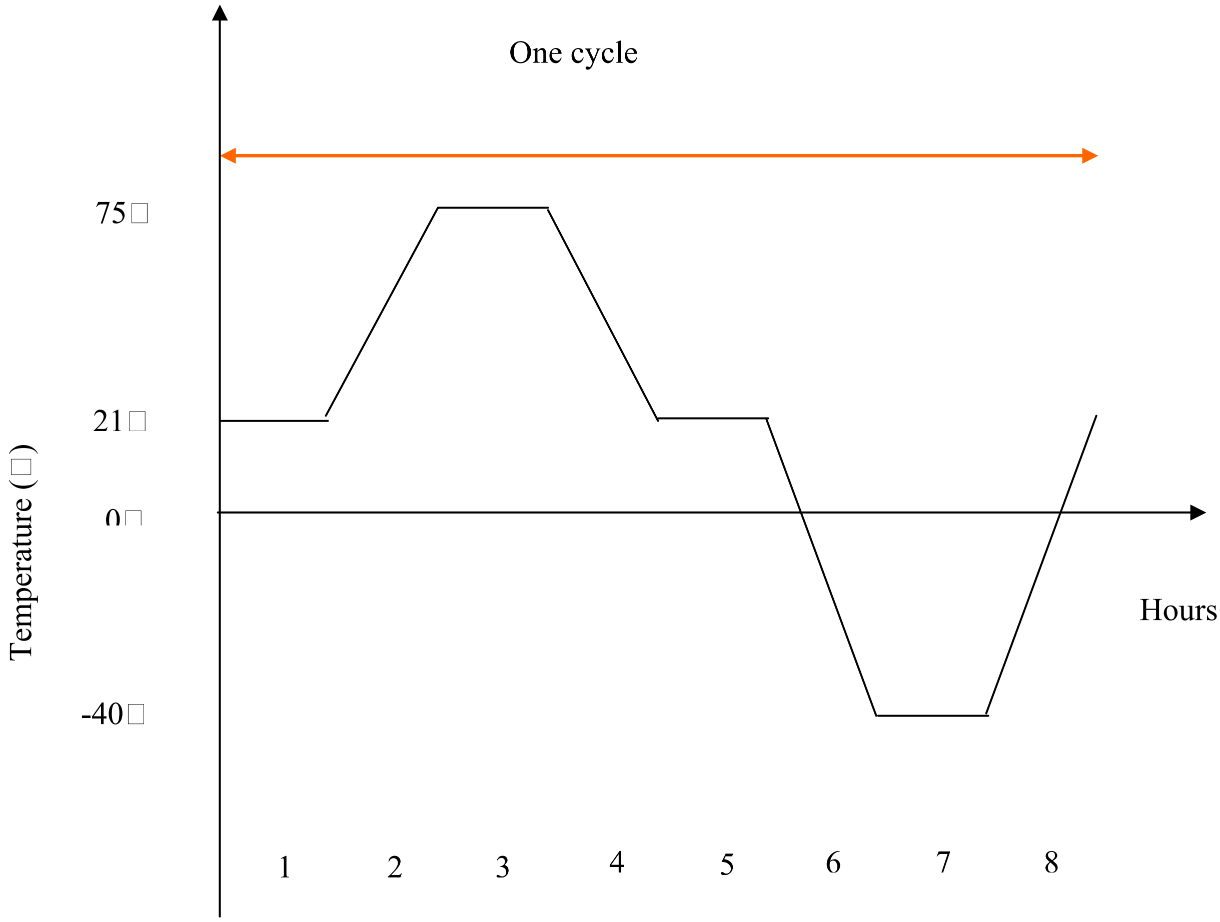


Figure 60: Temperature Humidity cycling profile

1. Testing criteria	As shown on Figure 2
2.Measurement	Measure centre wavelength position once per day during test
3. Acceptance level	Centre wavelength drift < 0.05nm

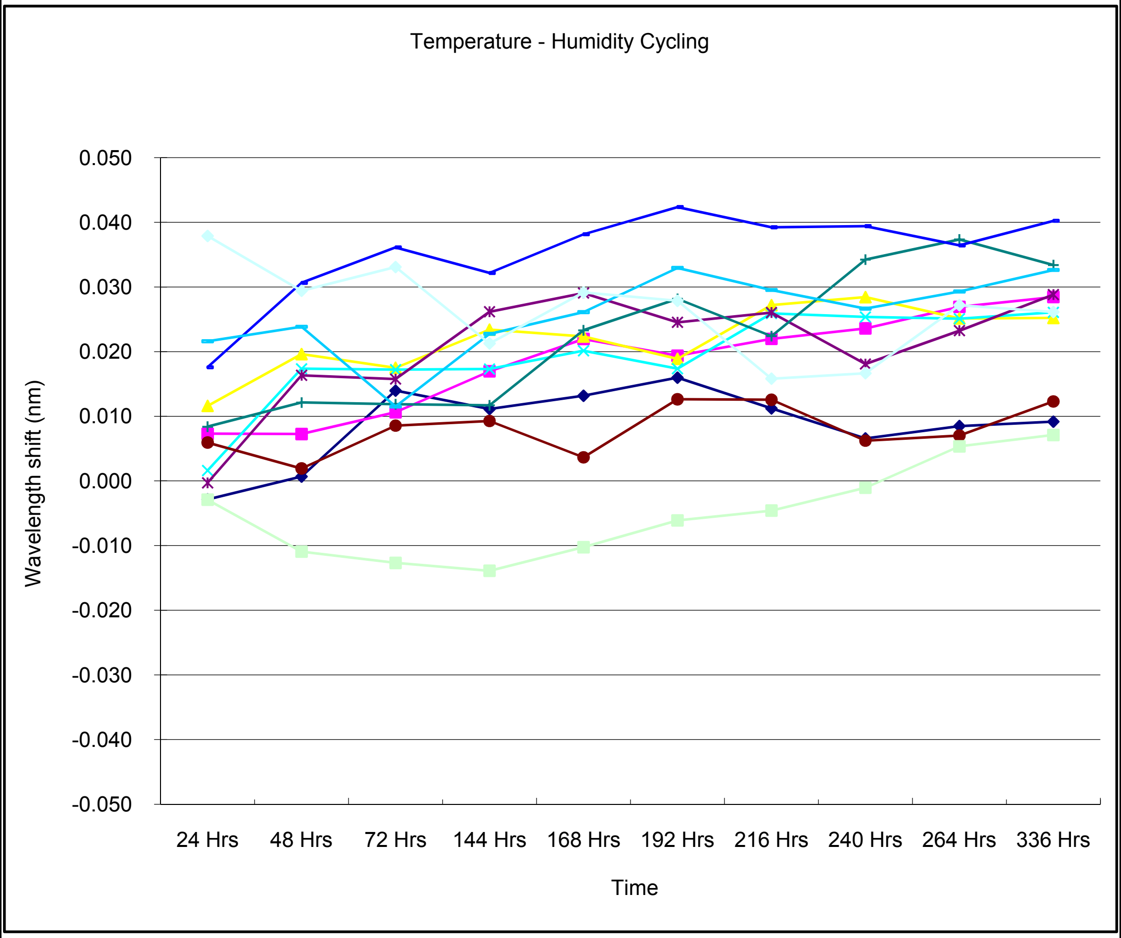
4. Result:	
	
5. Conclusion	PASS

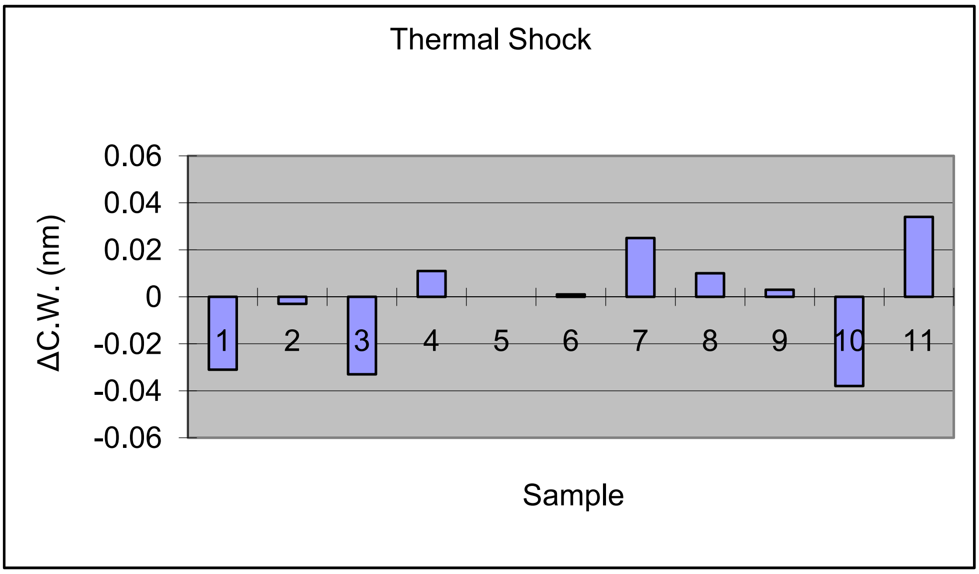
Figure 61: Results of Temperature Humidity Cycling

5.5.10 Thermal Shock

1. Testing criteria	Temperature Range	0 to 100 deg C
	Dwell time	5 min
	Transfer Time	10 sec
	Number of Cycles	15
2.Measurement	Measure centre wavelength position before and after the test	

3. Acceptance level	Centre wavelength drift < 0.05nm

4. Result:

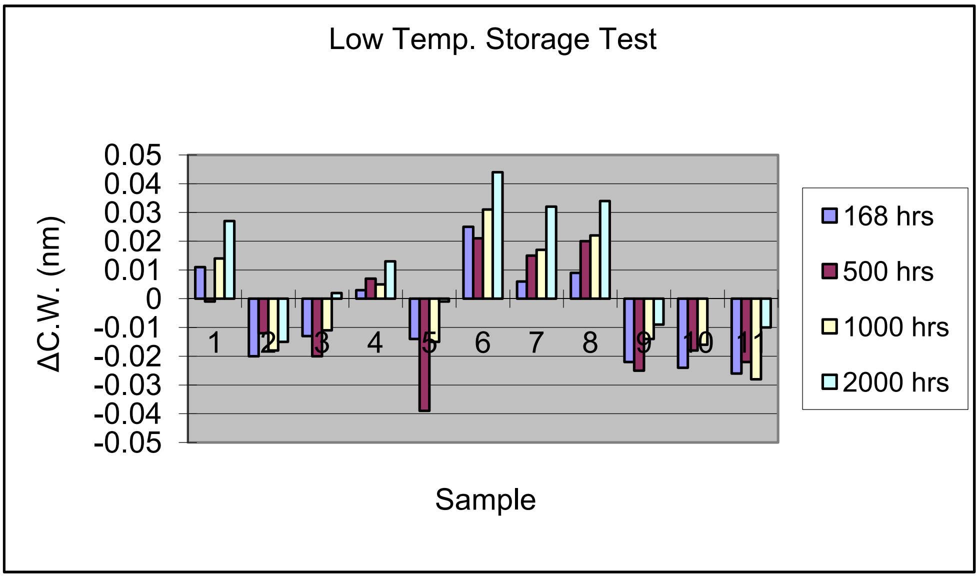


5. Conclusion	PASS

Figure 62: Results of Thermal Shock test

1. Testing criteria	Temperature	-35 to -45 deg C
	Duration	2000 Hours
2.Measurement	Measure centre wavelength position after 168, 500, 1000, 2000 hours	
3. Acceptance level	Centre wavelength drift < 0.05nm	

4. Result:



5. Conclusion	PASS

Figure 63: Results of Low Temperature Storage test

5.5.11 Further work during this joint activity

The following tests are planned to be done as part of this activity:

Temperature Cycling Test	Temperature	-40 to 85 deg C
	Dwell time	15 min
	Number of Cycles	500
Water Immersion	Temperature	45 deg C
	PH value	5 to 6
	Duration	168 Hours
Vibration	Per cycle (10Hz~55Hz~10Hz)	4 min
	Max. amplitude	1.52 mm
	3 Axes	2 hrs
Side Pull	Direction	90 °

	Distance	22 ~ 28 cm
	Min. tension	230 g
Cable Retention	Direction	180 °
	Distance	8 ~ 12 cm
	Min. tension	450 g
Impact Test	Height	1.8 m
	3 Axes	8 Times / Axis

In addition, new quasi periodic structures would be designed and fabricated. After this, reliability tests would be performed on these structures and compared against current FBGs and tested in FTTH networks to ensure FTTH network reliability when using these quasi periodic structures.

5.5.12 OLT design approach for resilient extended PON with OBS Dynamic Bandwidth Allocation sharing the OLT optical resources

The evolution to the next-generation PONs has several approaches. One is to augment the TDM speed up to 10 Gb/s, thus burst mode transceivers are to be developed. Another is to integrate a high number of PONs in a unique Optical Line Terminal (OLT) at the CO, saving opto-electronic costs. Finally, the use of Wavelength Division Multiplexing (WDM), increasing the number of wavelengths, permits to implement several PONs over the same trunk fiber, reaching a large number of users with a shared and improved infrastructure. The main characteristics to be achieved are: high speed, high bandwidth per user, passive outside plant, simple scalability, easy upgradeability, centralized management, resiliency, traffic efficiency, and robustness.

The Scalable Advanced Dense Access Network Architecture (SARDANA) is a proposal for the next-generation PONs []It is based on a WDM single or double-fiber ring with single-fiber wavelength-dedicated PON trees connected to a main ring at Remote Nodes (RNs). The RNs have remote amplification by means of Erbium Doped Fibers (EDFs) for compensating add/drop and filtering losses. The Optical Network Units (ONUs) at the end-users´ premises are equal and colorless; this is achieved with a Reflective-ONU (R-ONU), which is seeded from the OLT by an optical carrier sent by a laser diode (LD), used for both downstream and upstream transmission. In this work we propose a design for the OLT that shares its optical resources in higher degree, thus providing great traffic efficiency. The traffic is managed by a centralized Dynamic Bandwidth Allocation (DBA) protocol placed at the OLT and based on OBS that suits the employed modulation format. The network and DBA traffic performance of the designed OLT architectures are evaluated by simulations.

This section is organized in the following sections: subsection 2 describes the SARDANA network architecture, subsection 3 explains the proposed OLT designs approaches, subsection

4 is devoted to the DBA protocol that suits the considered network and OLT architectures, at subsection 5 traffic performance and simulations are reported and at section 6 the conclusions are discussed.

5.5.13 SARDANA network architecture

In the SARDANA network, the transceivers LDs and photodiodes (PDs) are coupled into a WDM ring through optical switches, and the remote tree PONs (tPONs) are power splitter based (Figure 56). In this network, a remote EDF amplification at the RNs, with pumping lasers located at the OLT, compensates the losses. In this way, a complete passive long-haul outside plant up to 100 km is achieved by a combination of double-fiber ring and single-fiber trees, then avoiding most of the Rayleigh Backscattering (RB) impairment. The RNs implement add/drop function, selecting the operating wavelength for each tPON, the 1-to-1 or 2-to-1 fiber section interface, and resilience in the ring against ring-fiber cuts, all by means of athermal fixed filters and splitters. Each RN is transparent for the remaining wavelengths allowing network scalability.

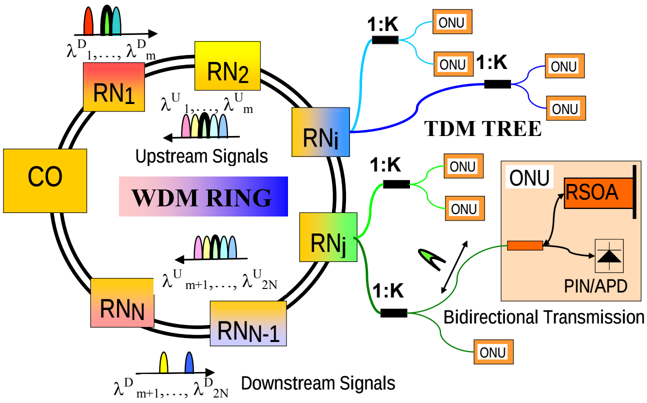


Figure 64: SARDANA network architecture with RNs and colorless R-ONUs

Two RN designs have been proposed, the first (figure 57(a)) was designed for a single fiber ring, requiring a tunable LD at the ONU, using then two different wavelengths for up and down transmission, or wavelength-shifting colourless R-ONUs to avoid RB impairments. The 90% (pass) and 10 % (drop) splitter couples the RN to the ring, the 3 dB splitter provides protection function. A second more complex RN design employs athermal thin-film filters for add/drop and wavelength selection at the ring, providing better power budget (figure 57(b)). Again the 3 dB splitters furnish protection. This design for a 2-fiber ring avoids most of the RB impairments, and therefore permits the use of a colourless R-ONU with the same wavelength for down and up transmission.

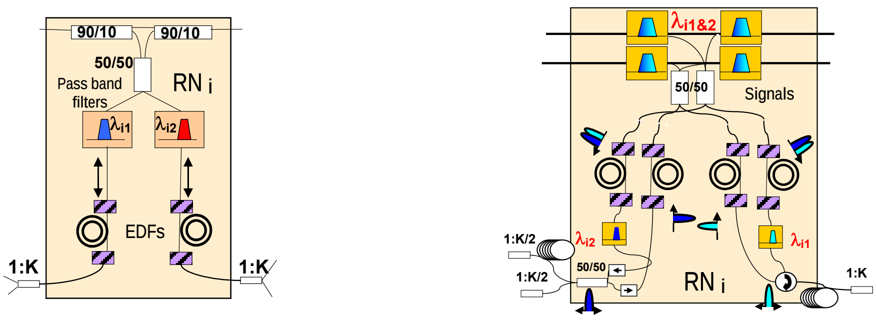


Figure 65: Different designs of SARDANA RNs. (a) Left, for different down and up-wavelengths and single-fiber ring. (b) Right, for using colorless R-ONUs with the same down and up-wavelength and double-fiber ring.

OLT design approaches

The tPON layout is based on a tree topology using a 1 x *K* splitter, with a dedicated wavelength for each tPON. Each RN can manage two tPONs. Thus, the total number of reached users with *N* RNs and a split ratio in the tree of *K* is $U = N \times 2K$ (e.g. 320 = 5 x 2 x 32). The SARDANA network can attain up to 16 RNs and its maximum split ratio is $K = 32$, therefore a maximum of 1024 users can be achieved with $M = 2N = 32$ tPONs. Hence, a maximum of 32 wavelengths are to be managed by the OLT. We will consider the double-fiber ring SARDANA architecture in order to ease RB impairments. If a single-fiber ring is utilized, just a circulator is needed at the OLT to separate the transmission from the reception part, one for east side and another for west side of the ring.

The simplest OLT architecture for transmission is to have a Fixed Laser Diode (FLD), e.g. a Distributed Feedback (DFB) LD, dedicated to each wavelength/tPON, a total of *M* FLDs (figure 58(a)). The *M* FLDs are connected to the east side or to the west side of the ring by employing Optical Switches (OSs). The FLDs signals after the OSs are all multiplexed in a unique output with an *M* x 1 Arrayed Waveguide Grating (AWG), one for each side of the ring. The RNs are bidirectional and then the same up wavelengths are up transmitted for both east and west sides. The same transmission structure can be used in the reception part (figure 58 (b)) need as many LDs as tPONs and wavelengths, then the LDs are only shared by the users of a tPON. To protect the network from LD failure, we require duplicating the LDs.

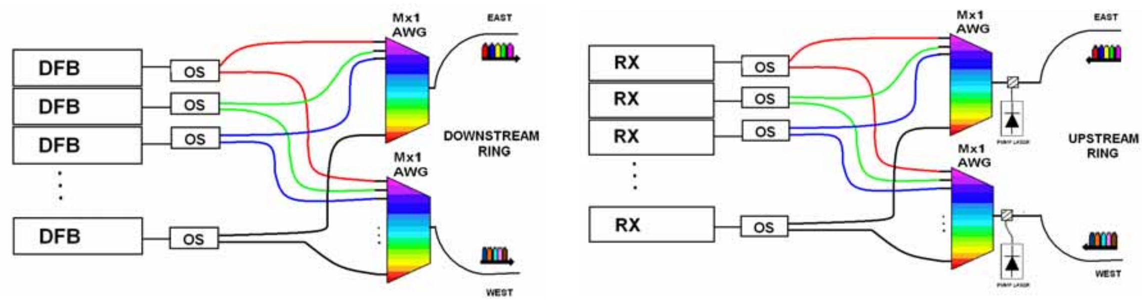


Figure 66: ***OLT simple structure. (a) Left, transmission part with FLDs, Optical Switches and AWG multiplexers. (b) Right, reception part with the same structure and a PD for each wavelength and tPON***

In the reception scenario we require as many PDs as wavelengths, but the PD is a cheap component and this structure avoiding tunable filters is resourceful even if the PDs are duplicated to protect from fail PD device.

In order to share optical transmission resources achieving a better traffic efficiency, we can use tunable LDs (TLDs) [61] shared by several tPONs; the TLDs also protect the network from LD failure (Figure 59). We divide the optical band in R optical regions; in that way the TLDs do not need to have full tunability in the whole band, but only tunability in the assigned sub-band region, which is a relaxed technological condition. Being L the number of wavelengths and tPONs in a region, the number of regions is $R = M / L$. An OS selects the side of the ring to which the TLD will transmit, one OS for each TLD. The number of TLDs T to be used in a region depends on the traffic conditions. The TLDs are gathered in a single output by a combiner, one for each region; finally the combiners are multiplexed in a unique output with a Coarse Multiplexer (CMUX), which multiplexes the R sub-bands, as shown in Figure 59. A typical number of wavelengths/tPONs per region may be $L = 8$ and, with a total of $M = 32$ tPONs, the number of regions is 4; the number of TLDs per region T may be from 1 to 8.

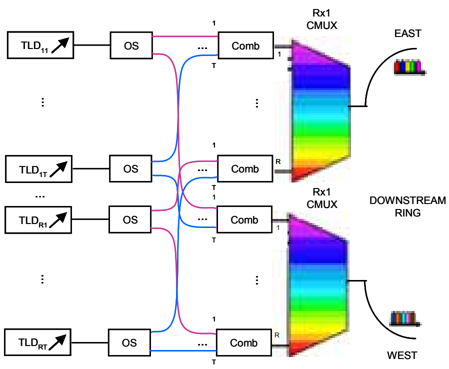


Figure 67: ***OLT with TLDs shared by several tPONs and laser tunability distributed in optical sub-band regions.***

In all of the OLT designs OSs are required to choose the working side of the ring, and they must be able to switch at optical burst level. For high speed there are 1 x 2 and 1 x S electro-optical switches; the oldest solution is based on Lithium Niobate ($LiNbO_3$) (LN) [62], a ferro-electric crystal having nonlinear and piezoelectric properties operating at a switching time less than 10 ns; however its major limitations are driving voltage versus device length, polarization dependence and DC drift. A more recent version of OS is based on a new waveguide material, Lead Lanthanum Zirconium Titanate $(Pb,La)(Zr,Ti)O_3$ (PLZT) [63], providing dense integration, miniaturization, low power dissipation and higher electro-optical coefficient than LN. The PLZT switches show low voltage drive and less than 10 ns response characteristics.

Dynamic Bandwidth Allocation

For down and up-transmission, data packets are assembled into variable bursts at the OLT and ONUs, and launched to the PON when a maximum burst length, or time limit t_{edge}, is reached in an Optical Burst Switching (OBS) transfer mode; so, large optical bursts composed by several Ethernet or IP packets are allowed, achieving a great transmission efficiency with less tuning and synchronization. The OBS procedure is handled by a DBA module, which combines WDM/TDM scheduling and Priority Queuing (PQ) with Quality of Service (QoS).

In the downstream direction, the OLT has the full bandwidth to transmit data bursts to the ONUs whenever it needs. In the upstream direction, the DBA module monitors the ONUs traffic status with a polling cycle [64]. The polling cycle T_c must be slightly lower than the aggregation time t_{edge}. It is divided into two periods: an update signalling period T_s and a dynamic transmission period T_d. The update period is divided into N_0 equal fixed control slots, being N_0 the number of the R-ONUs (Figure 60); the active R-ONUs are polled consecutively to inform their status to the OLT in request messages. The transmission period T_d is a wide window used for upstream and downstream data transmission on demand. The duration of the cycle is:

$$T_c = T_s + T_d = N_0 \left(t_{co} + t_{LD} \right) + T_d$$

where t_{co} is the ONU slot control time and t_{LD} is a guard time separating two consecutive slot times for the LD on/off switch and tuning, which nowadays can be inferior to 1’s.

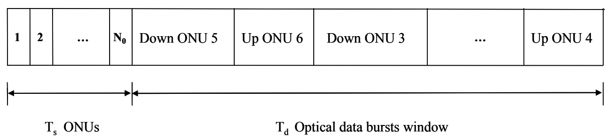


Figure 68: *Time resources for control signaling and variable down and up-data bursts.*

The control for down and up data transmission is located at the OLT, which is aware of the network traffic needs. A previous DBA protocol for the SUCCESS-HPON access network with polling cycle and scheduling algorithms has been proposed, lacking of QoS [65]. To provide QoS with differentiated P_i Classes of Service (CoS), scheduling data packets with PQ is required at the OLT for downstream and at the ONUs for upstream. We consider three priorities CoS: P_1, P_2 and P_3; with P_1 the highest priority and P_3 the lowest. The simplest QoS queuing rule is Strict Priority (SP); it maintains a First Input First Output (FIFO) queue for each priority level, and it always selects for transmission the first data burst from the nonempty FIFO queue with the highest priority.

The LDs at the OLT serve both downstream and upstream transmission in an Intensity Modulation/Direct Detection (IM/DD) format and a half-duplex operation. The incoming data burst requests are placed in a FIFO queue at the OLT DBA module or in three CoS queues if PQ is considered, applying then the SP queuing rule. In up-transmission, if equal distances OLT-ONUs, the way the carrier bursts are generated, the same way they arrive up-modulated at the PDs after the common Round Trip Time (RTT), which is twice the propagation time from OLT to ONU, and no additional consideration is needed in the DBA module. But this is not the general case and collisions may occur at the reception PDs, depending on each R-ONU RTT. To avoid collisions the up-burst can be delayed to the last received burst or, if the RTT is small, nested by using a nesting ranging algorithm [66].

5.5.14 Traffic performance and simulation results

We model each P_i CoS data source with a Variable Bit Rate (VBR) flow [64].The VBR data has a mean b_{in}; hence, the average burst length is $L_{burst} = t_{edge} b_{in}$. The output optical burst bit rate is b_{opt}, with $b_{opt} > b_{in}$, and the ratio $A = b_{opt} / b_{in}$ is the rate gain. The Wavelength Holding Time t_{WHTi} is

$$t_{WHT} = t_{idle} + t_t = t_{idle} + t_{edge} / A \cong t_{edge} / A$$

where $t_t = L_{burst}/b_{opt}$ is the transmission time of the burst, and t_{idle} is a guard time where the reserved wavelength is idle and not used to transmit, being $t_{idle} << t_t$. The optical load per active user L_{ou} in Erlangs, having every input flow the same b_{in}, does not depend on the aggregation time t_{edge}, thus it is independent of the CoS:

$$L_{ou} = t_{WHT} \big/ t_{edge} \cong 1 \big/ A << 1$$

with N_u active users, which include OLT and ONUs users, the data burst optical load is $A_d = N_u L_{ou} \cong N_u / A$.

In the SARDANA network, the optical rate b_{opt} for downstream is 10 Gb/s and for upstream is 2.5 Gb/s. A rate gain A = 100 guarantees a mean data source VBR b_{in} of 100 Mb/s and 25 Mb/s for down and up transmission, respectively. The signalling polling traffic is ignored in simulations because is less than 1% of the total traffic [64].

In a first simple simulation case we suppose Short Range Dependence (SRD) traffic exhibition, so we generate down and up-bursts in Poisson arrivals with arrival mean t_{edge} per burst and time of service exponentially distributed (M/exp) with mean service time t_{WHT}. In a more practical self-similar scenario, we consider Long Range Dependence (LRD) burstiness behavior, which we emulate with the M/Pareto model [64]: again, the bursts are generated randomly in a Poisson distribution, but with Pareto time of service distribution with mean service time t_{WHT}. The Hurst parameter H is chosen to be 0.7, not very high because burst assembly reduces slightly the self-similarity. We consider three differentiated P_i CoS, with traffic load distribution in 20% for the first and second CoS and 60% for the third best-effort CoS. The aggregation time t_{edge} is set to 20 ms for all CoSs and the bit rate gain ratio is $A = b_{opt} / b_{in} = 100$, providing a mean time of service t_{WHT} = 0.2 ms, equal for each CoS. First simulations have been executed for equal distance OLT-ONUs, one LD server and SP rule; this case matches the simple OLT structure (Figure 58) or the structure with TLDs with only one TLD per optical region (Figure 59):

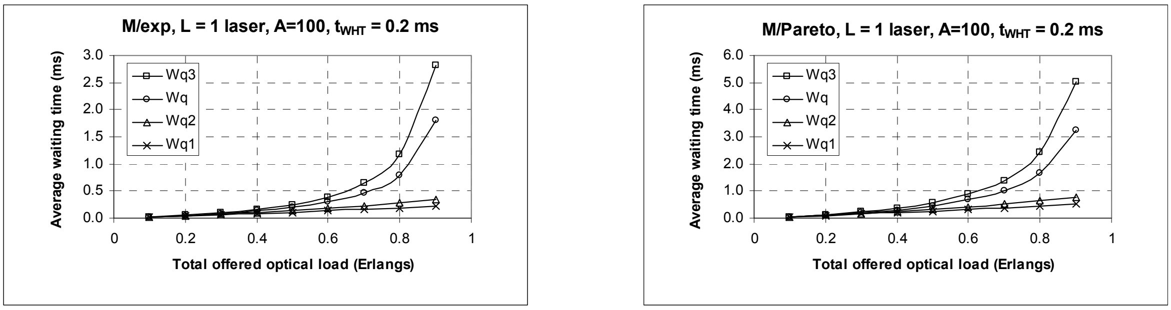


Figure 69: ***Total average waiting time W_q and W_{qi} for each CoS, with only one LD server and Strict Priority queuing with 3 CoS. On the left under M/exp (SRD) traffic, on the right under M/Pareto (LRD) traffic.***

The results under LRD traffic (Figure 61) show that the average waiting times for the first and second CoS to be served are very low; for a high load of A_d = 0.8 Erlangs, which corresponds to 80 active users, they are inferior to 0.6 ms, while for the best-effort CoS the average waiting time reaches up to 2.4 ms and the total W_q is 1.7 ms.

We consider now two TLDs servers in an optical region of several tPONs (Figure 59), equal distance OLT-ONUs and without PQ. The DBA module must take into account in which tPON each ONU is situated, because every tPON has its own wavelength and while an ONU is served in a tPON, no other ONU in the same tPON can be served simultaneously; therefore, a new ONU in queue to be served must wait the wavelength/tPON to be free, even though the second TLD is free. The ONUs are supposed to belong to the tPONs in a uniform distribution. Simulations results without PQ show the dependence of the waiting time with respect to the number of tPONs involved: the lower is the number of tPONs the greater is the waiting time, for the same total number of users. But this effect is only considerable for a very low number of tPONs, especially for two tPONs, and at high traffic load, and even in this case the average delays W_q are acceptable, as depicted in Figures 62 and 63:

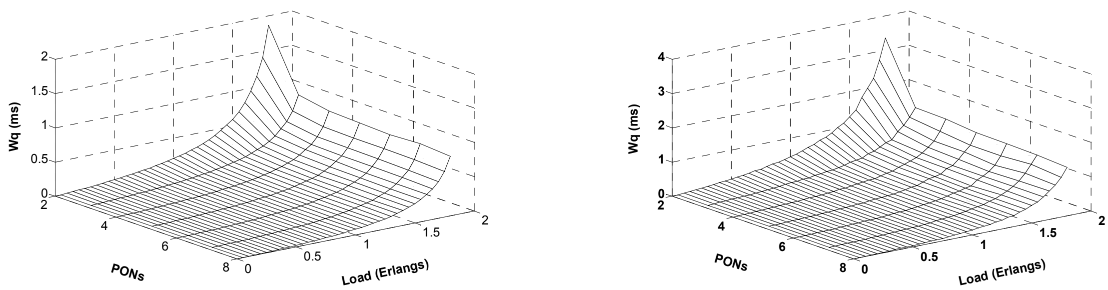


Figure 70: ***Average waiting time W_q with 2 TLDs for downstream and upstream, without Priority Queuing and different number of tPONs. On the left under M/exp (SRD) traffic, on the right under M/Pareto (LRD) traffic.***

When PQ with Strict Priority is considered in the simulations, the performance under LRD traffic for 8 tPONs exhibits for first and second CoS delays inferior to 0.3 ms for 1.8 Erlangs (Figure 63), which correspond to 180 active users. But with only 2 served tPONs these delays increase up to 2 ms because of the blocking tPON effect.

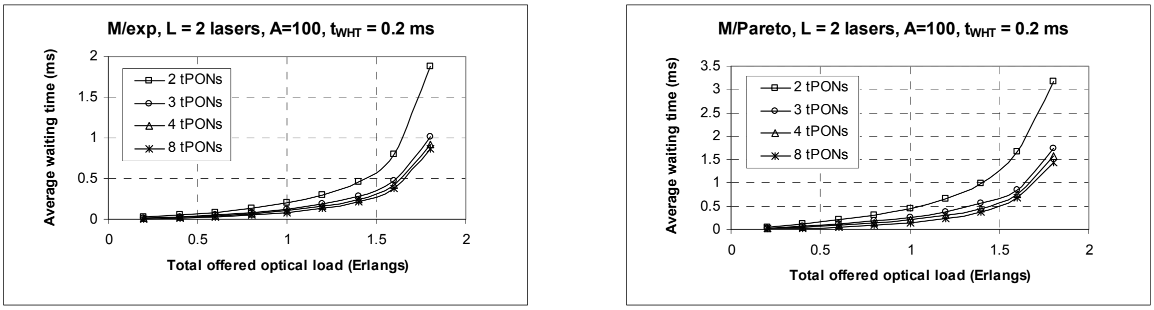


Figure 71: ***W_q with 2 TLDs for different number of tPONs; left under SRD traffic, right under LRD traffic***

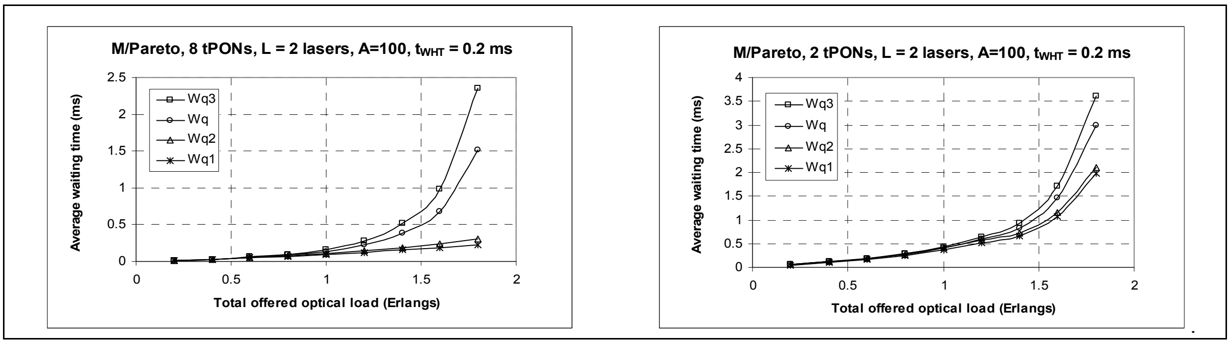


Figure 72: Total average waiting time W_q and W_{qi} for each CoS with 2 TLDs, Strict Priority queuing discipline and under LRD traffic; on the left for 8 tPONs, on the right for 2 tPONs

Two OLT designs for the SARDANA network have been presented. While in the first design there is a Fixed LD dedicated to each tPON and wavelength, in the second design Tunable LDs are shared by a number of tPONs in sub-band optical regions, in this way a better traffic efficiency is achieved. The TLDs also protect the network from device failure. A DBA based on OBS has been proposed to suit the traffic needs. Both OLT designs have been evaluated by simulations in SRD and LRD traffic behavior and Priority Queuing. The design with TLDs in optical regions has been simulated with two TLDs and users distributed uniformly in several number of tPONs. The results show that the use of shared TLDs does not increase significantly the delay, while furnishes better network efficiency and protection failure. Finally, employing PQ with a Strict Priority discipline improves the DBA: the latency of prioritized packets is notably reduced, even if TLDs shared by several tPONs are used.

5.5.15 References

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Annex 1: Inventory of Expertise – Summary

	Advanced G/E-PONs	WDM-PON architectures and techniques	Radio-over-fibre techniques - Fixed	Radio-over-fibre techniques - Mobile	High Bandwidth Free-Space-Optics (FSO)	Hybrid access architectures	Dynamic bandwidth allocation techniques	Techno-economic bench-marking of access solutions	Fault and performance monitoring in access	Communication protection and robustness.	Deployment field trials models	Quality of Service	Metro Access Convergence and Extended	Impact of RoF on wireless planning	VDSL-over-fibre techniques	Media Access	MAC layer design issues for access networks	Traffic Management and Billing	UWB over Fibre	Optical switching for radio-over-fibre infrastructures	Security issues in access networks	CDMA-PON
IT	X	X	X		X				X	X	X		X			X					X	X
POLIMI	X	X						X									X					
UoESSEX		X	X			X									X				X		X	X
RDTL			X	X		X								X	X							
UoE	X	X	X			X	X								X				X			
RDTL			X	X		X								X	X							
Ericsson									X													
UDE			X	X	X	X	X							X	X							
UNIROMA3	X	X																			X	X
UNIMORE	X						X															
UC3M		X	X																			
DTU	X	X	X	X	X	X	X					X				X						
TUe	X	X	X	X		X			X				X	X						X		
UCAM		X	X	X		X		X				X				X						
UoA		X																	X			
IBBT	X					X		X														
UPVLC		X	X	X		X		X	X	X	X	X	X	X	X							
TUW		X											X									
FUB	X	X				X	X	X		X	X	X	X		X	X						
KTH	X	X					X	X	X	X		X				X						
ENST	X	X				X	X					X	X	X								
GET		X				X	X		X			X	X			X						
CORITEL	X	X	X				X					X										
AGH		X					X	X				X						X				
UCL		X	X	X		X	X						X			X						
FT	X	X	X			X							X									
ISCON	X				X				X													
AIT		X						X					X				X					