SEVENTH FRAMEWORK PROGRAMME

Report on Y2 activities and new integration strategy

FP7-ICT-216863/UCL/R/PU/D13.2

Project Number: FP7-ICT-2007-1 216863

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

Contractual Date of Deliverable: 30/11/09

Actual Date of Delivery: 22/12/09

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, Mike Parker (UoEssex), Gabriella Cincotti (UniROMA3), Frédéric Lucarz (GET), Miroslaw Kantor (AGH), Francesco Matera (FUB

Abstract:

This 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 second 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 further in the third 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

The information, documentation and figures available in this deliverable, is written by the BONE ("Building the Future Optical Network in Europe*) – project consortium under EC co-financing contract FP7-ICT-216863 and does not necessarily reflect the views of the European Commission*

Table of Contents

1. Executive Summary :

The deliverable is the second 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 second 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 third year of the project.

Currently six joint activities have been identified as having critical mass across the partners. There are:

1) Hybrid optical wireless networks
2) Techno-economic analysis of optical access networks
3) Secure OCDMA based PONs
4) Millimeter-wave radio over fiber
5) Quality of Service in PONs
6) 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 three of the project.

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 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 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 by 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.

2. Integration Strategy

2.1 Introduction

Much integration had already been achieved in the previous e-Photon/ONe and e-Photon/ONe+ projects, and in the first year of the project as reported in FP7-ICT-216863/UCL/R/PU/D13.1. 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 as having the most economic impact by offering impartial and forward looking evaluations of appropriate new technologies.

2.2 Mechanisms of Integration

In the second year of the project the VCE has continued to create and demonstrate integration. A number of areas of integration were proposed. In the next sections we identify progress towards these aims and discuss future plans.

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

Originally 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 to the development of broadband access. This has been reviewed during this second year. 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 the inventory of expertise, 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 six joint activity areas have been identified:

1) Hybrid optical wireless networks
2) Techno-economic analysis of optical access networks
3) Secure OCDMA based PONs
4) Millimeter-wave radio over fiber
5) Quality of Service in PONs
6) 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.

2.2.2 New research proposals

Under the initiative of GET, AIT, UCL, UPC, IBBT and external industrial partners a STREP proposal was submitted for a European project called “Fixed Mobile Broadband Access convergence (FIMOBA)” to the FP7-ICT-2009-4. This project has not been selected, mainly because of the absence of a major wireless carrier or vendor in the consortium. Some of the BONE partners listed above aim to pursue their investigations in this direction in the context of JA1 of WP13.

It is estimated that future wireless networks (IEEE 802.16m WiMAX, LTE) operating at high carrier frequencies (above 5 GHz) will require a cellular density at least five times higher than it is the case in current cellular networks. In addition, the emergence of femto-cells should enable to increase considerably cellular networks capacity at the price of the integration of pico-cells within current macro or micro cells. Such evolutions induce two problems. First, a greater the superimposition of different types of cells using a priori the same radio technology increases considerably the complexity of cellular planning. Second, the current tree architecture adopted for Radio Access Networks is not scalable in terms of cost to a much higher and non-uniform density of the radio cells. The FIMOBA project aims to propose an innovative metro-access network architecture and control plane for seamless broadband ubiquity well suited to this new environment. It relies on the design of a physical all-optical WDM loop infrastructure on which are connected via OADM NG-WDM-PONs or NG-radio cells. Thanks to the development of original control/management planes, dynamic upstream/downstream optical and radio resources allocation should be facilitated. Functionalities such as dynamic radio signal power control should reduce considerably the OPEX cost of the network. In order to also reduce CAPEX costs, geographical and time traffic fluctuations are considered for bandwidth balancing between cells and PONs at the metropolitan scale, thanks to the design of innovative control and management planes. At the physical layer, FIMOBA proposed to exploit the benefits of advanced opto-electronic devices and systems (AWG routers, RSOA modulators) and of Radio-over-Fiber (RoF) modulation. New business models in multi-carrier environment can be considered on the FIMOBA architecture. The feasibility of basic elements of the this architecture have already been demonstrated by several partners of the consortium and that are also in BONE (UCL,AIT, UPC). The ambitious target of the FIMOBA’s project was to deal with RoF modulation formats operating at radio frequencies up to 60 GHz. For financial reasons, such an objective has to be abandoned in the context of BONE. In summary, the FIMOBA network architecture and control/management planes aim to reduce considerably CAPEX/OPEX costs for ISPs and radio-mobile operators. Optical transparency and dynamic radio power control could favor important energy savings. Based on broadband ubiquity, FIMOBA will allow the provision of new types of services from either the operators or the municipalities.

2.2.3 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 3.2. Further mobilities within the JA will be encouraged.

2.2.4 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 in year two:

- **BONE WP13 conference call** held on 23rd April 2009

- **European Workshop on photonic solutions for wireless, access and in-house networks** on May 18-20, 2009. The workshop took place at UDE and Fraunhofer InHaus2. A good resonance with over 80 participants and more than 50 papers presented in 7 sessions (1 poster session). (Link: http://www.ist-iphobac.org/workshop/program.asp) The workshop was co-organised by the following European projects: ALPHA, BONE, euroFOS, FUTON, GIBON, HECTO, IPHOBAC, ISIS, OMEGA, and UROOF. The aim of the workshop was to provide an overview on actual research activities in Europe in the area of photonic communications (wireline and wireless for access and in-house), to foster European cooperation in that areas and to provide a forum for discussing about future activities at a European level. Technical demonstrations were organised during the workshop as well as laboratory visits at UDE department and Fraunhofer Gesellschaft InHaus2.
- **JA 2 Meeting in Kraków** with Miroslaw Kantor (AGH), Attila Mitcsenkov (BME) Lena Wosinska (KTH) and Bart Lannoo (IBBT). They have discussed their research in the field of techno-economic analysis of optical access networks, including the in-depth cost analysis and BME topology designer framework, and found interesting new directions of joint research. Using the BME topology designer methodology allows handling larger, real-life scale scenarios and realistic topologies for different network architectures, and the proposed CapEx and OpEx investigations significantly improve the accuracy and strength of the techno-economic comparison. These altogether enable comparison of different network architectures not only in theoretic sample case studies but for realistic scenarios as well.
- **Special BONE and SARDANA session on Optical Access at the IEEE CONTEL Conference** (8-10 June 2009) that will be held in Zagreb, Croatia.
- **SARDANA-BONE Workshop on Access/Metro Networks** at 11th International Conference on Transparent Optical Networks June 28 - July 2, 2009 - Island of São Miguel, Azores, Portugal
- **LEOS Summer Topical** "Optical Code Division Multiple Access: Applications & Devices" New Port Beach, July 2009, organized and chaired by Gabriella Cincotti leader of JA 3
- **ECOC 2009**, Presentation of Invited paper on the work of BONE WP13, Vienna. "Radio over fibre Networks: Advances and Challenges"
- **SPIE Photonics West**, Presentation of Invited paper on the work of BONE WP13
- Chapter on "Free Space Optical Technologies" representing a joint work done between BONE and COST ICO802 in an e-book published by Intech.
- **Collaboration between WP13 and WP15** on a book chaper in the "Transmission Book" produced by WP15

Future Activities

- **IET Optoelectronics Journal** – A ***call for papers*** was issue for a BONE special issue of the IET Optoelectronic Journal (www.ietdl.org/IET-OPT) on ***Next Generation Optical Access*** which will be specifically linked to the BONE Virtual Centre of Excellence on Access. The deadline for submission has passed and submissions, a number of which cite BONE are currently under review.
- **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 for a proposal for this book.
- **Workshops** – A workshop and technical meeting is being planned for 2010. The current proposal is for a meeting to be held in April/May 2010.

2.2.5 Cooperation with other projects

- Formal connection between the **COST ICO0802** and EU FP7 BONE has been established in order to take benefit of the research on optical wireless carried out in the framework of the previously mentioned COST action. The fallout will interest different groups within the BONE project such as the ones related to WP13, WP02 and WP23.
- **European Workshop on photonic solutions for wireless, access and in-house networks** co-organised by the following European projects: ALPHA, BONE, euroFOS, FUTON, GIBON, HECTO, IPHOBAC, ISIS, OMEGA, and UROOF.
- **Special session on Optical Access at the IEEE CONTEL Conference** with FP7 project SARDANA
- **SARDANA-BONE Workshop on Access/Metro Networks** at ICTON 2009

3. Summary of VCE

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

3.1 Membership of the VCE

Coordinator: Dr John Mitchell, UCL.

Role	Partner Number	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	9	Centre Tecnològic de Telecomunicacions de Catalunya	CTTC	Spain
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

3.2 Mobility Actions

- *Experimental study of WiMedia-defined UWB and WiMAX 802.16e radio coexistence*
  Libera Cavallin, Student at PoliTO, hosted by UPVLC from 23/02/2009 to 31/03/2009
- *Technical feasibility study of a millimetre wireless-over-fibre link in a ring network for broadband communication*
  Florent Cougoule, Master Student at GET, hosted by UCL from 20/04/2009 to 18/09/2009
- *Resilient pump strategies for extended PON architectures*
  Victor Polo, PostDoc at UPC, hosted by ISCOM from 26/05/2009 to 29/05/2009
- *Reliability analysis of PON architectures*
  Lena Wosinska, Professor at KTH, hosted by AGH from 03/06/2009 to 06/06/2009
- *POF devices*
  Rebecca Chandy, PhD at Ericsson, hosted by UDE from 07/09/2009 to 15/09/2009
- *RoF Information Exchange*
  John Mitchell, Senior Lecturer at UCL, hosted by GET from 18/09/2009 to 18/09/2009

3.3 *Joint Papers - Year 2*

List by publication date (23)

1) J. Perez (UPVLC), M. Beltran (UPVLC), M. Morant (UPVLC), L. Cavallin (PoliTO), R. Llorente (UPVLC), *Protection Margins for Joint Operation of WiMAX 802.16e and WiMedia-defined UWB Radio in Personal Area Networks*, IEEE International Conference on Ultra-Wideband (ICUWB2009), Vancouver, Canada, September 2009.
2) J. Prat (UPC), J. Lazaro (UPC), P. Chanclou (FT), S. Cascelli (ISCOM), *Passive OADM Network Element for Hybrid Ring-Tree WDM/TDM-PON*, ECOC 2009, paper P6.23, September 2009.
3) M. Kantor (AGH), K. Wajda (AGH), L. Wosinska (KTH), J. Chen (KTH), *Techno-ekonomiczna analiza mechanizmów protekcji w optycznych sieciach dostępowych (in Polish), ("Techno-economic analysis of protection mechanisms in optical access networks")*, Polish National Conference 2009, Warsaw, September 2009
4) Valenti (FUB), S. Pompei (FUB), F. Matera (FUB), G. M. Tosi Beleffi (ISCOM), D. M. Forin (ISCOM), *Quality of Service control in Ethernet Passive Optical Networks based on Virtual Private LAN Service*, IET Electronics Letters, Vol. 45, No. 19, pp. 992-993, September 2009. (with WP11)
5) P. Reviriego (U. A. de Nebrija - UC3M), J. A. Hernandez (UAM), D. Larrabeiti (UC3M), J. A. Maestro (U. A. de Nebrija), *Performance evaluation of energy efficient ethernet*, Communication Letters, IEEE, Vol. 13, No. 9, pp. 697-699, IEEE, September 2009. (With WP21 WP22)
6) V. Sacchieri (UniRoma3), P. Teixeira (IT), A. Teixeira (IT), G. Cincotti (UniRoma3), *"A scrambling technique to enhance OCDMA network confidentiality*, IEEE Photonics Society Summer Topicals, Newport Beach, California, July 2009
7) D. Montero (UC3M), I. Gasulla (UPVLC), I. Möllers (UDE), D. Jäger (UDE), J. Capmany (UPVLC), C. Vázquez (UC3M), *Experimental analysis of temperature dependence in multimode optical fiber links for Radio-over-Fiber applications*, 11th International Conference on Transparent Optical Networks ICTON 2009, July 2009. (with WP16)
8) S. Fedderwitz (UDE), A. Stöhr (UDE), M. Weiß (UDE), V. Rymanov (UDE), A. Patra (UDE), E. Tangdiongga (TUE), D. Jäger (UDE), *1.3µm GaNAsSb/GaAs UTC-Photodetectors for 10 Gigabit Ethernet Links*, IEEE Photonics Technology Letters, Vol. 21, No. 13, pp. 911-913, USA, July 2009. (with WP16 WP23)
9) Valenti (FUB), S. Pompei (FUB), L. Rea (FUB), F. Matera (FUB), G. M. Tosi Beleffi (ISCOM), F. Curti (ISCOM), S. Di Bartolo (ISCOM), G. Incerti (UniRoma3), D. Forin (ISCOM), *Experimental Investigation of Quality of Service in an IP All-Optical Network Adopting Wavelength Conversion*, IEEE/OSA Journal of Optical Communications and Networking, Vol. 1, No. 2, pp. A170-179, July 2009. (with WP11 WP15)
10) M. Svaluto Moreolo (CTTC), V. Sacchieri (UniRoma3), G. Cincotti (UniRoma3), *Signal processing based on trigonometric transforms for high-speed optical networks*, International Conference on Optical Transparent Networks (ICTON) , Island of São Miguel, Azores, Portugal, June 2009. (with WP15)
11) V. Sacchieri (UniRoma3), S. di Lucente (UniRoma3), P. Teixeira (IT), A. Teixeira (IT), G. Cincotti (UniRoma3), *Multi-user application of code scrambling for enhanced optical layer confidentiality*, International Conference on Optical Transparent Networks (ICTON), Azores, Portugal, June 2009

12) V. Sacchieri (UniRoma3), G. Cincotti (UniRoma3), P. Teixeira (IT), A. Teixeira (IT), *Tecniche di scrambling per incrementare la sicurezza nelle reti di accesso ottiche*, Convegno Nazionale sulle Tecniche Fotoniche nelle Telecomunicazioni (FOTONICA), Pisa Italy, June 2009.
13) M. Militello (University of Palermo), D. Forin (ISCOM-Tor Vergata), G. Incerti (ISCOM-Tor Vergata), L. Porcari (University of Palermo), A. Busacca (University of Palermo), G. M. Tosi Beleffi (ISCOM), F. Curti (ISCOM), L. Costa (IT), A. L. Teixeira (IT), *Optical dynamic monitoring in next generation networks*, IEEE CONTEL Conference, Vol. ISBN: 978-953-184-130-6, pp. 289-291, Zagreb, June 2009. (with WP15)
14) S. Fedderwitz (UDE), A. Stöhr (UDE), M. Weiß (UDE), V. Rymanov (UDE), A. Patra (UDE), D. Jäger (UDE), E. Tangdiongga (TUE), *14-GHz GaNAsSb Unitraveling-Carrier 1.3-µm Photodetectors Grown by RF Plasma-Assisted Nitrogen Molecular Beam Epitaxy*, IEEE Electron Device Letters,2009, Vol. 30, No. 6, pp. 590-592, June 2009. (with WP16 WP23)
15) R. Llorente (UPVLC), M. Morant (UPVLC), J. Puche (DAS Photonics S.L.), T. Alves (IT), J. Romme (IMST GmbH, Germany), *Cognitive Radio by Photonic Analog-to-Digital Conversion Sensing*, Second International Workshop on Cross-Layer Desing, IWCLD2009, Palma de Mallorca, Spain, June 2009. (with WP23)
16) J. Pérez (UPVLC), M. Morant (UPVLC), L. Cavallin (PoliTO), M. Beltrán (UPVLC), R. Gaudino (PoliTO), R. Llorente (UPVLC), *Experimental Analysis of WiMedia-defined UWB and WiMAX 802.16e Coexistence in Personal Area Networks*, ICT Mobile Summit 2009, Santander, Spain, June 2009. (with WP23)
17) L. Wosinska (KTH), J. Chen (KTH), C. Mas Machuca (TUM), M. Kantor (AGH), *Impact of Protection Mechanisms on Cost in PONs*, ICTON 2009, Ponta Delgada, June 2009.
18) B. Lannoo (IBBT), M. Kantor (AGH), L. Wosinska (KTH), K. Casier (IBBT), J. Van Ooteghem (IBBT), S. Verbrugge (IBBT), J. Chen (KTH), K. Wajda (AGH), M. Pickavet (IBBT), *Economic analysis of future access network deployment and operation*, ICTON 2009, Ponta Delgada, June 2009.
19) F. Matera (FUB), A. Valenti (FUB), S. Pompei (FUB), G. M. Tosi Beleffi (ISCOM), D. M. Forin (ISCOM-Uni Tor Vergata), *Unbundling and Quality of Service control in ethernet passive optical networks based on virtual private LN service technique*, 10th International Conference on Telecommunications, Vol. ISBN: 978-953-184-130-6, pp. 283-284, Zagreb, June 2009
20) M. Casoni (UNIMORE), C. Raffaelli (UNIBO), *TCP Performance over Optical Burst-Switched Networks with Different Access Technologies*, OSA/IEEE Journal of Optical Communications and Networking (JOCN), No. 1, pp. 103-112, June 2009. (with WP11 WP24)
21) R. Gaudino (PoliTO), M. Bellec (FT), I. Möllers (UDE), D. Cardenas (PoliTO), B. Charbonnier (FT), N. Evanno (FT), P. Guignard (FT), S. Meyer (FT), A. Pizzinat (FT), D. Jäger (UDE), *Future Internet in Home Networks: Towards Optical Solutions?*, Towards the Future Internet", G. Tselentis et al. (Ed.), IOS Press, ISBN 978-1-60750-007-0, pp. 160-172, Amsterdam, The Netherlands, May 2009. (with WP16 WP23)
22) Stöhr (UDE), R. Buß (UDE), B. Charbonnier (FT), F. Van Dijk (FT), A. Enard (FT), S. Fedderwitz (UDE), D. Jäger (UDE), M. Huchard (FT), J. Marti (UPVLC), R. Sambaraju (UPVLC), M. Weiß (UDE), *60 GHz Radio-over-Fiber Technologies for Broadband Wireless Services*, Journal of Optical Networking (Invited), Vol. 8, No. 5, pp. 471-487, May 2009. (with WP16 WP23)

23) L. Rea (FUB), A. Valenti (FUB), S. Pompei (FUB), L. Pulcini (FUB), M. Celidonio (FUB), D. Del Buono (ISCOM), G. M. Tosi Beleffi (ISCOM), *Quality of Service Control in a multi-access integrated network based on Virtual Private LAN Service*, IPHOBAC 2009, Duisburg, May 2009.

4. Current Joint Activities

4.1 Joint Activity - Techno-economic analysis of access networks

4.1.1 Members

AGH, BME, IBBT, KTH, AIT, FUB, PoliTo

4.1.2 Objectives

Access networks are one of the fastest growing parts of the telecommunication area. They include electrical, optical and radio resources, and a variety of protocols to facilitate the communication. Finding the right techniques, protocols and functionalities, fulfilling all required factors, as a universal solution is hard to obtain.

There are many factors that have to be taken into account when implementing and managing access networks. Among the most important factors are the ones related to cost efficiency. Thus, the major objective of this joint activity is to provide research on selected domains in access networks towards increasing cost efficiency of interaction between new and existing networks implementations.

4.1.3 Research Topics

List of the research topics considered within JA2:

- Economic analysis of future access network deployment and operation
- Impact of protection mechanisms on cost in PONs
- Accurate cost analysis by topology design for FTTx access network, based on geographic and infrastructural information

4.1.4 Collaborations/Joint Experiments and Mobility Actions

Meetings:

- AGH, BME, IBBT, KTH – Krakow, 29th September 2009.

Planned joint papers:

- conference papers: ECOC 2010, CTTE 2010
- journal papers: Communications Magazine, JLT, JOCN

Mobility actions

- KTH → AGH, June 4 – 6, Lena Wosinska

Planned mobility actions (incl. mutual visits):

- BME → KTH – dates to be decided
- IBBT → KTH – dates to be decided

4.1.5 Impact

- Bart Lannoo, Miroslaw Kantor, Lena Wosinska, Koen Casier, Jan Van Ooteghem, Sofie Verbrugge, Jiajia Chen, Krzysztof Wajda, Mario Pickavet: ***Economic analysis of future access network deployment and operation,*** ICTON 2009, June 28 - July 2, 2009, Ponta Delgada, Portugal.

- Lena Wosinska, Jiajia Chen, Carmen Mas Machuca, Miroslaw Kantor: ***Impact of Protection Mechanisms on Cost in PONs***, RONEXT 2009, June 28 - July 2, 2009, Ponta Delgada, Portugal.
- Miroslaw Kantor, Krzysztof Wajda, Lena Wosinska, Jiajia Chen: ***Techno-ekonomiczna analiza mechanizmów protekcji w optycznych sieciach dostępowych*** (in Polish), KSTiT 2009, 16-18 September, 2009, Warsaw, Poland **.**
- P. Kourtessis (chapter editor), C. Almeida, C.-H. Chang, J. Chen, S. Di Bartolo, P. Fasser, M. Gagnaire, E. Leitgeb, Mário Lima, M. Löschnigg, M. Marciniak, N. Pavlovic, Y. Shachaf (assistant editor), A. L. J. Teixeira, G. M. Tosi Beleffi and L. Wosinska: ***Evolution of Optical Access Networks***, chapter in the book COST 291 - Towards digital optical networks (I. Tomkos et al., eds), LNCS 5412, April 2009.
- L. Wosinska, J. Chen and C.P. Larsen: ***Fiber Access Networks: Reliability Analysis and Swedish Broadband Market***, (Invited paper), IEICE Transaction on Communications, Vol.E92-B, No.10, pp.3006-3014, October 2009.
- L. Wosinska and J. Chen: ***How Much to Pay for Protection in Fiber Access Networks: Cost and Reliability Tradeoff***, (Invited paper), to be presented at IEEE ANTS 2009, December 14-16, 2009, New Delhi, India.
- Attila Mitcsenkov, Géza Paksy, Tibor Cinkler: ***Efficient heuristic methods for FTTx topology optimization and architecture cost minimization***, NOC 2009, 10-12 June, 2009, Valladolid, Spain.
- Attila Mitcsenkov, Géza Paksy, Tibor Cinkler: ***Topology Design and Capex Estimation for Passive Optical Networks***, BroadNets 2009, 14-16 September, 2009, Madrid, Spain.
- Koen Casier, Bart Lannoo, Jan Van Ooteghem, Sofie Verbrugge, Didier Colle, Mario Pickavet, Piet Demeester: ***Game-Theoretic Optimization of a FTTH Municipality Network Rollout***, Journal of Optical Communications and Networking, Vol. 1, Issue 1, pp.30-42, June 2009.
- Koen Casier, Bart Lannoo, Jan Van Ooteghem, Bart Wouters, Sofie Verbrugge, Didier Colle, Mario Pickavet, Piet Demeester: ***Game-Theoretic Evaluation of a Municipality FTTH Rollout***, NFOEC2009, 22-26 March, 2009, San Diego, US.

4.1.6 Research Contributions

- **Economic analysis of future access network deployment and operation**

Broadband Internet is becoming a commodity product in the Western world. The last decade, in some countries, optical fibre access or fibre to the home (FTTH) networks are extensively deployed, mainly in Asia (Japan, South-Korea…) and more recently in the US.

- **Optical fibre access networks**

Several implementations of an optical access network exist. Depending on the end point of the fibre path they are referred to as fibre to the x (FTTx).

There are two main categories of FTTx technologies, i.e. active and passive. Active optical networks (AONs) provide a (logical) point-to-point (P2P) connection between the central office (CO) and each user. Most used AON topologies are home run (HR, with a dedicated fibre from the CO to each user, also known as P2P network) and active star (AS, with a switch or router installed between the CO and the user, e.g. Ethernet switch in the street cabinet). Passive optical networks (PONs) on the other hand are point-to-multipoint (P2MP) networks, where the access fibre is shared by several users (e.g. 32, 64…) through a branched tree topology.

- **Cost components of optical fibre access networks**

The overall cycle for a fibre access network rollout is shown in Figure 1 [1]. The main costs are related to the outside plant, and especially the trenching cost for rolling out an optical fibre to every home. Another specific cost for a fibre network (and more generally a fixed network) is the physical termination at the user side.

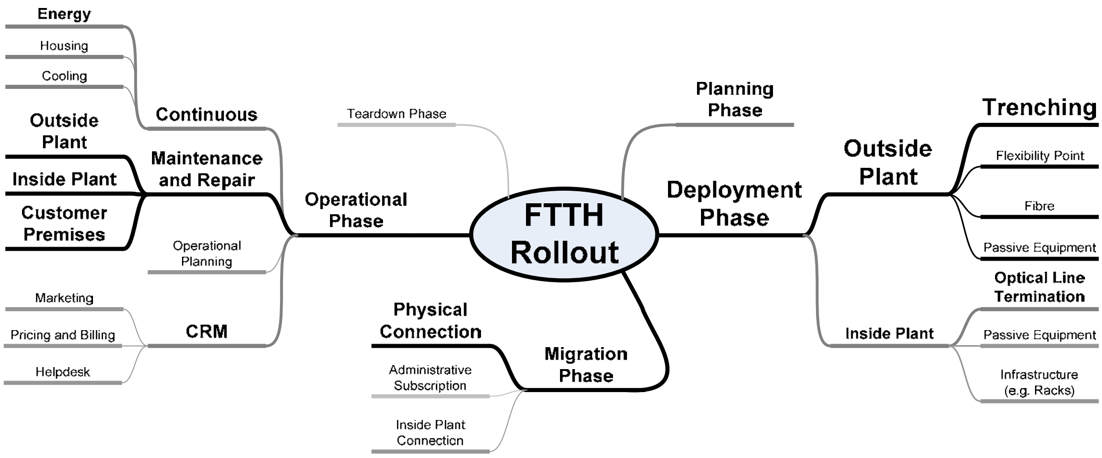
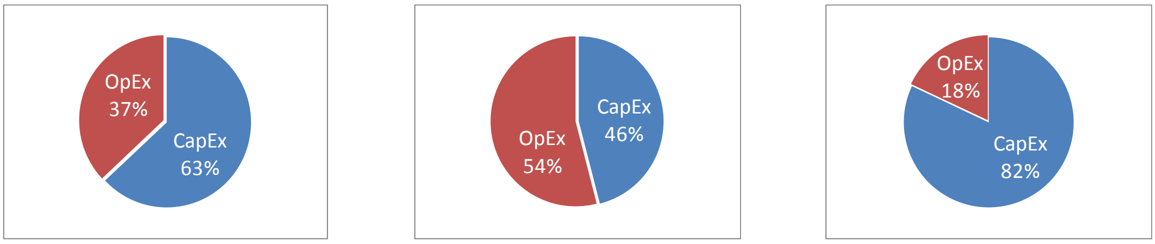


Figure 1: Cost breakdown approach for the rollout cycle of an FTTH network [1]

- **Cost comparison of fibre access networks**

To compare the cost of different fibre access deployments, three scenarios (urban, long-distance suburban, long-distance rural) have been analysed over a duration of 15 years. The detailed assumptions and more results for analysed scenarios are presented in [2].The first scenario is related to an FTTH rollout in the city centre of Ghent (Belgium) [3]. The other two scenarios consider a long-distance FTTH network (20 km between CO and user) in a suburban (i.e. collective case) and a rural area (i.e. dispersive case), respectively [4].

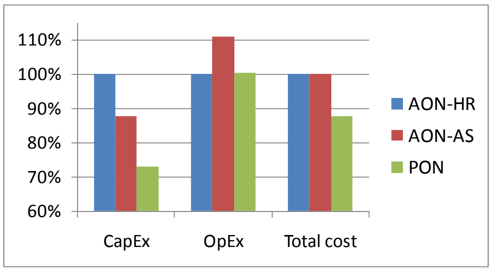
The CapEx-OpEx ratio is presented in Figure 2 for an AON-HR (or P2P) architecture. Note that a discount rate of 10% is used to incorporate the time value of money. The urban and long-distance rural cases experience the highest CapEx due to a high unit cost for trenching in an urban area vs. long distances and a high amount of fibre and trenches in a rural area. Both factors are much smaller for the considered suburban case, leading to a lower CapEx.



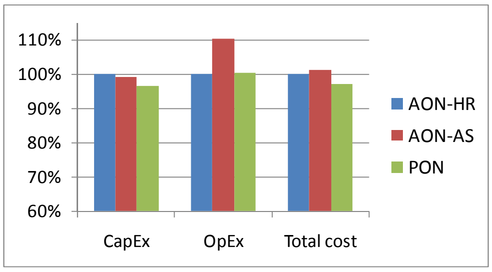
a) Urban *b) Suburban, long-distance* *c) Rural, long-distance*

Figure 2: Division between CapEx and OpEx for three considered scenarios, using an AON-HR (or P2P)

For the two long-distance cases, Figure 3 shows a relative comparison between three different FTTH architectures (AON-HR, AON-AS, PON), with AON-HR depicted as 100%. CapEx is highest for AON-HR and lowest for PON. OpEx is highest for AON-AS, containing a lot of active equipment in the field, and almost equal for PON and AON-HR. We see that the CapEx difference between the architectures decreases when going to a more expensive (rural) scenario, because the advantage of sharing fibres will decrease.



a) Suburban, long-distance



b) Rural, long-distance

Figure 3: Comparison between AON-HR, AON-AS and PON for the two long-distance scenarios

An overview of a more detailed division between CapEx and OpEx from the viewpoint of the operator is given in ***Figure 4*** for the urban case.

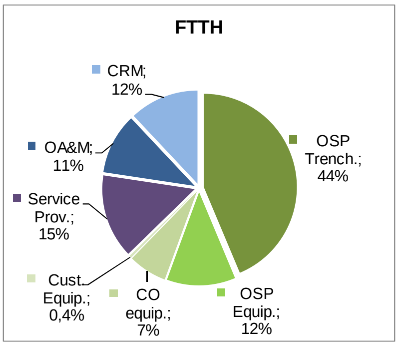


Figure 4: Detailed CapEx and OpEx breakdown for urban FTTH scenario

The largest CapEx part is the cost for the outside plant (OSP), consisting of digging and equipment (ducts, fibre) costs. Other CapEx are related to the CO and customer side. The OpEx division can be split between network related (indicated as operations, administration and maintenance (OA&M)) and service related (service provisioning and customer relationship management (CRM), consisting of pricing & billing, helpdesk, marketing) costs.

- **Cost of optical fibre access network deployments – Athens case**

To compare the cost of different optical fibre access network deployments, four scenarios (dense-urban, urban, suburban and rural) were analysed. Since the deployment of such a network is primarily a matter of population density, Athens municipalities were categorised according to their population statistics. For comparison, two architectures were considered, namely Passive Optical Network (PON), also indicated as Point-to–Multipoint (P2MP), and Active Optical Network - Home Run (AON-HR), also indicated as Point-to-Point (P2P). The difference between P2MP PON and P2P architectures is the reduced amount of feeder fibres, which depends on the splitting ratio. This model focuses mainly on the estimation of the cost/meter/duct, as well as on the estimation of an extra cost of labour/meter that includes trenching, splicing, and labour for installing ducts and micro-cables inside the trench.

In this deployment, a local convergence point (LCP) was assumed, where the feeder cables were reaching a cabinet and splitters placed inside the cabinet were used to distribute the optical signals.

Based on the above assumptions, the following results were obtained (***Figure 5***) on the "cost per subscriber" and "cost per household (HH) passed" for the case of Athens municipalities.

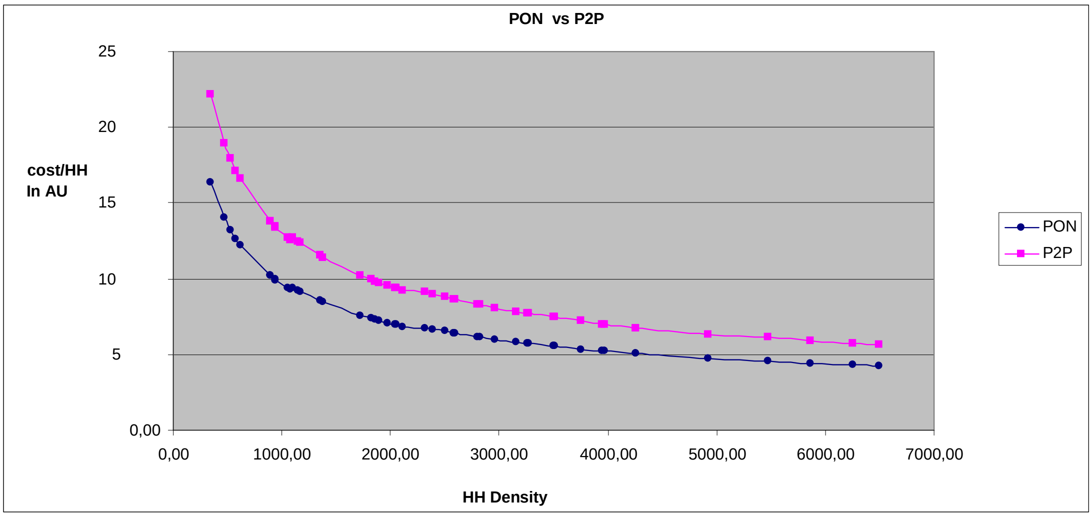


Figure 5: PON vs. P2P

The model shows a slight increase of the order of 8% of the difference of the cost/HH while one moves from dense to rural areas. The fact that in rural areas loop lengths are higher than in densely populated ones makes PON the preferable solution when deployment costs are considered.

Figure 6 shows the relation of the cost/meter/duct to the resulted cost/HH passed in the aforementioned four different scenarios.

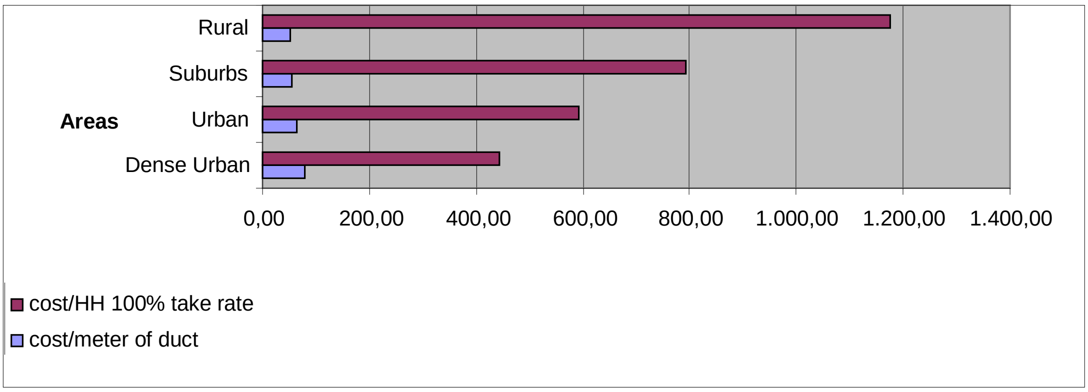


Figure 6: OSP Cost/meter vs. Cost/HH passed

Labour is typically the single largest cost for any wire-line network installation. This is shown in the results of Figure 7.

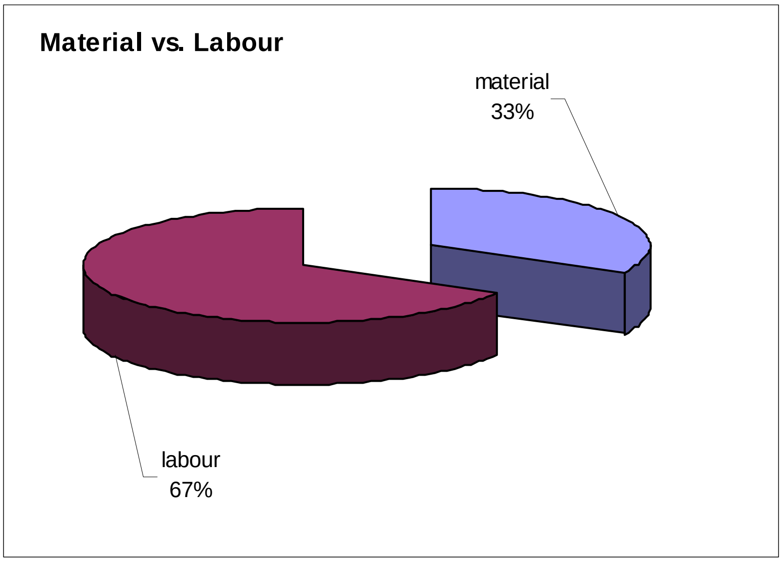


Figure 7: Labour vs. material costs

- **Impact of protection mechanisms on cost in PONs**

Passive optical networks (PONs) are considered as a promising solution for broadband access networks. Due to the growing demand for reliable service delivery, fault management in the network is becoming very significant. However, there is a trade off between the cost of protection and the level of service reliability.

Here a cost comparison of different protection mechanisms that can be applied in passive optical networks is presented. The impact that different protection approaches have on the cost related both to the equipment to be deployed and the failure reparation and service penalties to be paid is evaluated. The detailed assumptions and results are presented in [5].

- **Protection schemes in PONs**

The evolution of PON protection architectures can be divided in two phases. The first phase took place in late 90's and was based on adding more redundant components and systems. It was reflected in development of the standard PON protection architectures that were defined by ITU-T [6] around a decade ago. These standard PON protection schemes are referred to as type A, B, C and D. In Type A only the feeder fibre (FF) is redundant. Type B protection duplicates the shared part of the PON, i.e. FF and optical interfaces at the optical line terminal (OLT). Type C represents 1+1 dedicated path protection with full duplication of the PON resources. Type D protection specifies the independent duplication of FF and distribution fibres (DFs) and thus, it enables network provider to offer differentiated reliability level for the users.

In the second phase of the PON protection scheme evolution the effort was put on the development of cost-efficient architectures. In [7-9] two neighbouring optical network units (ONUs) protect each other using interconnection fibres IFs for the TDM PON, WDM PON and hybrid WDM/TDM PONs. In this way, the large amount of investment cost for burying redundant DFs to each ONU can be saved and, consequently, the CAPEX can be reduced.

- **Cost and reliability performance consideration**

In both CAPEX and OPEX studies, for all the studied architectures we consider two deployment scenarios with respect to the population density, namely, dispersive and collective. In the dispersive scenario which corresponds to the access network deployed in sparsely populated areas, we assume that FF, DF and interconnection fibre IF are 15, 5 and 2 km long, respectively. Meanwhile, the collective scenario corresponds to the access network deployed in densely populated areas where FF, DF and IF are assumed to be 19.5, 0.5 and 0.2 km long, respectively. Furthermore, access networks based on TDM PON and WDM PON are assumed to host 32 ONUs while a hybrid PON consists of 16 TDM PONs each of which supports 16 ONUs. In our study, the lifetime of a PON is considered to be 20 years. The results are based on the reliability and cost parameters presented in [10].

Deployment cost (total CAPEX) per user, for the considered PON architectures is presented in Figure 8. In our study, the total CAPEX includes the component related cost (component and fibre cost) and burying fibres. In Figure 9 the component related cost per user is presented, i.e. the burying fibre is not included here. One can observe that in general, the component related cost is much higher for architectures with protection.

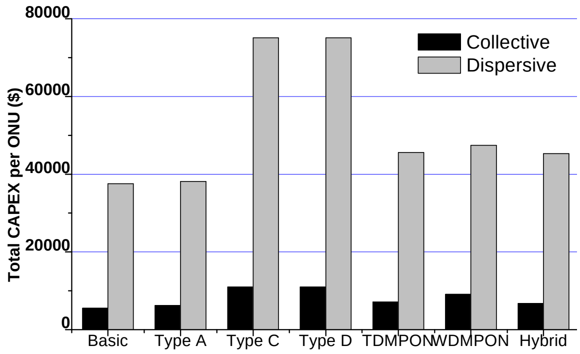


Figure 8: Capex

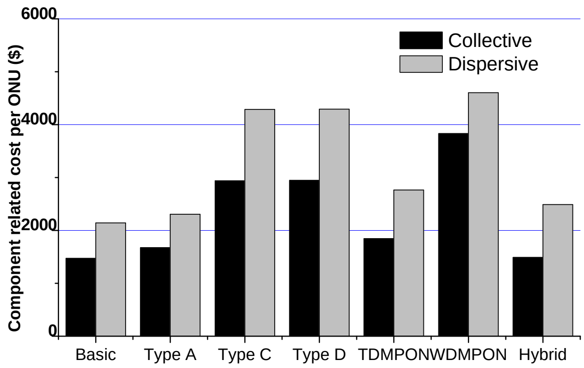


Figure 9: Component related cost

One of the most costly OPEX processes is failure reparation [11], which has been depicted in Figure 10. There are two OPEX processes associated with the impact of failures: (i) the failure reparation cost which includes the salary, spare equipment, etc. required to repair the failures that occur during the PON lifetime and (ii) the cost penalties to be paid due to the duration of the connection interruption (*costv*). The failure reparation cost has been evaluated for a 20 years lifetime. The simulation considered random failures of the network components with an exponential distribution with a parameter equal to the failure rate in FITs (Failures in 10^9 hours Time). The reparation cost, which has been plotted in Figure 11, is obtained by multiplying the reparation time with the cost per hour of one reparation employee. It can be observed that the dispersive scenario requires longer reparation times than the collective case due to the longer fibres which causes higher number of fibre failures and longer travel distances.

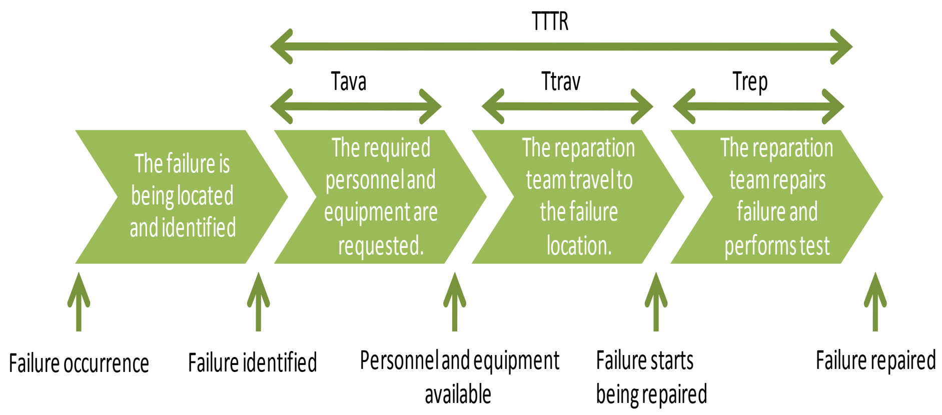


Figure 10: Failure reparation sub processes

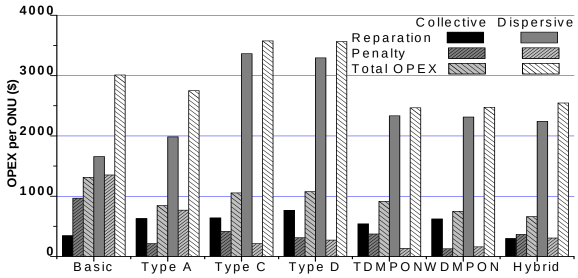


Figure 11: OPEX

The penalties that have to be paid when the connection is lost have also been computed. These penalties are proportional to the number of hours that the connection is interrupted and have also been plotted in Figure 11. Here, we assumed a service interruption penalty of 100$ per hour. The total OPEX comparison, as the sum of reparation and penalty costs, has been plotted in Figure 11.

- **Total cost vs. reliability**

In *Figure 12* we compare the component related cost and OPEX for the considered architectures while in *Figure 13* the connection unavailability is compared.

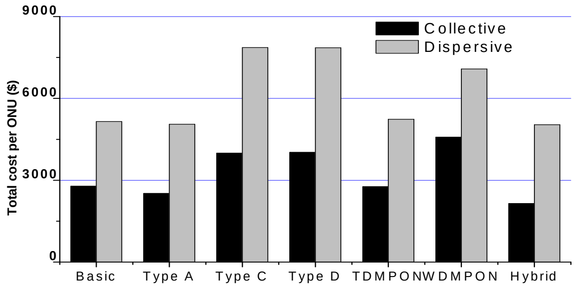


Figure 12: Total Cost

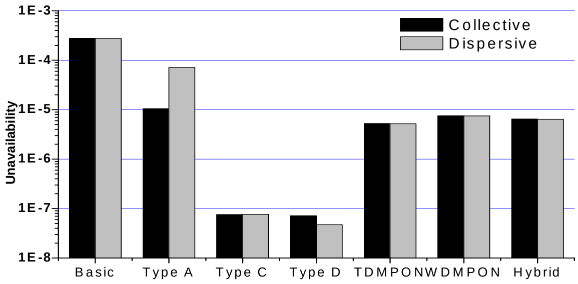


Figure 13: Unavailability

It can be seen that the total cost of the protection schemes based on the neighbouring protection, in particular TDM PON and hybrid PON, is on the same level as for the unprotected scheme and Type A while the connection availability of 99.999% (5 nines) can be achieved. In contrast, the connection availability is not acceptable in the case of unprotected PON and Type A.

- **Accurate cost analysis by topology design for FTTx access network, based on geographic and infrastructural information**

The accuracy of the cost analysis may be increased by using more information about the investigated scenarios. Typically the techno-economic comparisons are carried out on pre-defined models as scenarios, described purely by typical average values for e.g. the connection distances. Even if these models represent important, characteristic setups, the reality is slightly different: the area covered by a service provider is typically a mixture of these with densely and rarely populated areas, sometimes with significant diversity in parameters (e.g. connection distances) that are difficult to be described by average values solely.

To overcome these uncertainties, the analysis needs to be carried out on FTTx network topologies designed specifically for the chosen, characteristic scenarios. During the topology design process, the geographic and infrastructural data is taken into consideration: the actual location of subscribers, central office and network equipments, existing cable paths (ducts, manholes, etc.). The achieved network topology contains information about all the important cost components, especially for CAPEX.

However, the problem of optimal topology design is NP-hard, and due to the naturally large scale of problems (10,000s of subscriber nodes), extremely difficult to solve. Therefore an efficient heuristic methodology was developed, specific for the different FTTx network technologies (i.e. Point-to-Point dedicated fibre, PONs, VDSL and Active Ethernet). The developed algorithms provide results within the magnitude of minutes for computation, and approximate optimal (lowest CAPEX) topologies within 10-15%. A specific approximation algorithm has been developed, specifically for each network technology, in order to handle their distinct characteristics.

Detailed cost models were used, representing all the necessary information for optimization of real cost components: both cable deployment (work) and raw fibre expenses (stock) are taken into consideration, with respect to possible savings on work costs via parallel connections; the equipment costs, both for the central office and the outside plant. The network model contains all the necessary geographic (subscriber locations, street system) and infrastructural information (cable ducts, manholes, already existing networks, etc).

The development of an FTTxDesigner Framework has been started, for processing GIS (Geographic Information System) and infrastructure information, topology design based on the introduced heuristic methodology, and for the in-depth analysis of the resulting topology (e.g. CAPEX and OPEX calculations). Initial results were published in [12] and [13]. The achieved results show that the framework is suitable for the in-depth, accurate techno-economic analysis of any chosen, real network scenario.

REFERENCES

[1] K. Casier, S. Verbrugge, R. Meersman, D. Colle, M. Pickavet, P. Demeester: ***Techno-economic evaluations of FTTH roll-out scenarios***, in *Proc. of NOC2008*, pp. 113-120, Krems, Austria, 1-3 Jul. 2008.

[2] B. Lannoo, M. Kantor, L. Wosinska, K. Casier, J. Ooteghem, S. Verbrugge, J. Chen, K. Wajda, M. Pickavet: ***Economic analysis of future access network deployment and operation,*** ICTON 2009, June 28 - July 2, 2009, Ponta Delgada, Portugal.

[3] B. Lannoo, K. Casier, J. Van Ooteghem, B. Wouters, S. Verbrugge, D. Colle, M. Pickavet, P. Demeester: ***Economic Benefits of a Community Driven Fiber to the Home Rollout***, in *Proc. of IEEE Broadnets 2008*, London, UK, 8-11 Sep. 2008.

[4] L. Wosinska, J. Chen: ***Reliability performance analysis vs. deployment cost of fiber access networks***, in Proc. of IEEE Conference on Optical Internet COIN2008, Tokyo, Japan, 14-16 Oct. 2008.

[5] Lena Wosinska, Jiajia Chen, Carmen Mas Machuca, Miroslaw Kantor: ***Impact of Protection Mechanisms on Cost in PONs***, RONEXT 2009, June 28 - July 2, 2009, Ponta Delgada, Portugal.

[6] *Broadband optical access systems based on passive optical network (PON)*, ITU-T rec. G983.1, 1998.

[7] J. Chen, B. Chen, and S. He: ***Self-protection scheme against failures of distributed fiber links in an Ethernet passive optical network***, *J. of Optical Networking*, vol. 5, pp. 662-666, Apr. 2006.

[8] T. Chan, C. Chan, L. Chen, and F. Tong: ***A self-protected architecture for wavelength division multiplexed passive optical networks***, *IEEE Photon. Technol. Lett.*, vol. 15, pp. 1660–1662, Nov. 2003.

[9] J. Chen, and L. Wosinska: ***Protection schemes in PON compatible with smooth migration from TDM-PON to Hybrid WDM/TDM PON***, *J. of Optical Networking*, vol. 6, pp. 514-526, May 2007.

[10] L. Wosinska, and J. Chen: ***Reliability Performance Analysis vs. Deployment Cost of Fiber Access Networks***, 7th International Conference on Optical Internet, COIN'08, 2008.

[11] C. Mas Machuca, O. Moe, M. Jäger: ***Modelling of OpEx in network and service life-cycles***, in *ECOC 2007 OpEx Workshop* September 2007.

[12] Attila Mitcsenkov, Géza Paksy, Tibor Cinkler: ***Efficient heuristic methods for FTTx topology optimization and architecture cost minimization***, NOC 2009, 10-12 June, 2009, Valladolid, Spain

[13] Attila Mitcsenkov, Géza Paksy, Tibor Cinkler: ***Topology Design and Capex Estimation for Passive Optical Networks***, BroadNets 2009, 14-16 September, 2009, Madrid, Spain

4.2 Joint Activity - Secure OCDMA-based PONs

4.2.1 Members

UNIROMA3, NICT, IT, UCL, UCAM, UoEssex, CTTC, IT

4.2.2 Objectives

The key requirement for the next-generation of passive optical networks (PON) is to provide significantly more bandwidth per subscriber than is currently available in commercial fiber-to-the-home (FTTH) systems, relying on larger splitting ratios and low-cost optical network units (ONUs). Wavelength division multiplexing (WDM)-PON is considered an effective solution to upgrade existing systems, in which a logical point-to-point (P2P) link in the access infrastructure is established by assigning a separate upstream/downstream wavelength to each end user. The primary advantage of this technology is that each subscriber can use his preferred data rates, independent of the signal rates and formats used by the other subscribers; the main drawbacks are the cost of the optical components to generate and filter different wavelengths, and their limited confidentiality. In fact, the current FTTH standards IEEE 802.3ah and ITU G.983 for Ethernet PONs (EPONs) and broadband PONs (BPONs) do not specify any authentication or encryption mechanisms, whereas ITU G.984 for Gigabit-capable PON (GPON) use Advanced Encryption Standard (AES) for downstream transmission. The complexity of cryptographic methods used in the secure sockets layer (SSL) protocol is proportional to the corresponding key length, and electronic encryption can become a real bottleneck in high-speed secure networks. Optical cryptography can overcome this limitation, with the additional advantage that encrypted optical data are difficult to record for off-line deciphering. During the past years, optical code-division multiple access (OCDMA) technology has proven to be a promising alternative solution for next-generation PONs that, like WDM-PON, allows independent data rates and formats for each user; in addition, OCDMA-PON generally does not require multiple or tuneable laser sources, and cost-effective solutions have been demonstrated.

In this JA, we investigate the confidentiality of OCDMA-based PONs, considering different bit and block ciphering schemes, or different code scrambling techniques. We have demonstrated secure full duplex OCDMA-based transmission, with 8 10 Gb/s users access e network in a complete asynchronous way. Furthermore, we have investigated different modulation formats, like OFDM, that can enhance the system performance.

4.2.3 Research Topics

Confidentiality of bit and block ciphering

Field-trial OCDMA-based PONs

Scrambling techniques to enhance security

OFDM- OCDMA transmission

Mitigation of Group Velocity Dispersion in Optical CDMA using Electronics

4.2.4 Collaborations/Joint Experiments and Mobility Actions

UNIROMA3 and CTTC had a technical discussion during the conference ICTON 2009, Azores Portugal.

UNIROMA3 and NICT had a technical discussions during the conference ICTON 2009, ECOC2009 and OFC2009.

4.2.5 Impact

1. G. Cincotti, N. Wada, K.-i. Kitayama, “Secure OCDMA-based PONs,” invited paper Fiber Communication Conference (OFC), San Diego, California 2009.
2. G. Cincotti, N. Kataoka, N. Wada and K.-i. Kitayama, “Perspectives of optical coding/decoding techniques in OCDMA networks,” invited paper Asia Communications and Photonics Conference and Exhibition (ACP) Shanghai, China 2009.
3. G. Cincotti, “On the security of spectrally encoded quantum-encryption protocols,” IEEE Photonics Society Summer Topicals 2009, Newport Beach, California 2009.
4. T. Kodama, N. Nakagawa, N. Kataoka, N. Wada, G. Cincotti, X. Wang, T. Miyazaki, K.-I. Kitayama, "Secure 2.5Gbit/s, 16-ary OCDM block-ciphering with XOR using a single multi-port en/decoder and its transmission experiment with true clock recovery,” Optical Fiber Communication Conference (OFC), San Diego, California 2009.
5. N. Kataoka, T. Kodama, N. Wada, G. Cincotti, X. Wang, T. Miyazaki, K.-I. Kitayama, "Demonstration of secure 2.5 Gbps, 256-ary polarization-multiplexed OCDM transmission using a single multi-port encoder/decoder,” Conference on Laser and Electrooptics (CLEO), Baltimore, Maryland, USA 2009.
6. N. Kataoka, N. Wada, X. Wang, G. Cincotti, A. Sakamoto, Y. Terada, T. Miyazaki, K.-i. Kitayama, "Field trial of duplex, 10 Gbps x 8-user DPSK-OCDMA system using a single 16x16 multi-port encoder/decoder and 16-level phase-shifted SSFBG encoder/decoders,” IEEE/OSA Journal of Lightwave Technology, 27, 3, 299-305 (2009).
7. N. Kataoka, N. Wada, X. Wang, G. Cincotti, T. Miyazaki, K.-I. Kitayama, "A bandwidth-symmetric, scalable NGN FTTH system: demonstration of full-duplex, asynchronous, DPSK-OCDMA System with 10Gbps x 4-uplink and 8-downlink without FEC,” 13th Conference on Optical Network Design and Modelling (ONDM), Braunschweig, Germany 2009.
8. N. Kataoka, X. Wang, G. Cincotti, N. Wada, K.-i. Kitayama, “Performance improvement of 16-level-phase-shifted SSFBG encoder/decoder for OCDMA system using apodization technique,” 14th OptoElectronics and Communication Conference (OECC) HongKong, China 2009.
9. N. Kataoka, X. Wang, N. Wada, G. Cincotti, K.-I. Kitayama, “8x8 Full-duplex demonstration of asynchronous, 10Gbps, DPSK-OCDMA system using apodized SSFBG and multi-port en/decoder,” European Conference on Optical Communication (ECOC), Wien, Austria 2009.
10. V. Sacchieri , P. Teixeira, A. Teixeira, G. Cincotti, “A scrambling technique to enhance OCDMA network confidentiality,” IEEE Photonics Society Summer Topicals 2009, Newport Beach, California 2009.
11. V. Sacchieri , S. Di Lucente, P. Teixeira, A. Teixeira, G. Cincotti, “Multi-user application of code scrambling for enhanced optical layer confidentiality,” International Conference on Optical Transparent Networks (ICTON) Azores, Portugal 2009.
12. V. Sacchieri, G. Cincotti, P. Teixeira, A. Teixeira, “Tecniche di scrambling per incrementare la sicurezza nelle reti di accesso ottiche,” Convegno Nazionale sulle Tecniche Fotoniche nelle Telecomunicazioni (FOTONICA), Pisa, Italy 2009.

13. Svaluto Moreolo, V. Sacchieri, G. Cincotti, “Signal processing based on trigonometric transforms for high-speed optical networks”, 11th International Conference on Transparent Optical Networks (ICTON 2009), June 28-July 2, 2009, Island of São Miguel, Azores, Portugal.

4.2.6 Research Contributions

OCDMA could potentially be considered a suitable solution for physical-layer secure transmission, because each user encrypts each bit of the message into an optical code, and the transmitted data cannot be detected without the matched decoder. However, standard OCDMA transmission corresponds to a simple bit-ciphering protocol, and a system employing two different codes to transmit logical marks and spaces can be easily broken by differential cryptanalysis, using a differential phase shift keying (DPSK) receiver. In this case, the increase of the number of possible optical codes and/or the use of sophisticated techniques, while useful to protect data against ciphertext only attacks, do not help against known-plaintext attacks, where the eavesdropper is able to sift through plaintext and ciphertext pairs. In general, bit-ciphering schemes cannot be considered secure, and only stream and block-ciphering schemes should be used [1-3]. In the latter case, a block of *n* bits of the plaintext is transformed into a ciphertext with at least 2^n determinations. For instance, electronic symmetric encryption systems are 64 or 128-bit block ciphers, designed to generate a one-to-one mapping that looks random. UNIROMA3 and NICT have experimentally demonstrated a fully optical block-ciphering scheme, that has also a larger spectral efficiency with respect to standard bit-ciphering OCDMA [4]. This scheme is the optical implementation of the electronic codebook (ECB) encryption, where the message is divided into blocks of 4 bits via parallel to serial conversion, that are encrypted separately using 16 different optical codes and transmitted at a speed of 2.5Gb/s. The system has two levels of privacy protection: first of all, an adversary has to be able to detect the optical code (physical layer security), and later he or she has to find the correspondence between the code and the sequence of the 4 bits (computational security). This scheme is completely secure against brute-force attacks, but it can be broken with differential cryptanalysis, since it cannot hide data patterns; in fact, in this first proof-of-principle experiment, a fixed code word corresponds to a given 4-bits sequence, so that identical plaintext blocks are encrypted into identical ciphertexts. To increase the confidentiality, it is necessary to encrypt many times the same message, generating different ciphertexts, by programming the field programmable gate array (FPGA). Complete confidentiality has been achieved by substituting the line encoder with a cipher block chaining (CBC) encryption module, where each block of plaintext is XORed with the previous ciphertext block before being encrypted [5].

UNIROMA 3 and NICT have performed many field-trial experiments of OCDMA-based PONs, where a multi-port encoder/decoder is employed in the optical line terminal (OLT); this device has the unique capability of simultaneously processing multiple time-spread optical codes and therefore its use allows use to reduce the number of devices needed. On the other hand, in the ONUs, we can use phase-shifted superstructured fiber Bragg grating (SSFBG) encoder/decoders, that is polarization insensitive and presents low and code-length independent insertion loss, compactness as well as low cost for mass production. Hybrid using different types of the encoder/decoder in an OCDMA network is expected to significantly improve the system flexibility and performance [6-9].

UNIROMA3 and IT are continuing their join research on scrambling-based OCDMA networks, that are highly secure since a potential attacker cannot detect the message without knowing the codes; in fact, to guess the code, it is necessary to test all the possible combinations between the available code words and therefore the degrees of freedom of the cryptographic system are increased. Numerical simulations of a point-to-point (P2P) transmission with a scrambling approach based on super structured fibre Bragg gratings (SSFBGs) have been done over a 20-km link, showing that after the scrambling the signal is fully distorted and the secret key space grows exponentially with the number of encoders used and with the number of available code words. BER measurements show that the eavesdropper cannot reveal the transmission, whilst the authorized user can detect correctly the signal after the fibre link, achieving a BER<10-9 [10, 11]. In addition, two different configurations for a multi-user environment have been considered [12]: In the first one, each user is equipped with a cascade of two OCDMA encoders, that operate as encoder and scrambler, and system performance with one and two interfering channels have been investigated. In both cases, the eye diagram of the intended receiver is adequately open, whereas the eye diagram measured for the eavesdropper has many levels, leaving the signal fully distorted. The scrambled signals from the users are combined together and sent over 30-km single mode fibre. BER measurements have been performed to compare the performance of the authorized and unauthorized user and for both one and two interfering channels (*Figure 14*). The multiuser access interference (MAI) noise helps in hiding the message, making worse the detection for an eavesdropper not equipped with the matching codes. In the second configuration, the signal of each user is encoded with a single encoder, then all the signal are combined together by using an optical combiner and the multiplexed OCDMA signal is scrambled with another encoder, before being transmitted over a 20-km link. Also in this case eye diagrams and BER have been measured, showing that the intended user receives correctly the transmission, while the eavesdropper has difficulties in signal decryption. This solution reduces the number of devices necessary to scramble the signals and can be suitable for a passive optical networks (PON) scenario. Furthermore, BER measurements for the two different configurations have been compared (*Figure 15*).

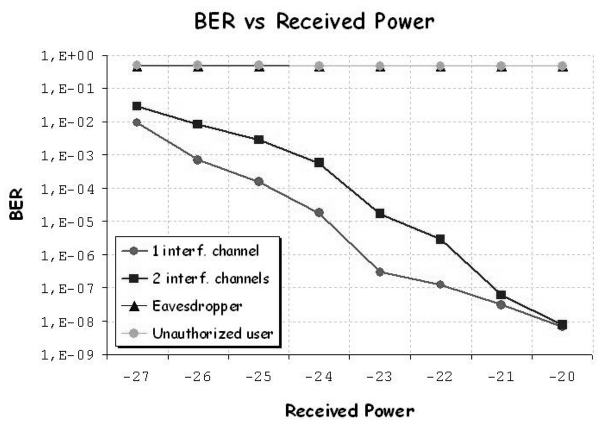


Figure 14: BER measurements for user scrambling configuration

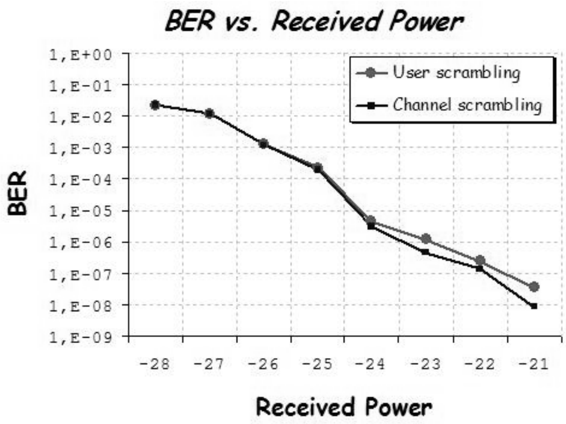
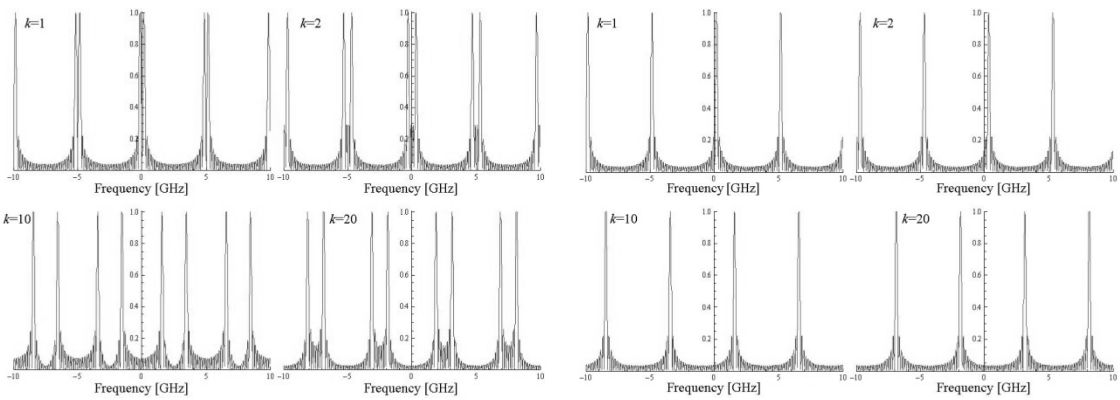


Figure 15: BER comparison between user and channel scrambling configurations

The use of orthogonal frequency division multiplexing (OFDM) in optical networks meets the twofold requirement of mitigating transmission impairments and providing high data rate transmission. CTTC and UNIROMA3 investigate OCDMA transmission in combination with OFDM, to exploit the advantages of both techniques in PON networks with enhanced spectral efficiency and security [13]. A new OFDM modulation/demodulation has been studied that uses real trigonometric transforms to simplify the TX/RX schemes and reduce the number of devices, the power consumption and the computational complexity. OFDM is a multi-carrier transmission technique, where a signal data stream is transmitted over several lower-rate orthogonal sub-channels, by applying a fast Fourier transform (FFT) algorithm. CTTC and UNIROMA3 have investigated the possibility of replacing the FFT with a real trigonometric transform, the discrete Hartley transform (DHT), that offers some advantages as demonstrated in high-speed wireless communications. The DHT and DFT frequency responses of a symbol sequence over N=32 points are shown in *Figure 16*(a) and (b), respectively for different OFDM subcarriers k. Frequency sub-channels separation and orthogonality are preserved, and since the DHT spectra are split into mirror-symmetric subbands, the frequency diversity is enhanced.



(a) (b)

Figure 16: (a) DHT and (b) DFT normalized frequency responses for different values of k.

The proposed DHT-based OFDM system for optical networks is depicted in *Figure 17*. If the input sequence has a real constellation, the inverse fast Hartley transform (IFHT) gives real values, without Hermitian symmetry constrain on the input signal; so that only the real component of the OFDM signal has to be processed. This reduces the number of required electronic devices, since that the number of digital-to-analog and the analog-to-digital converters (DAC/ADCs) is halved.

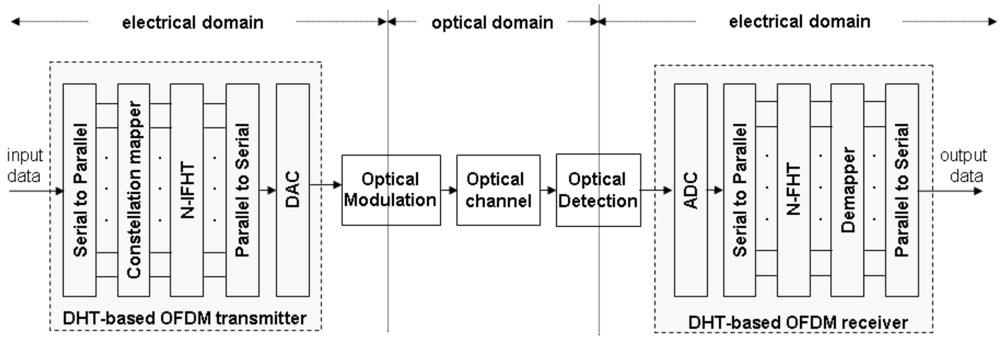


Figure 17: Optical DHT-based OFDM system.

Furthermore, the computational complexity of FHT is lower than FFT: only real operations have to be performed and the direct and inverse Hartley transforms are identical. So that at the transmitter and at the receiver side, the same digital signal processing device (DSP) can be used, which implements a faster and simpler algorithm.

- **Mitigation of Group Velocity Dispersion in Optical CDMA using Electronics**

Wavelength-Hooping Time-Spreading (WHTS) Optical Code Division Multiple Access (OCDMA) networks provide 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.

We propose 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 18*. 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 19* and its temporal response is described by the Equation 1. The electrical GVD compensator is effectively a front-end transversal filter.

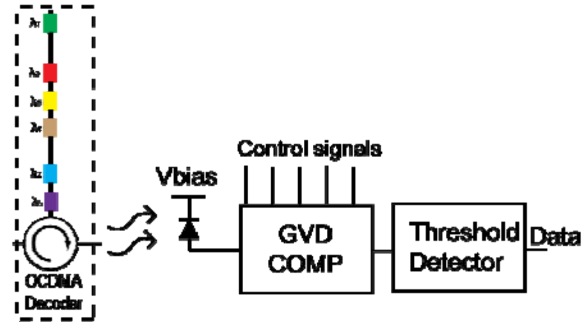


Figure 18: Block diagram of the proposed OCDM receiver

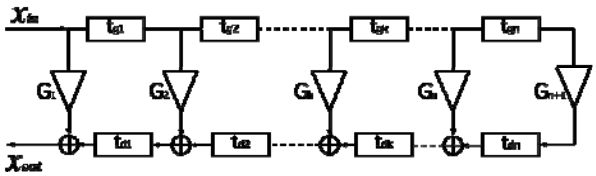


Figure 19: Distributed transversal filter block diagram

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

For verification purposes, an experimental demonstration of time skewing compensation in Fibre Bragg Grating based OCDMA networks, with an electronic fractionally-spaced transversal filter is proposed. This part of the project was implemented in 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)
    - **Eigth** time slots (transmission at 20/8 = 2.5 GBit/s)

For verification purposes, a set of optical orthogonal codewords were designed based on codes proposed by Antonio Mendez [JLT, Nov 2004]. The following codewords have zero auto-correlation and normalized cross-correlation equal to one:

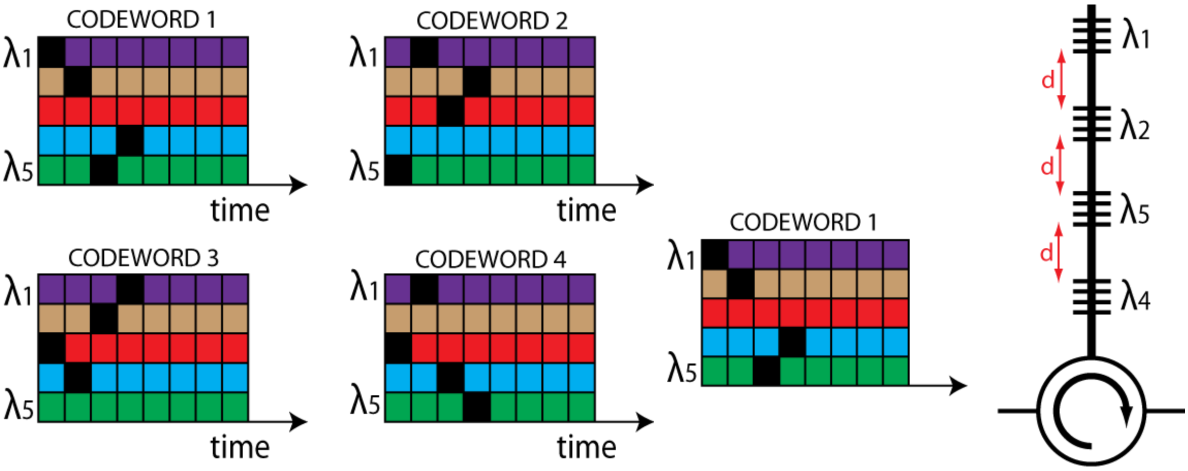


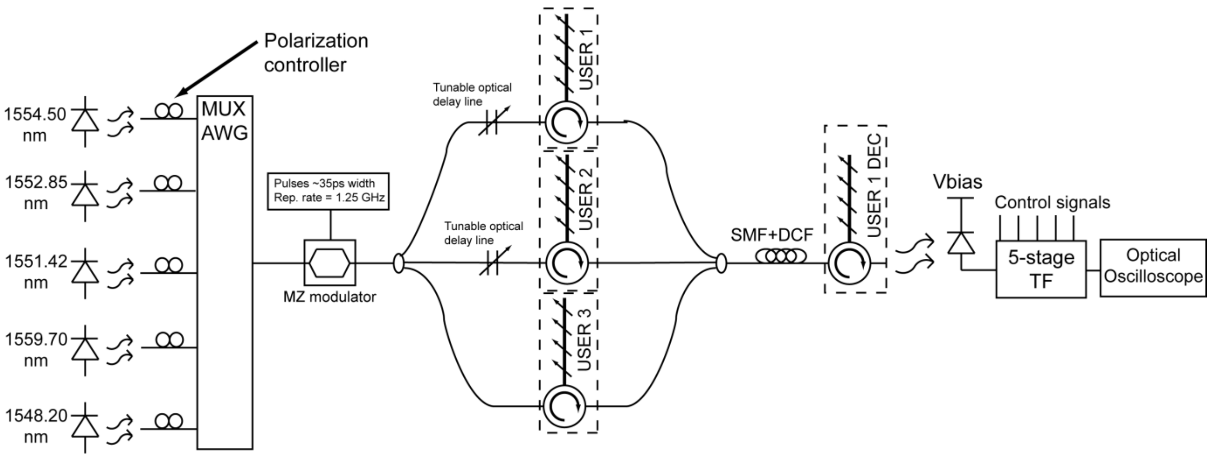
Figure 20: Codewords and Implementation

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:

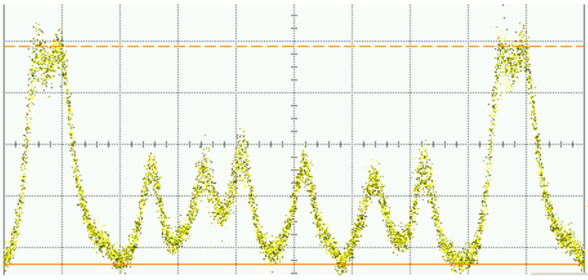
$$d = \frac{c.T_{chip}}{2.\eta_g} = \frac{3 \times 10^8 \times 50 \times 10^{-12}}{2 \times 1.447} = 5.183\, mm$$

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). *Figure 20* shows the user 1 codeword and the correspondent encoding FBG array:

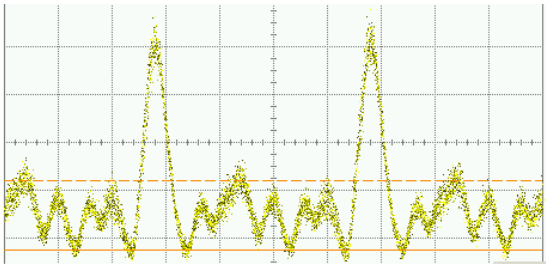
The following figure shows the proof-of-concept prototype. The system comprises five Continuous Wave lasers with central wavelengths separated by 200 GHz (1548.20 to 1554.50 nm). The pulses are obtained with a Mach-Zehnder modulator after which the light is divided in a 3:1 coupler. The codeword for 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.



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

4.3 Joint Activity – Radio Over Fibre Systems

4.3.1 Members

UoESSEX, UPVLC, UDE, UC3M, UoA, UCL, Ericsson, TUe, POLITO, IT, GET

4.3.2 Objectives

We aim to provide a forum for the exchange and consolidation of the latest research and developments in radio-over-fibre (RoF) techniques. Different technologies such as 3.1-10.6 GHz UWB (ultra-wideband) signal distribution, 60 GHz high data capacity applications, microring lasers for RoF applications, SMF & MMF implementations, within-building distributed antenna systems (DAS), and energy efficiency and low carbon footprint designs are being considered in various scenarios.

Specific objectives of JA4 are:

- To integrate RoF research efforts directed to broadband access in Europe.
- To establish a benchmarking platform for the various RoF technologies, providing guidelines relating to the deployment of the most promising and effective techniques in different scenarios across Europe.
- Provide insight into the integration of RoF techniques into next-generation 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.

4.3.3 Research Topics

We have written a collaborative research paper on radio-over-fibre technologies, with a particular focus on the following aspects:

- 3.1-10.6 GHz UWB (ultra-wideband) signal distribution
- 60 GHz high data capacity applications
- Microring lasers for RoF applications
- SMF & MMF implementations
- Within-building distributed antenna systems (DAS)
- Energy efficiency and low carbon footprint designs
- Photonic analogue-to-digital converter architectures
- Photonic ADC and UWB distribution using dispersive fibre

4.3.4 Collaborations/Joint Experiments and Mobility Actions

Completed Mobility Actions:

- **Libera Cavallin POLITO → UPVLC (Completed, 23/2/2009-31/3/2009)**

A mobility action of the student Libera Cavallin from Politecnico di Torino (PoliTO) to UPVLC at Nanophotonic Technology Center premises and further studies in collaboration has been performed. The purpose of this joint experiment is to develop a field trial to analyise coexistence performance between WiMedia defined UWB and WiMAX 802.16e link in a short-range communications scenarios as in personal area networks. The spectral coexistence between UWB and other radio services is a challenging issue. The results of this mobility action will include relevant analysis of coexistence between OFDM-UWB and WiMAX 802.16e devices. Relevant information as the protection margin considering each time a victim main communication user, will be identified for the analyzed scenario.

This mobility action has been completed successfully and the student Libera Cavallin has finished her degree in Telecommunication Engineering.

- **Tiago Alves IT → UPVLC (Completed, 14/12/2008-19/12/2008)**

A mobility action of the Ph.D. student Tiago Alves from Instituto de Telecomunicaçoes (IT) to UPVLC at Nanophotonic Technology Center premises and further studies in collaboration has been performed. This joint experiment is related with the in-building networks architectures for the convergence wireless services. The main target of the photonic analogue to-digital converter (Ph-ADC) is to provide information to perform the spectrum monitoring and management of orthogonal frequency division multiplexing (OFDM) –ultra wideband (UWB) radio signals transmitted in wireless in-building networks. The real time spectral management of the UWB band (3.1 GHz-10.6 GHz) has been appointed as a good solution to overcome the low EIRP impairment of UWB systems. This solution allows the radiated power control in an UWB pico-cell through a communication protocol. In this work, the experimental analysis of the proper operation of the Ph-ADC system is performed.

Particularly, the Ph-ADC photonic structure operation performance is assessed experimentally. The Ph ADC structure is used to time stretch and spectrum compressing of the signals located along the UWB band in order to relax the analogue to-digital electrical bandwidth requirements.

- **Florent Cougoule, GET→ UCL (Completed 20/04/2009 to 18/09/2009)**

A study of the technical feasibility of a millimeter wireless-over-fibre link in a ring network has been performed. This study has been held regarding key points for future broadband-for-all communication such as low cost and high data rate (> 2Mb/s).

Indeed, the millimeter frequency band (26-70 GHz) allows having a higher throughput by reducing the cell size, thus the number of users per cell. In order to decrease the cost of such future systems, the BSs’architecture has been simplified by performing the routing and signal processing at the Central Station (CS) using Wireless-over-Fiber technology.

This study pointed out two major issues: Local Oscillator (LO) distribution management and fiber impairments on signals to be delivered at the BSs. Concerning the LO distribution, the use of optical generation avoids complex electronic frequency doublers. Moreover, it allows taking advantage of the fiber immunity to electromagnetic interferences. Fiber impairments such as Chromatic Dispersion can be overcome by using a suitable optical configuration such as DSB-SC.

Regarding the LO and IF power management, two potential uses have been investigated. In both configurations, the LO signal is generated at λLO = 1550 nm thus matching the EDFA range to get a strong LO. These configurations differ in the IF wavelength that is set to 1300 nm and 1570 nm respectively. The interest of using the 1300nm wavelength is reducing the possibility of channel crosstalk between the LO and IF signals. Since there is no need of IF amplification, IF signals can be withdrawn from the EDFA range. Error-free transmissions have been achieved for both configurations.

Another possible configuration may consist of putting the LO frequency at 1300nm and the IF frequency at 1550nm. A Semiconductor Optical Amplifier (SOA) can be used to provide gain to the LO signal. This device is cheaper than an EDFA amplifier thus reducing the cost of the system. Using an EDFA for DWDM IF signals centred at 1550nm will avoid channel crosstalk that may have been introduced by an SOA.

Mobility Actions:

Dr. Rebecca Chandy, Ericsson -> UDE, (planned for Nov. 2009)

Ingo Möllers, UDE -> Ericsson (planned for Dec./Jan. 2010)

Maria Morant, UPVLC - > UEssex (planned for Oct./Nov. 2010)

4.3.5 Impact

Joint paper written and submitted to IET Optoelectronics Journal, special issue on Next-Generation Access Networks. Title of paper is "Radio-over fibre technologies arising from the Building the future Optical Network in Europe (BONE) project".

Additional joint publications from this joint activity include:

- Marta Beltran(UPVLC), Maria Morant(UPVLC), Joaquin Perez(UPVLC), and Roberto Llorente(UPVLC), "Performance Evaluation of OFDM and Impulse-Radio Ultra-Wideband over Fiber Distribution for In-Building Networks", IEEE International Conference on Ultra-Wideband, Vancouver, Canada, 9-11 September 2009.
- Joaquin Perez (UPVLC), Maria Morant(UPVLC), Roberto Llorente(UPVLC) and Javier Marti(UPVLC), "Joint Distribution of Polarization-Multiplexed UWB and WiMAX Radio in PON", IEEE Journal of Lightwave Technology Converged Optical Network Special Issue, Vol. 27, Issue 12, pp. 1912-1919, June 2009.
- J. Pérez (UPVLC), M. Morant (UPVLC), L. Cavallin (PoliTO), M. Beltrán (UPVLC), R. Gaudino (PoliTO), R. Llorente (UPVLC), "Experimental Analysis of WiMedia-defined UWB and WiMAX 802.16e Coexistence in Personal Area Networks", ICT Mobile Summit 2009, Santander, Spain, June 2009. (JOINT)
- J. Perez (UPVLC), M. Beltran (UPVLC), M. Morant (UPVLC), L. Cavallin (PoliTO), R. Llorente (UPVLC), "Protection Margins for Joint Operation of WiMAX 802.16e and WiMedia-defined UWB Radio in Personal Area Networks", IEEE International Conference on Ultra-Wideband (ICUWB2009), Vancouver, Canada, September 2009. (JOINT)
- J. Perez (UPVLC), M. Beltran (UPVLC), M. Morant (UPVLC), R. Llorente (UPVLC), A. R. Biswas (CREATE-NET), R. Piesiewicz (CREATE-NET), M. Cotton (Institute for Telecommunication Sciences), D. Führer (European Commission Joint Research Center), B. Selva (Thales Communications), I. Bucaille (Thales Communications), S. Zeisberg (University of Applied Sciences Dresden, Germany), "Interference Analysis of WiMAX 802.16e Transmissions in the 3.5 GHz Band on WiMedia defined UWB wireless", IEEE 69th Vehicular Technology Conference VTC Spring, Barcelona, Spain, April 2009.
- R. Llorente (UPVLC), M. Morant (UPVLC), J. Puche (DAS Photonics S.L.), T. Alves (IT), J. Romme (IMST GmbH, Germany), "Cognitive Radio by Photonic Analog-to-Digital Conversion Sensing", Second International Workshop on Cross-Layer Design, IWCLD2009, Palma de Mallorca, Spain, June 2009. (JOINT)
- Roberto Llorente(UPVLC), Maria Morant(UPVLC), Torger Tokle (OFS), Terry Quinlan (UESSEX), Manoj Thakur(UESSEX) and Stuart Walker(UESSEX), "UWB Radio-over-Fibre and Photonic Sensing for Cognitive Optical Access Networks", 22nd Annual Meeting of the IEEE Photonics Society, Turkey, 4 - 8 October 2009. (JOINT)
- Maria Morant (UPVLC), Joaquin Pérez (UPVLC), Marta Beltrán(UPVLC) and Roberto Llorente(UPVLC), "Performance Evaluation of In-Building Radio-over-Fiber Distribution of Multi-Band OFDM UWB Signals", 2009 IEEE International Topical Meeting on Microwave photonics, Valencia, Spain, 14-16 October 2009.
- Joaquin Pérez(UPVLC), Maria Morant(UPVLC), Marta Beltrán(UPVLC) and Roberto Llorente(UPVLC), "Performance of MB-OFDM UWB and WiMAX IEEE 802.16e Converged

Radio-over-Fiber in PON", 2009 IEEE International Topical Meeting on Microwave photonics, Valencia, Spain, 14-16 October 2009.

- D. Montero (UC3M), I. Gasulla (UPVLC), I. Möllers (UDE), D. Jäger (UDE), J. Capmany (UPVLC), C. Vázquez (UC3M), /Experimental analysis of temperature dependence in/ /multimode optical fiber links for Radio-over-Fiber applications/, 11th International Conference on Transparent Optical Networks ICTON 2009, July 2009.

4.3.6 *Research Contributions*

More detailed aspects of the mm-wave RoF research contributions are detailed as follows:

- *UWB and WiMAX distribution using polarization multiplexing techniques*

The feasibility of the joint distribution of ultra-wideband (UWB) and WIMAX wireless using polarization multiplexing as a coexistence technique is proposed and experimentally demonstrated within the framework of passive optical networks (PON). Four single- and orthogonal-polarization multiplexing schemes are studied targeting to reduce the mutual interference when UWB and WiMAX are distributed jointly through standard single-mode fibre (SSMF) without transmission impairments compensation techniques and amplification. Experimental results indicate successful transmission up to 25 km, in SSMF exceeding the range in typical PON deployments. The radio link penalty introduced by optical transmission is also investigated in this activity.

Different orthogonal-PM schemes are studied targeting to reduce the mutual interference when UWB and WiMAX are distributed jointly through standard single-mode fibre (SSMF) as described in Figure 21.

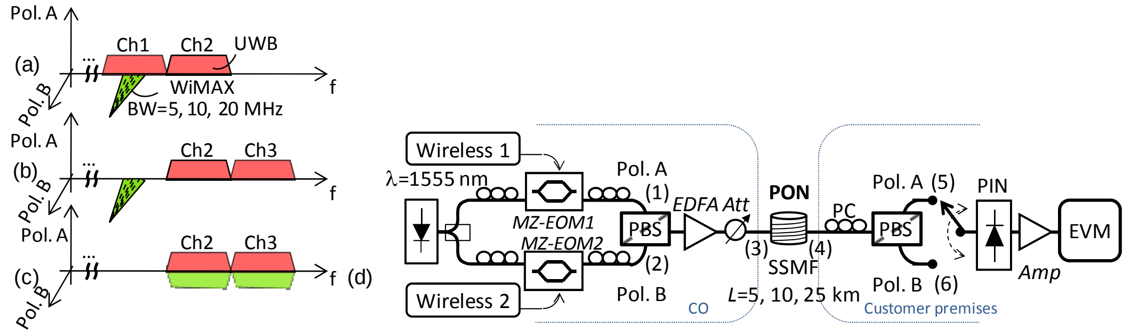


Figure 21. Different polarization-division techniques evaluated: (a) Co-channel polarization scheme. (b) Adjacent-channel polarization scheme. (c) UWB polarization multiplexing scheme. (d) Experimental setup

The experimental results demonstrate the feasibility of the polarization-division technique proposed for typical PON distances. The obtained results are summarized in Figure 22.

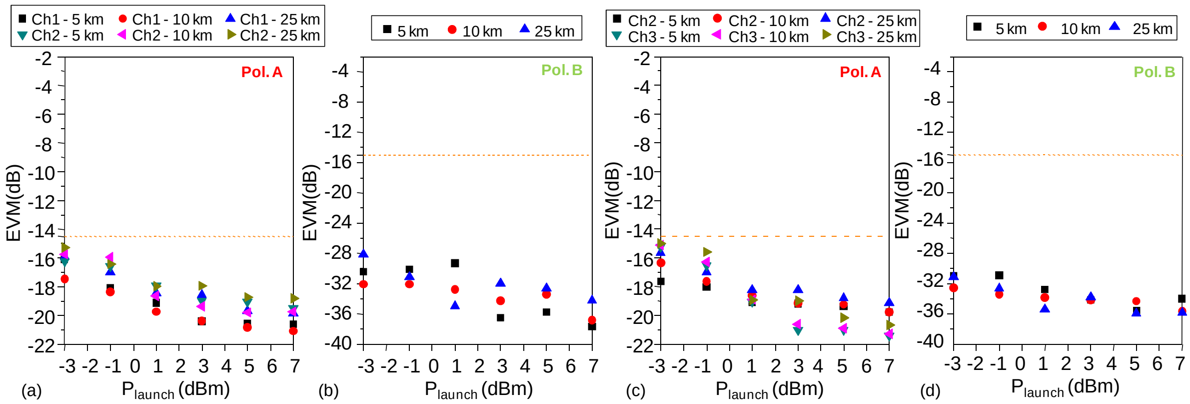


Figure 22. EVM vs. fiber length vs. optical launch power for: (1) co-channel polarization and (2) adjacent-channel (a,c) UWB Ch 1 and Ch 2 in pol. A, and (b,d) WiMAX (10 MHz BW) in pol. B.

The proposed co-channel PM technique (Figure 21(a)) achieves 25 km reach with -17.5 dB EVM for UWB signal and -31 dB EVM for WiMAX signal.

The adjacent-channel UWB and WiMAX PM proposed scheme (Figure 21(b)) achieves 25 km reach with -18 dB EVM for UWB signal and -32.5 dB EVM for WiMAX signal.

The third case considered (Figure 21(c)) is when UWB radio is transmitted in both polarizations providing the maximum transmission bitrate of 800 Mbit/s per user. These results are shown in Figure 23.

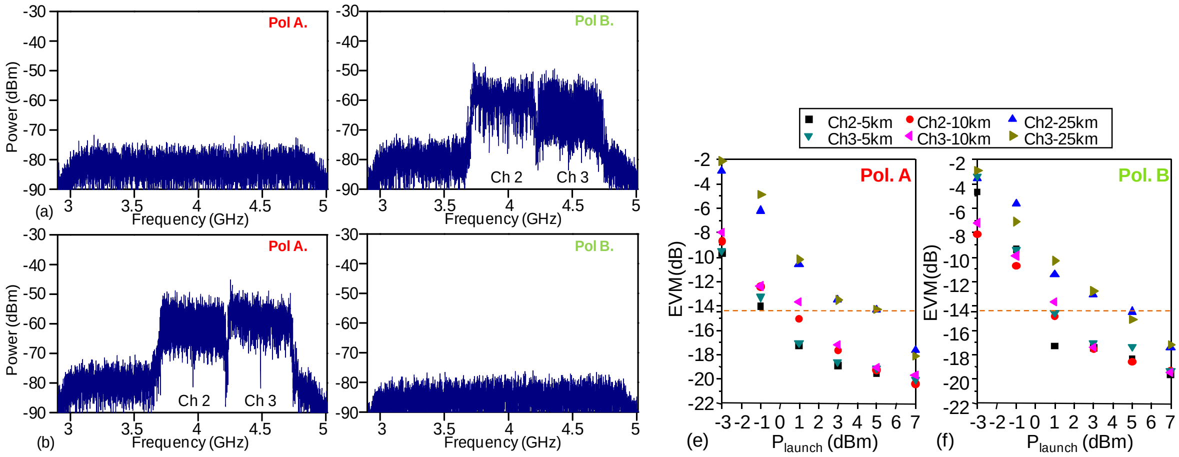


Figure 23. (a) RF received spectrum after 25 km SSMF transmission measured in points (5) and (6) of, and (b) cross-polarization residual crosstalk, (c,d) EVM vs. fiber length vs. optical launch power for both polarizations

The UWB orthogonal PM scheme (doubling the given spectral efficiency) achieves 25 km reach with 2 dB EVM penalty compared with UWB single-polarization distribution scheme.

- *Radio coexistence of WiMAX and UWB signals sharing frequency allocation*

A coexistence study of WiMAX 802.16e and WiMedia-defined UWB signals on Wireless Personal Area Networks has been performed in this mobility action. The experimental analysis addresses the coexistence between OFDM-UWB and WiMAX 802.16e in both directions: WiMAX over UWB and vice-versa.

The measurement scenario considered in this analysis is a complex radio office environment where OFDM-UWB and WiMAX are operating in the presence of other wireless technologies. In order to estimate IEEE 802.16e WiMAX link performance in presence of MB-OFDM UWB has been implemented a MB-OFDM UWB interferer located in LOS from the WiMAX link. WiMAX link performance is measured for different UWB frequency hopping configurations and bit-rate at different distances.

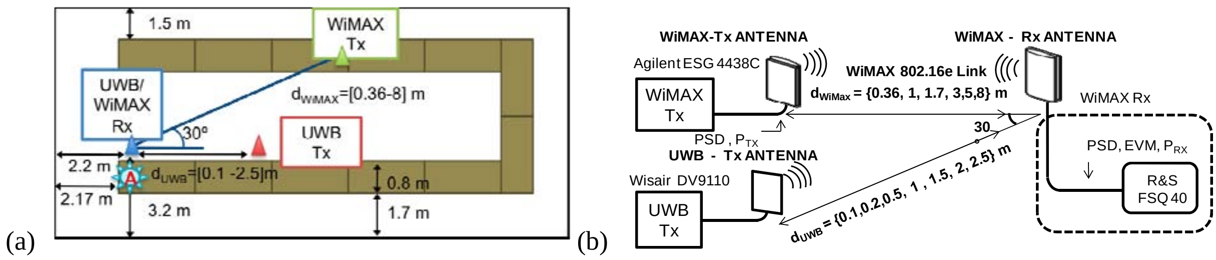
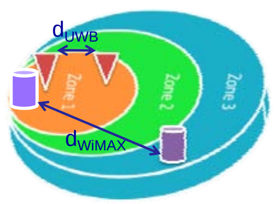


Figure 24. (a) Measurement description inside the meeting room and (b) experimental setup

In the same way to assess UWB link performance in presence of WiMAX 802.16e, UWB and WiMAX signals are utilized as described above. An IEEE 802.16e WiMAX interferer is located 30º from the UWB link line of sight direction as can be observed in the setup described in Figure 24. MB-OFDM UWB link performance has been evaluated for different WiMAX configurations at different WiMAX interferer distances. In order to evaluate link degradation, the error-vector magnitude (EVM) parameter is measured for each received constellation both in the UWB and in the WiMAX link.



Zone 1	0,36 m	1 m	1,7 m
Zone 2	3 m		5 m
Zone 3	8 m		

WiMedia UWB specifications

Time frequency coding	TFC 1	TFC 5
Hopping sequence	{1,2,3,1,2,3}	No hopping
Band frequency	Band group # 1, {3.168 – 4.752 GHz}	Band # 1 {3.168 – 3.696 GHz}
Center frequency	3.96 GHz	3.432 GHz
Bit rate	200 Mbit/s	
EIRP	-41.3 dBm/MHz	

WiMAX mobile specifications

Center frequency	3.5 GHz		
Bandwidth	5 MHz	10 MHz	20 MHz
FFT-points	1024		
Subchannel spacing	5.46875 kHz	10.9375 kHz	21.875 kHz
Oversampling rate	24/28		
Guard period	1/8		
Symbol duration	182.86 µs	102.85 µs	57.14 µs
Modulation	QPSK (½ CTC)		
Downlink data rate	3.17 Mbit/s	6.34 Mbit/s	12.68 Mbit/s

Figure 25. Evaluated distances and UWB and WiMAX signal specifications

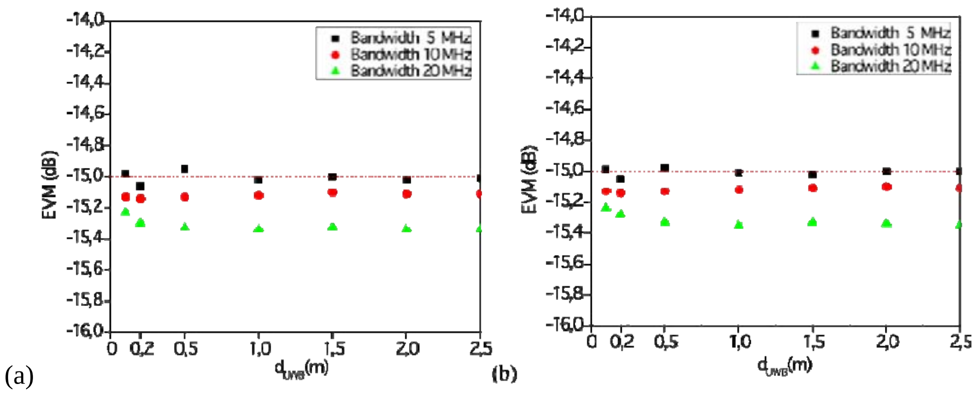


Figure 26. WiMAX 802.16e EVM results for a fixed distance in the WiMAX link (8 m) and different UWB interferer distance with UWB configuration (a) TFC1 and (b) TFC5

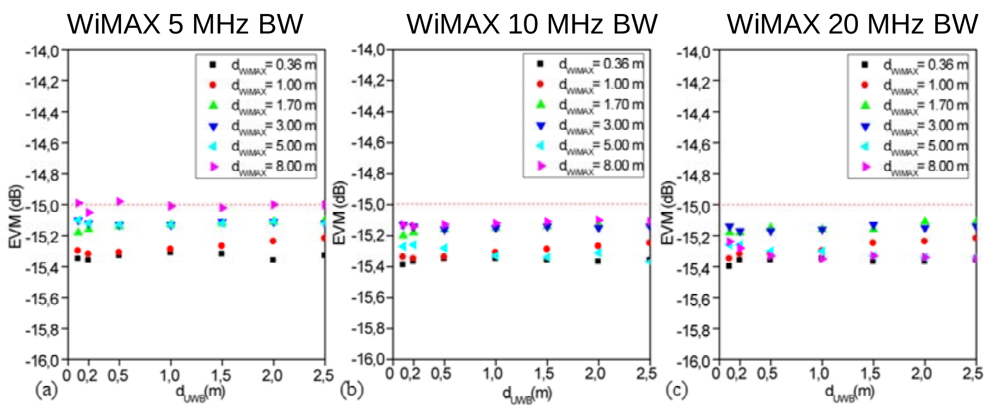


Figure 27. WiMAX 802.16e EVM impact results for different distances of the WiMAX link and UWB TFC5 interferer

Relevant protection margins are derived from the experimental results. The measurements indicate that a WiMAX link with 10 and 20 MHz bandwidth achieves successful communication even if there is a UWB interferer at 2.5 m distance. In the case of 5 MHz BW WiMAX, successful communication can be guaranteed up to 5 m with a UWB interferer at 2.5 m vicinity.

The study has been done too in the other way to evaluate the impact of a WiMAX interferer in an UWB communication link:

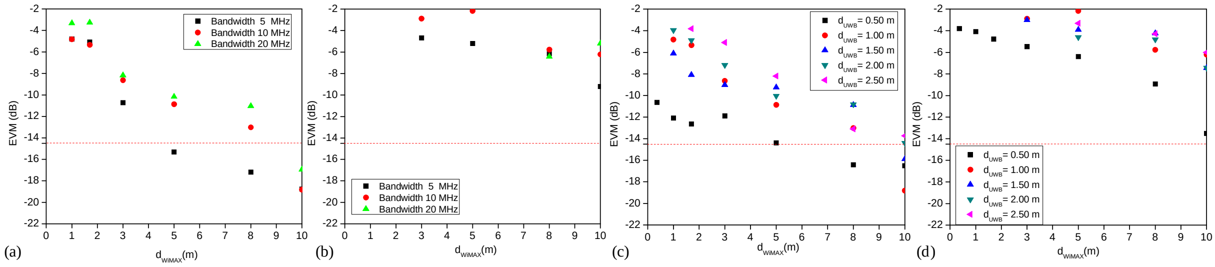


Figure 28. WiMedia EVM impact results for UWB communication link 1 m using (a)TFC1 and (b) TFC5,and at different distances with WiMAX bandwidth 10 MHz using (c) TFC1 and (d) TFC5

The results indicate that UWB systems working on TFC 5 have to perform cognitive radio issues in order to maintain a successful transmission in presence of WiMAX. UWB devices operating in TFC 1 we can perform an UWB link of up to 2 m with a WiMAX 10 MHz interferer 10 m close the UWB link.

- *60 GHz high data capacity applications*

Photonic generation of 57 GHz IR-UWB monocycles at 1.244 Gb/s with transmission over 100 m of SMF has been achieved. Optical pulses from an actively mode-locked laser have been modulated with data by a MZ-EOM (Mach-Zehnder electro-optical modulator) and time-stretched in 10 km SMF to adjust the pulse width as required. A commercial photoreceiver and suitable delay have been employed to shape the appropriate UWB monocycle spectral envelope exhibiting 3.8 GHz bandwidth, and maximising the 1.244 Gb/s spectral efficiency.

- *Super-broadband photonic wireless system demonstrations*

University Duisburg-Essen and France Telecom have realized a super-broadband 60 GHz photonic wireless system and demonstrated wireless transmission with a world record data throughput and spectral efficiency of 27 Gb/s and 3.86 bit/s/Hz [1]. The compact system is based upon a cascaded RF and data modulation approach. By using an 8-QAM and 16-QAM OFDM modulation format we achieved record spectral efficiencies up to 3.86 bit/s/Hz. Experiments have been carried out with 10 m fibre-optic and 2.5 m wireless transmission. For 8-QAM OFDM modulation a data rate of 20.28 Gbit/s with a measured mean EVM of 18.8 % and a SNR of 18.9 dB resulting in a BER of $2.2 \cdot 10^{-4}$ has been achieved. For 16-QAM OFDM modulation a record throughput of 27.04 Gbit/s was successfully achieved. In that case, the measured mean EVM and SNR were 17.6 % and 21.5 dB, respectively resulting in a BER of $4.2 \cdot 10^{-3}$ which is slightly above the FEC limit. The transmit power and antenna gain used in the experiments were -1 dBm and 23 dBi, respectively. By increasing the transmit power and antenna gain, we expect being able to extend the wireless span up to a few 100 m given the measured wireless receiver sensitivity.

- *Microring lasers for RoF applications*

In a numerical simulation, UWB signals have been produced utilizing MB-OFDM in the 3.1-10.6 GHz range. The impact of the transmitter's microring laser nonlinearity and intensity noise has been rendered in constellation diagrams and EVM calculation, whilst tunable WDM operation has also been investigated and observed through phase-shifted feedback from the bus waveguide.

- *MMF implementations*

Theoretical simulations of a 50 µm core MMF link frequency response for different lengths (L=3050m, L= 6100m and L=9150m have been performed for two situations: considering the effects of mode coupling (MC) and differential mode attenuation (DMA). Indoor applications requiring 300m of RoMMF, covering most of the connections associated with office networks, have been evaluated, featuring distribution of OFDM and IR UWB following the setup shown in Figure 29.

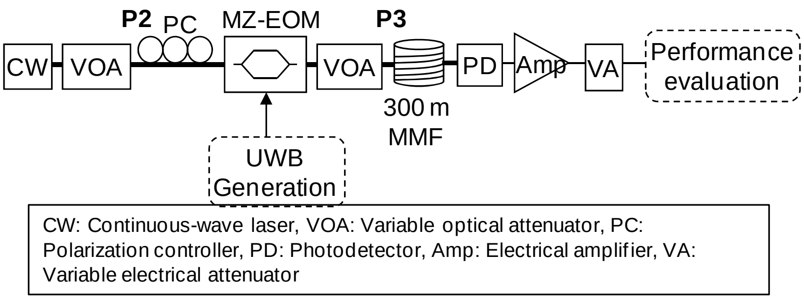


Figure 29. Experimental setup for performance evaluation of OFDM and impulse-radio UWB distribution over 300 m MMF.

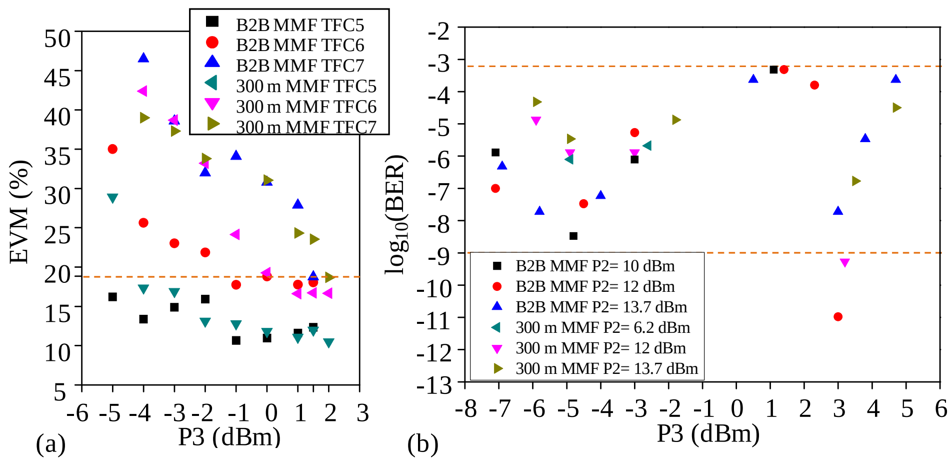


Figure 30. Measured results of UWB distribution over 300 m MMF: (a) EVM for OFDM-UWB using different frequency bands, and (b) BER for IR-UWB for different input power

As can be seen in Figure 30 Successful transmission over 300 m MMF has been achieved with launch powers of +2 dBm for complete OFDM-UWB, or +3 dBm for IR UWB.

Theoretical simulations of a 50 µm core MMF link frequency response for different lengths (L=3050m, L= 6100m and L=9150m have been performed for two situations: considering the effects of mode coupling (MC) and differential mode attenuation (DMA), see Figure 31.

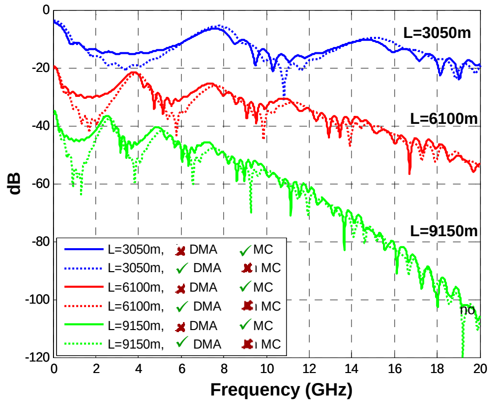
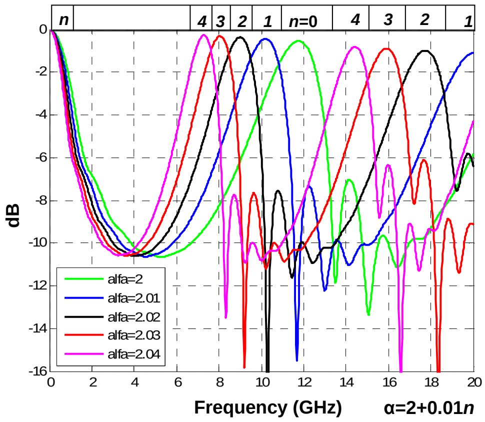


Figure 31: Frequency response of the MMF fibre link when considering or not the mode coupling (MC) and the differential mode attenuation (DMA) effects, with α=2 (graded index exponent of the fibre) and for different fibre lengths.

This periodic frequency response could permit broadband RF transmissions far from baseband in the microwave and millimetre wave regions in short (2-5 Km) and middle (10 Km) reach distances. It has also been analysed the influence of different MMF profiles, α, and temperature on the frequency response. Figure 32 (a) and Figure 32 (b) show the frequency response of a MMF link for L=2Km and L=3Km, respectively, depending on the graded index exponent, α, of the fibre. Significant displacements of the higher order resonances over the frequency spectrum can be achieved with regards to this parameter. For example, from Figure 32 (a), an increase of 2%, α'=α+0.02, produces a change of the first order resonance up to 2.8GHz. From both figures it can be seen that higher order resonances placed far from baseband change the -3dB bandwidth depending of such parameter.

(a)



(b)

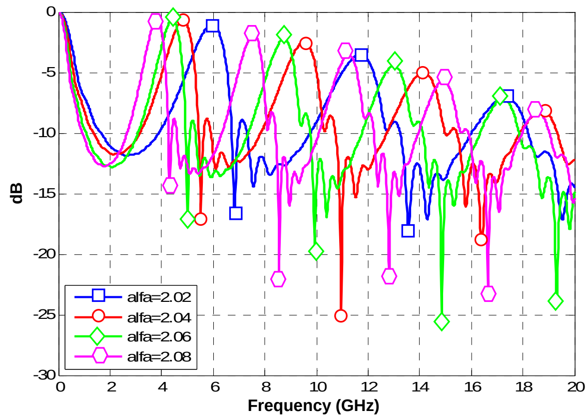


Figure 32: (a) Frequency response of the MMF fibre link for different graded index exponents, α, when L=2Km. (b) Frequency response of the MMF fibre link for different graded index exponents, α, when L=3.05Km.

Finally, the temperature dependence of the bandwidth in a RoF multimode silica fibre link is experimentally tested when environmental temperature changes. The measurements are taken at temperatures from T=28ºC (environment) to T=67ºC. The hysteresis cycle of the measurements has also been evaluated at the environmental temperature.

A multimode silica 62.5/125μm optical fibre link has been implemented to experimentally validate the influence of temperature. A Fabry-Perot optical source at 1300nm (Agilent 81655A) modulated up to 20GHz by a Lightwave Component Analyzer (LCA, Agilent 8703B) has been employed to launch optical power into the fibre. The optical power at the end of the fibre is, then, collected by a wide bandwidth InGaAs PIN photodiode and, finally, analyzed in terms of the frequency response by the LCA. Several temperatures have been tested for a L=3050m MMF fibre link at λ=1300nm up to 20GHz with an average factor of Avg=16 at each temperature test measurement. Test equipment was isolated from the heating source thus affecting the temperature deviation only to the MMF fibre spool. Figure 33(a) shows the experimental measurement of the frequency response, at T=28ºC and T=67ºC, averaged *Avg*=16. It can be seen that the frequency spectrum takes its higher and lower values at the same frequencies but with a power offset up to 5dB in case of Figure 33 (a), where an average is applied, whereas Figure 33 (b) shows a maximum deviation of 20dB at 4GHz without averaging factor.

As the fibre frequency response seems to be unpredictable under arbitrary operating conditions it is reasonable to assume that the spectral transmission bands in a RoF system could change significantly. Furthermore, the RoF link can be affected by temperature deviations which have also been demonstrated to change some of the optical properties of multimode fibres and an analysis of its influence over the frequency response is needed. By controlling how the temperature affects the fibre link it is possible to avoid the influence of this parameter over the higher order resonances and, consequently, to increase the bandwidth capability of these radio-over-fibre broadband transmissions.

(a) (b)

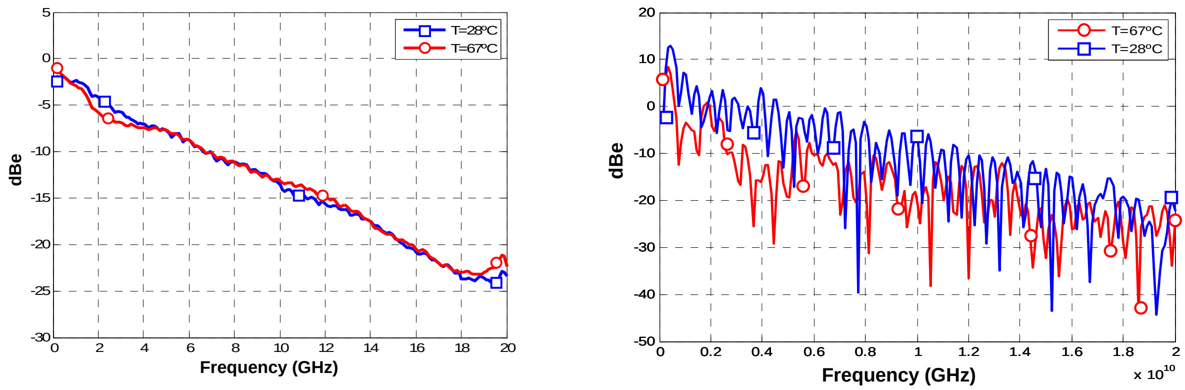


Figure 33: (a) Experimental frequency response of the MMF fibre link at T=28ºC and T=67ºC for L=3050m and λ=1300nm with Avg=16. (b) Measurement of the frequency response of a L=3050m MMF fibre link at λ=1300nm for a single sweep.

- *Within-building distributed antenna systems (DAS)*

Four DAS infrastructures (coax, SMF, MMF, and POF) have been compared with respect to installation effort, CAPEX, system dynamic range (SDR) and attenuation. The use of a passive, low-power and low-cost optoelectronic WDM transceiver, containing a modulator (modulation wavelength 790nm, quasi-transparent at 850nm) super-integrated with a PD (850nm) for single-fibre, full-duplex bidirectional RoMMF transmission at the base-station has been demonstrated [2]. EVM (error vector magnitude) measurements have shown that multiple-standard transmission (GSM, DPRS, UMTS, WLAN 802.11b) can be achieved using the modulator for uplink transmission with more than 200 m of glass MMF, and perfluorinated POF (50 m) [3].

- *Energy efficiency and low carbon footprint designs*

Theoretical and experimental studies have demonstrated that antenna arrays allow additional link gain to be won (i.e. cloned transmitters and receivers) with additional advantages due to the holographic redundancy of such a system. Software control of cloned antennas formed from multiple-input/multiple-output (MIMO) configurations also allows the minimisation of power dissipation. The experimental demonstration of cloned 2x2 transmitter and 2x2 receiver arrays has shown an overall link gain of 22dB, comparing favourably with the theoretical reciprocity advantage of 24 dB

- *Photonic ADC architectures*

A joint experiment of Universidad Politécnica de Valencia (UPVLC) and Instituto de Telecomunicações (IT) of Portugal investigate the use of photonic analogue-to-digital converter (Ph-ADC) for localization, fingerprinting and spectral management applications, indicated for cognitive radio applications. A time-stretch Ph-ADC scheme with optimum configuration of optical and electrical amplification stages is proposed and evaluated experimentally. This technique increases the bandwidth and sensibility of electronic ADC and can be used for detecting signals with extremely low power. The usage of the proposed Ph-ADC jointly with cognitive radio algorithms allows to minimize interference and to optimize user's capacity in a given picocell cluster area. The analogue to digital conversion based on the Ph-ADC has been shown for a pure tone signal of high frequency. In this joint activity, the experimental time stretching demonstration of UWB radio signals based on the photonic analogue-to-digital conversion (Ph-ADC) has been accomplished. A proof of concept has been performed for radio signals located along the UWB band. Different electrical power levels have been used in order to emulate different free space losses due to the UWB radio signals broadcasting. Furthermore, the experiments have been performed with and without erbium doped fibre amplifiers (EDFAs) in order to analyze the influence of the amplified spontaneous emission (ASE) noise on the detected/sampled signal. The time stretched signal has been initially captured by an oscilloscope.

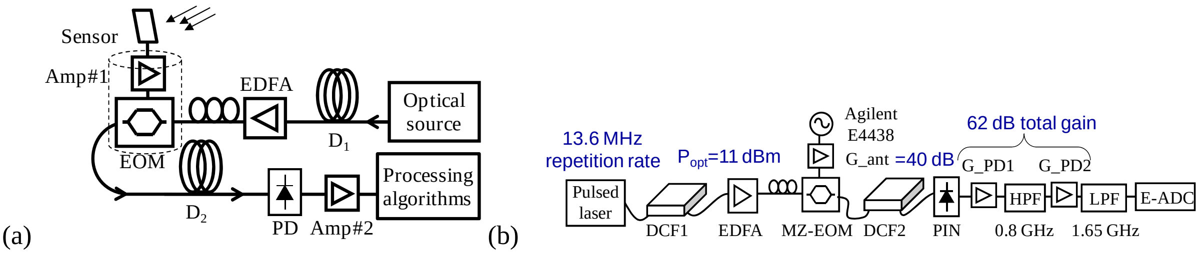


Figure 34. (a) Proposed time-stretching Ph-ADC with engineered optical and electrical amplification and (b) laboratory experimental setup

Afterwards, the electrical analogue-to-digital converter (E-ADC) with 2 GHz of bandwidth has been included in the setup to acquire the time stretched signal.

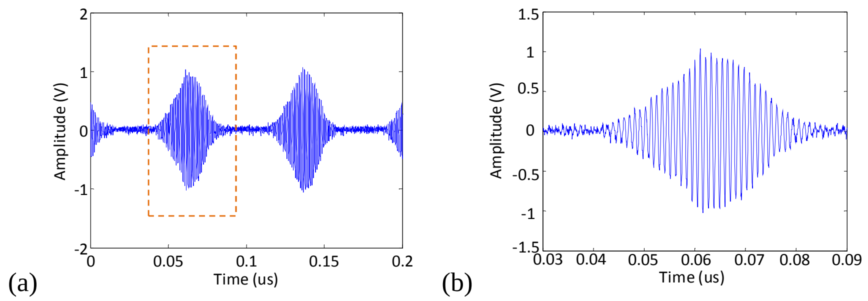


Figure 35. (a) Time signal captured with the real-time oscilloscope and (b) zoom

As can be observed in the time signal captured with the E-ADC after the time stretching Ph-ADC shown in Figure 35, there is no overlapping between successive optical pulses after time-stretching. The sinusoid signal amplitude is convoluted by the envelope of the optical pulse. This envelope can be obtained using processing algorithms.

The obtained results have shown that the electrical power level of the radio signal applied to the Ph-ADC photonic structure is a key parameter on the performance of the time stretched signal. Furthermore, the experiments have also indicated that, for the setup analyzed, the influence of the ASE noise on the detected signals can be neglected. Instead, the electrical noise induced by the electrical amplifiers has been revealed as an important system performance impairment.

- *Photonic ADC and UWB distribution using dispersive fibre*

A joint experiment of UPVLC and UESSEX was performed to develop a laboratory proof-of-concept regarding the feasibility of sensing using a Ph-ADC architecture as described previously and the simultaneous UWB distribution over dispersive fibre. The laboratory setup is shown in Figure 36 and comprises a time-stretch Ph-ADC which performs the sensing operation and an UWB access node. UWB distribution from the central office is possible at distances from 10 to 75 km with EDFA amplification. Device specifications are shown in Table 1. The Ph-ADC comprises a Pritel femtosecond fibre laser source with 13.6 MHz repetition rate and the optical spectrum shown in Figure 36(a). A 1564 nm centre wavelength was used to avoid possible interference with the UWB radio-over-fibre signal travelling at 1550 nm. Spectral components are resolved in time through the DCF1 fiber.

TABLE 1. DEVICE SPECIFICATIONS

Ph-ADC	RoF
G_ant=34 dB	G_UWB=34 dB
D1=-1513.1 ps/nm	*D2*=-2538.1 ps/nm *D2*=-3612.2 ps/nm
Covega 6538015	Photline MZ-LN-40-PD
Keopsys P_{sat}=13 dBm	Exelite P_{sat}=19 dBm
G_PD1=36 dB, G_PD2=26 dB	G_R=40 dB

TABLE 2. ACCUMULATED DISPERSION IN SSMF PATHS

Fibre length *L*	Accumulated dispersion
10 km	170 ps/nm
25 km	428.4 ps/nm
50 km	854.59 ps/nm
75 km	1281.9 ps/nm

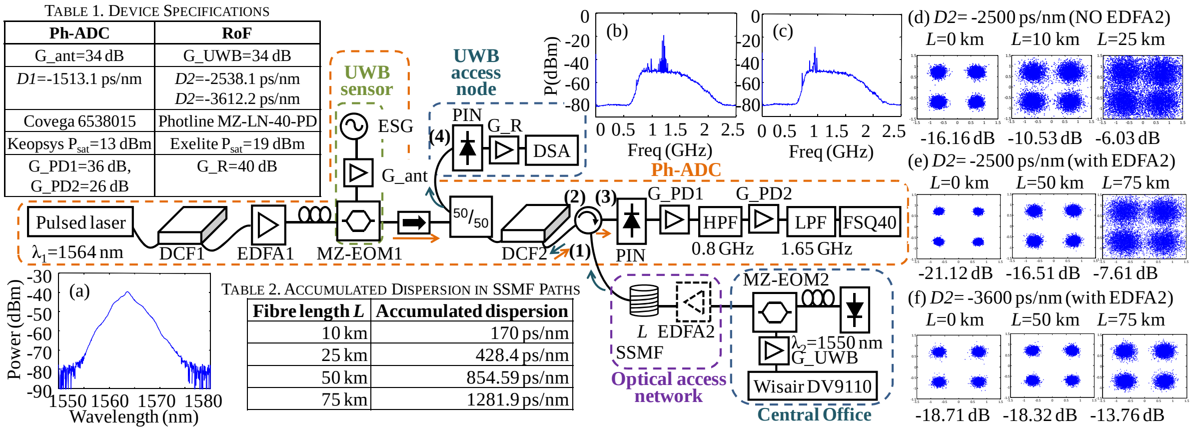


Figure 36. Laboratory setup for Ph-ADC and UWB distribution. Insets (a) Pulsed laser optical spectrum employed. Time stretched signal for (b) D2≈ -2500 ps/nm and (c) D2≈ -3600 ps/nm. EVM and constellations measured for (d) D2≈ 2500 ps/nm without second EDFA2, (e) D2≈-2500 ps/nm with EDFA2 at Pout=2 dBm, (f) D2≈-3600 ps/nm with EDFA2 at Pout=2 dBm

Different SSMF paths with total length (*L*) of 10, 25, 50 and 75 km are evaluated. The accumulated dispersion values of the SSMF are shown in Table 2. At the central office, the error vector magnitude (EVM) of the UWB signal is measured with an Agilent digital signal analyzer DSA80000B. Current ECMA-368 regulation set a maximum EVM of -14.5 dB for UWB signals up to 200 Mbit/s. The first spool of fiber (DCF1 in Figure 36) exhibits D1=-1513.1 ps/nm dispersion. In the second module DCF2, dispersion can be D2=-2538.1 ps/nm for M=1+D2/D1=2.67, or D2=-3612.2 ps/nm for M=3.38.

Different time-stretched signals were measured at point (3) for both DCF2 values and shown in Figure 36(b)-(c). A -50 dBm sinusoid input signal, generated with an ESG with 3.146 GHz frequency is used for simplicity in the Ph-ADC evaluation. This confirms that the Ph-ADC monitoring part keeps operating correctly (with 28 MHz offset) while UWB-over-fibre is transmitted in the opposite direction. The UWB signal is measured at Figure 36 point (4) with and without SSMF propagation. The EVM and demodulated constellations are shown in Figure 36(d)-(f).

This experiment confirms that the Ph-ADC fibres can be used for UWB signal distribution at DCF dispersion values D2≈ -2500 ps/nm in in-building communications. Higher dispersion values distort severely UWB carrier constellation.

In the case of a signal distributed in an optical access network in SSMF, the positive optical access dispersion compensates to a limited extent the DCF2 negative dispersion enabling transmission at values D2≈ -2500 ps/nm or D2≈ -3600 ps/nm (50 km SSMF with EDFA amplification).

- *Millimetre wireless-over-fibre link in a ring network for broadband communication*

This joint work between UCL and GET used the OPTSIM platform to study the technical feasibility of a 40GHz RoF link in a ring configuration. Both Coarse Wavelength Division Multiplexing (CWDM) and Dense Wavelength Division Multiplexing (DWDM) configurations are being investigated.

The overall ring architecture of the RoF transmission system is composed of a downlink and an uplink path. This is a half-duplex configuration given that the data from the uplink and downlink paths do not travel through the fibre medium simultaneously (see Figure 37). In order to improve the comprehension of the ring arrangement, the optical path has been represented in red and the electrical path in blue on Figure 37.

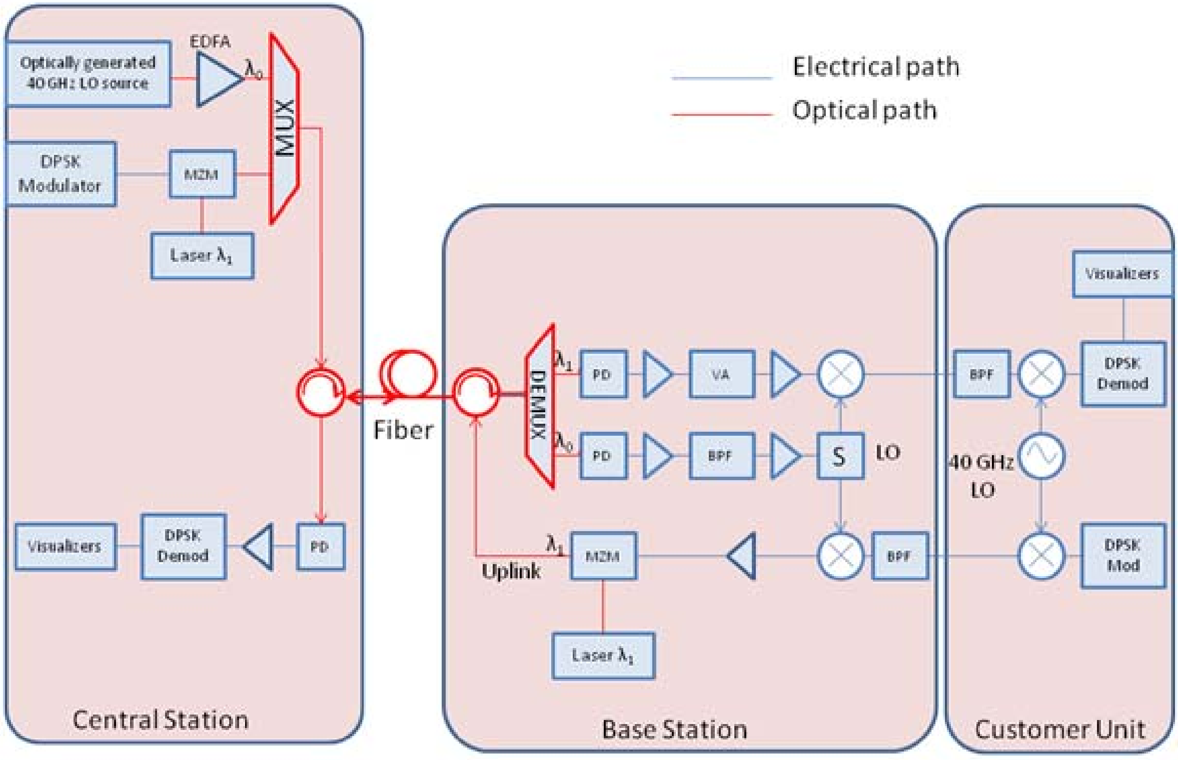


Figure 37 : overall ring architecture for the millimeter-wave Gb/s WoF transmission

In the downlink path, the LO is optically generated at the Central Station (λ_0=1550 nm for CWDM) and distributed to the BSs via the optical fibre. The DPSK data is modulated at 5 GHz (IF) and filtered by a Low Pass Filter (LPF) to limit the occupied spectrum. Then the data is introduced into the MZM that is externally modulated by a Continuous Wave Laser (λ_1=1570 nm for CWDM). The two optical fields are multiplexed over a 2.2 km fibre length and transmitted to the Base Station where they are demulitplexed by optical filtering using Band Pass Filters (BPF) at different frequencies according to CWDM or DWDM configuration. The optical-electrical conversion is operated by an Avalanche PhotoDiode (APD). On the IF path at the Base Station, the data is up-converted to 40 GHz using the photodetected LO. The wireless path between the Base Station and the Customer Unit is represented by a Variable Attenuator (VA) and a noise source on the IF path. At the CU, a BPF at 35 GHz is used to suppress the 45 GHz image frequency. Then the signal is down-converted to 5 GHz using an external LO source.

Concerning the uplink path, the 5 GHz DPSK signal is up-converted to 40 GHz using an independent LO source at the Customer Unit. After wireless transmission, the signal is filtered using a BPF centred at 35GHz to suppress the image frequency. Then the electrical signal is down-converted to 5 GHz using the optical LO and fed into a MZM that converts the electrical signal into an optical one by using external modulation. After being propagated into a 2.2 km optical fibre, the signal is photodetected and introduced into the DPSK Demodulator that recovers the baseband data.

In order to get the overall CWDM system perfomance, the optical link on the IF path has to be characterized. The optical link of the ring network spreads from the LPF output after the DPSK Modulator to the APD output at the BS. The parameters to be determined are the Noise Floor of the system, its RF gain, its RF Noise Figure (NF) and its SFDR value. The RF gain is the power difference between the electrical signal at the LPF output and the electrical signal after PD at the BS. The noise figure is the measure of the noise added by the optical link and can be calculated by:

where *k* is the Boltzman's constant, *G* is the RF gain and *Nout* is the total output noise.

Nout is calculated by adding all the noise contribution on the link. It includes thermal noise n_{th}, shot noise n_{sh} and laser relative intensity noise n_{RIN}. In order to get the SFDR, the IIP3 point has to be determined by using a two tone operation on OPTSIM. A two tone operation is used on OPTSIM to get the IIP3 value. According to Figure 38, the optical link has an IIP3 value of 26 dBm.

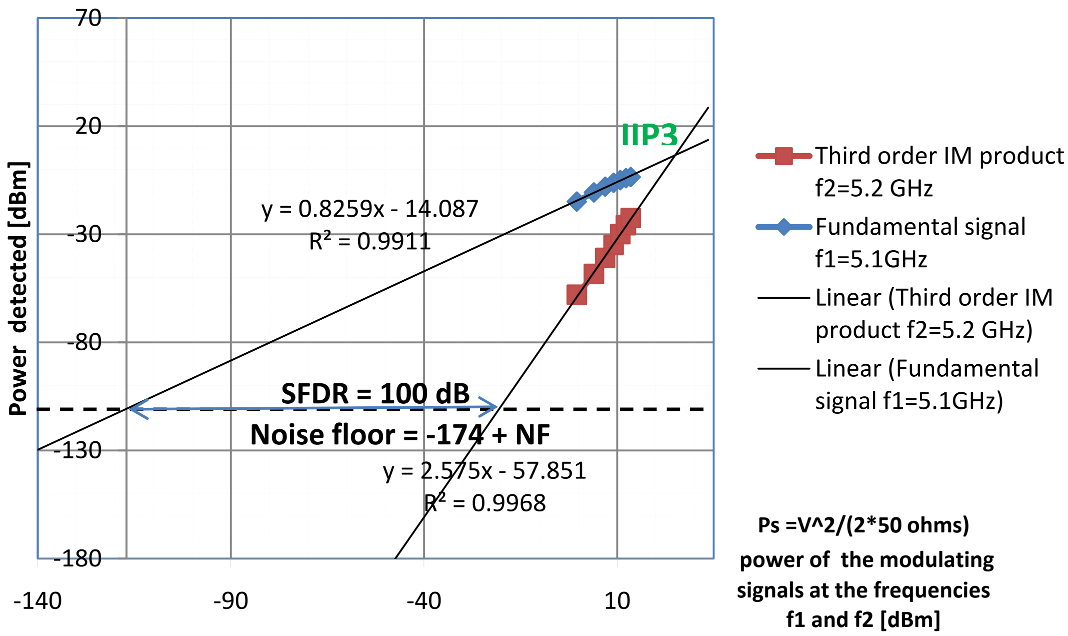


Figure 38: two tone operation on the optical downlink to determine the IIP3 value

The RF gain value is -36 dB, the RF Noise Figure is 64 dB and the SFDR is 90.6 dB for the optical downlink. Concerning the uplink, the RF gain is -30.4 dB, the RF Noise Figure is 64.3 dBm and the SFDR is 90.4 dBm. These results match the requirement of an optical link performance (10).

The overall downlink performances have been obtained using the Appcad Software from Agilent. The software uses the Friis formulae (12) to calculate the output Signal to Noise Ratio (SNR). For instance we can consider a system whose NF is 4 dB. Thus, an input SNR of 100 dB will result of an output SNR of 96 dB. For more complexed systems such as the overall downlink path of the ring network, the total NF is calculated by using the NF of each component and the Friis formulae. Outputs SNR of 34.96 dB and 46.64 dB have been calculated for the CWDM downlink and uplink respectively.

The simulated received BER and the theoretical BER for a DPSK receiver for the downlink and the uplink have been represented Figure 39 and **Error! Reference source not found.** respectively. In order to achieve a free error transmission, the minimum SNR value is 13 dB. The simulated SNR value is +2 dB greater on the downlink path and +1 dB greater on the uplink path.

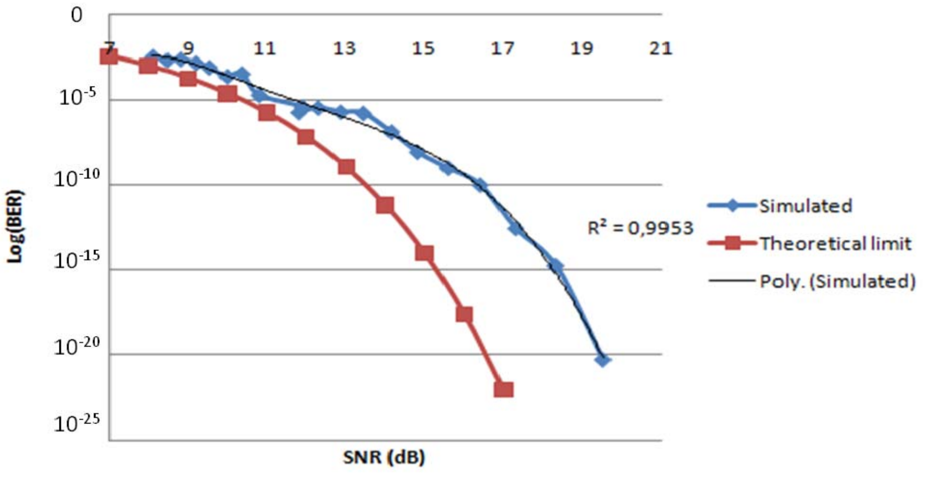


Figure 39: BER for Gb/s DPSK (CDWM downlink)

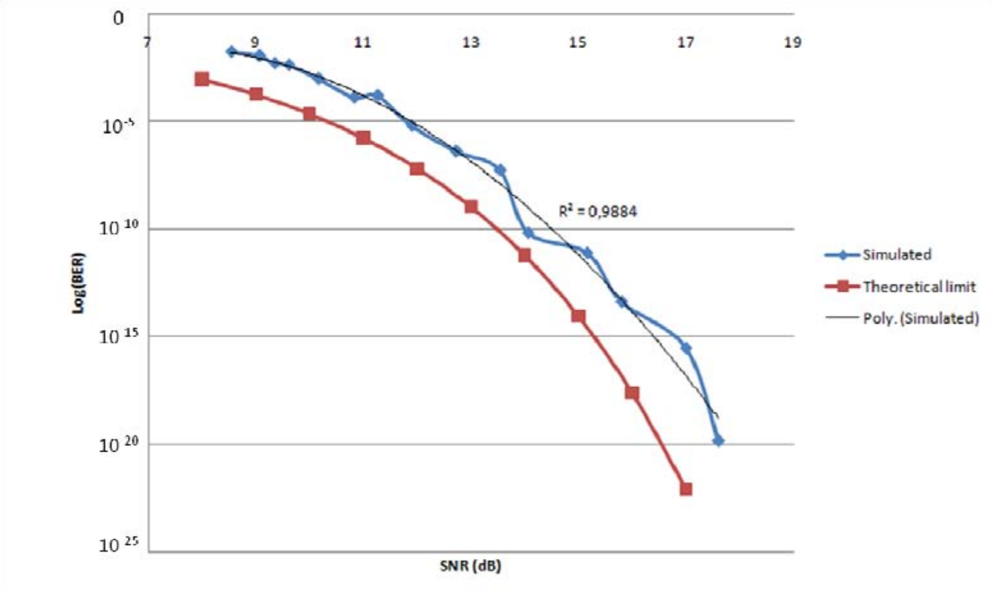


Figure 40: *: BER for Gb/s DPSK (CDWM uplink)*

References:

[1] M. Weiß A. Stöhr, F. Lecoche, B. Charbonnier, 27 Gbit/s Photonic Wireless 60 GHz Transmission System using 16-QAM OFDM, International Topical Meeting on Microwave Photonics, MWP 2009, Oct. 14-16, Valencia, Spain, 2009, (post deadline paper)

[2] I. Möllers, D. Jäger, “Transparent Radio-over-Multimode Fiber Transmission System with Novel Transceiver for Picocellular Infrastructures”, European Conference and Exhibition on Optical Communications, September 20-24, Vienna, Austria, 2009

[3] I. Möllers, D. Jäger, “Bidirectional Multi-Standard RoMMF Transmission Using a Reflective Electro-Optic Transceiver”, European workshop on photonic solutions for wireless, access, and in-house networks, Duisburg, Germany, 2009

4.4 *Joint Activity – QoS in PONs*

4.4.1 Members

- FUB, ISCTI, GET, UNIMORE

4.4.2 Objectives

Passive Optical Networks (PONs) 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 PONs is much wider with respect to other access techniques based either on copper or on radio, in future applications also current PONs 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, this JA aims to propose and introduce Quality of Service mechanisms in access networks, in particular in PONs.

Specific objectives of the JA are:

- Integration of PONs, in particular Ethernet PONs (EPONs), and Carrier Ethernet technique to better manage QoS;
- To introduce tagging techniques for QoS control in PONs;
- Services over PON (CDN based PON, TV over PON)

4.4.3 Research Topics

In this JA we investigated on QoS in PON looking for and optimizing techniques to improve the network performance including PONs.

In 2009 the main research topics illustrated in 1.6 have regarded:

- End-to-End techniques to improve the QoS in EPON networks; in particular, we focused on the VPLS&VLAN tagging techniques.
- Use of wavelength conversion in EPON
- Control Plane implementation in EPON based access networks

4.4.4 Collaborations/Joint Experiments and Mobility Actions

Joint experiments:

- FUB – ISCOM: study of network performance improvement on EPON by using Carrier Ethernet techniques, as Virtual Private LAN Service

4.4.5 Impact

Joint Pubblications:

- F. Matera, A. Valenti, S. Pompei, G. M. Tosi Beleffi, and D. Forin, "Unbundling and Quality of Service in Ethernet Passive Optical Networks based on Virtual Private LAN Service technique" in Proc. Of CONTEL 2009, Zagreb, June 8-10
- L. Rea, A. Valenti, S. Pompei, L. Pulcini, M. Celidonio, D. Del Buono, G.M. Tosi Beleffi "Quality of Service control in a multi-access integrated network based on Virtual Private LAN Service", in Proc. Of IPHOBAC 09, Duisburg, May 18-20
- A. Valenti, S. Pompei, F. Matera, G. Tosi Beleffi, and D. Forin, "Quality of Service control in Ethernet Passive Optical Networks based on Virtual Private LAN Service", IET Electronics Letters, Vol. 45, Issue 19, pp. 992-993, September 2009-09-22

- A. Coiro, A. Valenti, S. Pompei, G. Tosi Beleffi, F. Curti, S. Di Bartolo, A. Rufini "Experimental demonstration of the All Optical Network Wavelength Conversion in a Passive Optical Network", in proc of PS2009, Pisa, September 15-19
- M. Casoni, C. Raffaelli, "TCP Performance over Optical Burst-Switched Networks with Different Access Technologies", OSA/IEEE Journal of Optical Communications and Networking, Vol. 1, Issue 1, pp. 103-112, June 2009.
- M. Casoni, "TCP Performance in Hybrid EPON/OBS Networks", Proc. of 13th International Conference on Optical Networking Design and Modeling - ONDM 2009 - Braunschweig (Brunswick), Germany, Feb 18-20, 2009.

Joint paper written and submitted to IET Optoelectronics Journal, special issue on Next-Generation Access Networks. Title of paper is "Experimental investigation on the Quality of Service Control based on Virtual Private LAN Service technique in hybrid optical access networks**".**

4.4.6 Research Contributions

More detailed aspects of the QoS in PONs research contributions are detailed as follows.

- **Experimental tests on QoS in EPON**

Passive Optical Networks (PONs)[1-3] will be one of the key points for Internet improvement with optical technology. However, it has to be pointed that, even if the capacity of PONs is much wider with respect to other access techniques based either on copper or on radio, in future applications also current PONs could be congested by user traffic. 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 procedures have to be introduced also at PON level, and, in particular, traffic priorities can be introduced at edge level following the indications reported in [4], where a QoS management method based on Virtual Private LAN Service (VPLS) was demonstrated to guarantee the transmission of HD TV streamings in xDSL accesses. In this section, we show how to extend such a method to EPON networks.

The network test bed, Figure 41, is composed of 4 core routers, fully meshed by using the fibre cable of the experimental ring Roma-Pomezia-Roma (50 km), and three edge routers. The communication among routers is obtained by means of OSPF, (G)MPLS and BGP protocols. The access section of the network is based on xDSL and Fiber To The X (FTTx) access technologies. In particular a PON was included consisting of an Ethernet Passive Optical Network (EPON), AN5116-03 ePON FiberHome, with an Optical Line Termination (OLT) and eight Optical Network Units (ONU). The OLT and the ONUs are connected by means of short single mode fibres (100-1000 m) with the downstream wavelength at 1490 nm and upstream wavelength at 1310 nm.

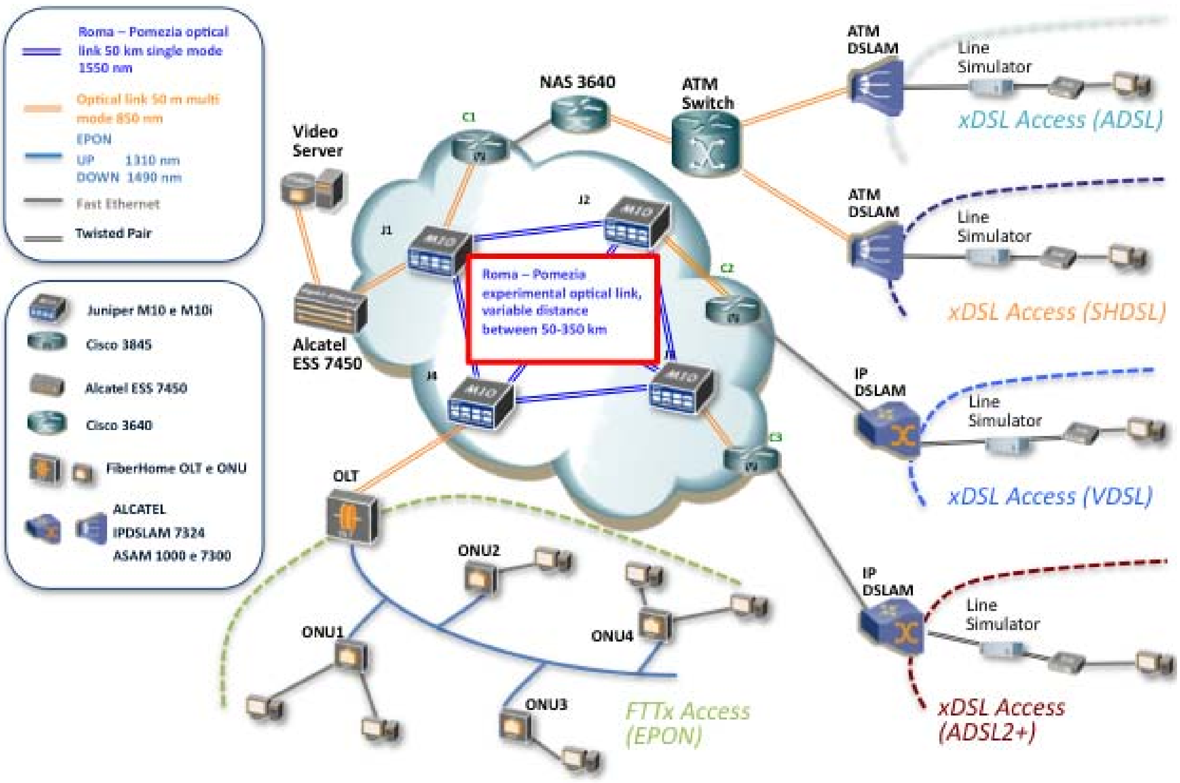


Figure 41: Complete TEST BED

As shown in Figure 42, we implemented an E-line VPLS between PE1 and PE2, and VLAN tagging from CE1 to PE1 and from PE2 to the ONUs. In particular, a tunnel based on VPLS&VLAN tagging between SITE1 and the ONU2 is established permitting the QoS control with Gold class [5].

To test the impact of the network congestion, a traffic generator is included in the Test Bed for introducing background traffic of 1 Gbit/s between PE2 and the OLT. We considered the downstream scenario sending a data stream from PC1 to the user (ONU2), and we overloaded the link between PE2 and the OLT to evaluate 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 high bit-rate traffics that can induce a congestion between PE2 and the OLT, with a consequent degradation manifested at the ONU output.

The advantages of our method are illustrated by the Figure 43 reporting the effects of the congestion on throughput-at the ONU2 output for 40 Mbit/s streams coming from PC1, both for Gold class VPLS and Best Effort VPLS; we indicate as “congestion” the time between 10 sec and 30 sec, when we introduced the background traffic of 1 Gbit/s between PE2 and the OLT. Figure 43 shows that, by means of VPLS&VLAN tagging Gold instance, we can guarantee QoS since no network performance degradation is manifested when a congestion event occurs. Jitter, delay and packet have been also evaluated confirming results on network performance but they are not reported.

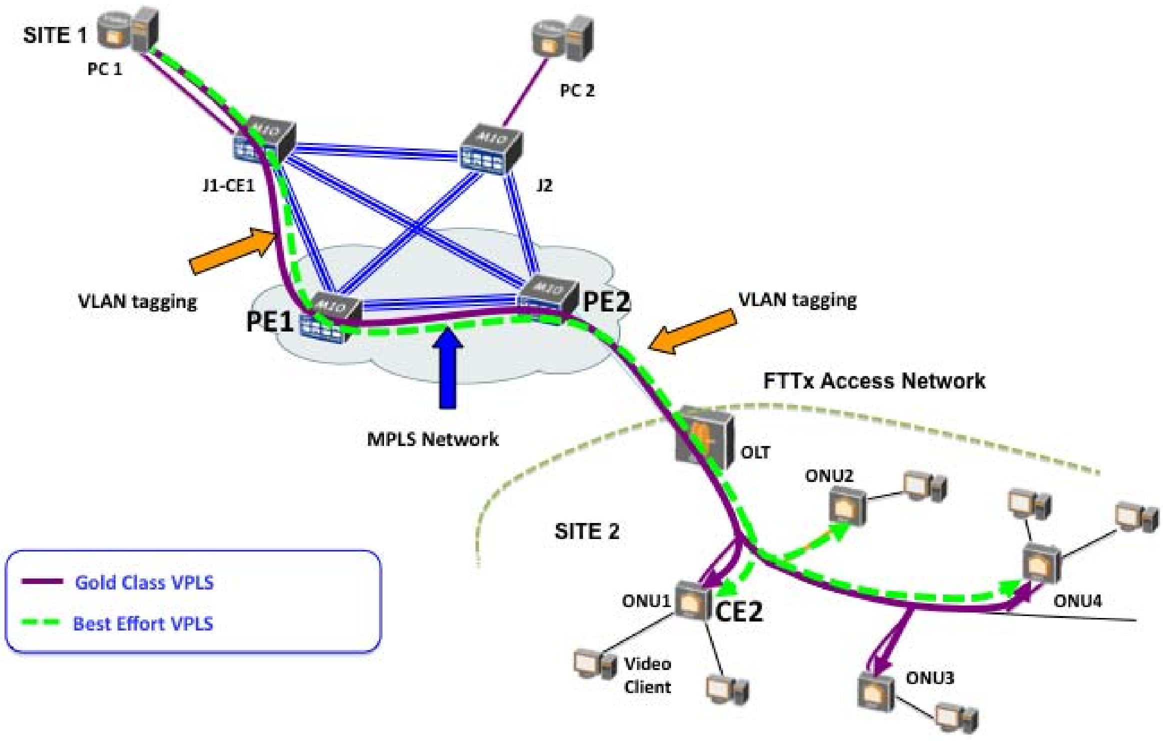


Figure 42: VPLS implementation

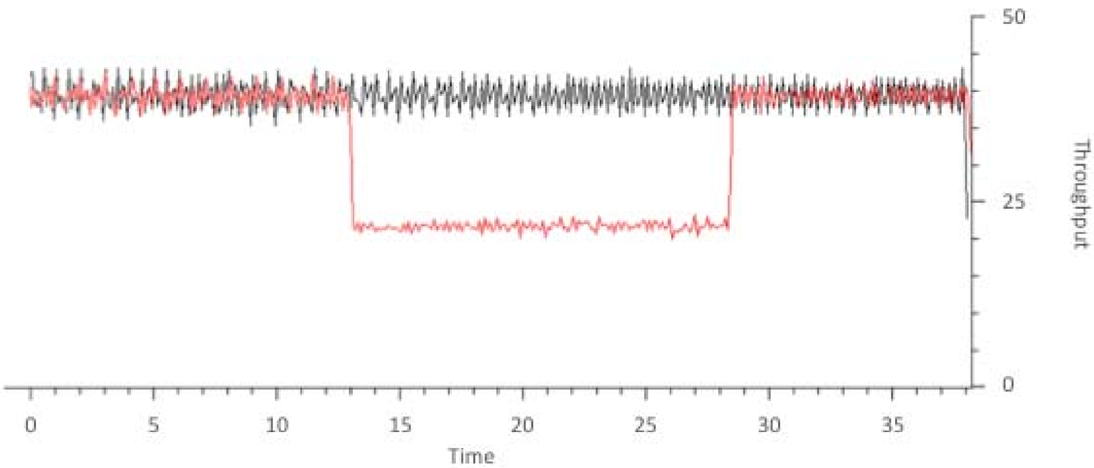


Figure 43: Throughput of the 40 Mb/s fluxes at the ONU2 output (downstream) with and without VPLS/VLAN tagging

In Figure 44, throughput evaluation is reported for upstream direction (at the output of PC1). Results show network performance for 40 Mbit/s data stream both for Gold Class VPLS and Best Effort VPLS, when a network congestion event occurs.

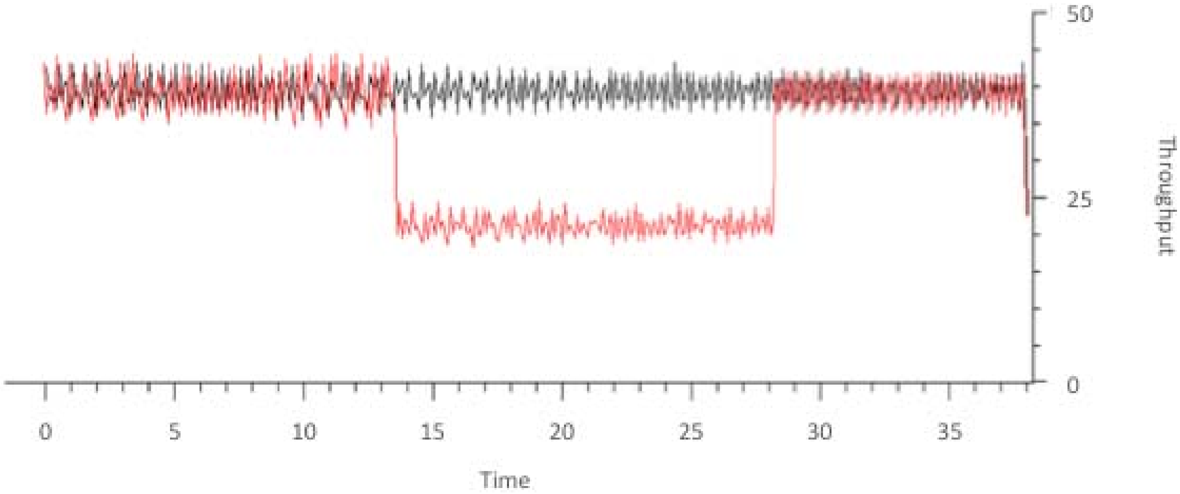


Figure 44:Throughput of the 40 Mb/s fluxes at the CE1 output (upstream) from ONU2 with and without VPLS/VLAN tagging.

- **Wavelength conversion in EPON**

Future PONs will be upgraded with WDM transmission so that multiple wavelengths may be used in either or both upstream and downstream directions. Such PONs are known as WDM-PON [6] and permit to deeply increase the bandwidth, and different independent PON sub-networks can operate over the same fibre infrastructure. A WDM-PON is transparent to the protocols or signals, meaning that it can carry any kind of signal format. However, receivers at the OLT and at the ONU should satisfy the specifications required by the adopted protocol. If a wavelength is assigned for an EPON group, then only the MAC protocol of the EPON system is used since this wavelength does not have any interaction with other channels; however, this scheme may not utilize bandwidth efficiently, especially when some wavelengths are overloaded, and therefore novel protocols can be proposed to assign both time slot and wavelengths according to the user requirements [6]. To complete the WDM-PON overview, it has to be pointed out that Super PONs have been also proposed to use much longer distance (hundreds of km). In this scenario, it is clear that in the future we will see a deep fibre penetration in the access with WDM transmission with wavelengths both in configuration point-to-point and point-to-multipoint. In particular, channels could be dedicated to specific services, for example as backhaul for TV stations and radio Base Station [7]. In this scenario, conflicts among wavelengths can occur, especially if more EPONs are present in the same PON infrastructure, and therefore All Optical Wavelength Conversion method (AOWC) could be required also in the access segments [8].

This is the reason why in this Section we experimentally investigate the AOWC in the EPON network by using Semiconductor Optical Amplifiers (SOA) that should result a quite cheap solution. This way, we show that the architecture described in Figure 42 can be upgraded allowing a data stream to be carried through the whole network and to be optically converted in the PON segment.

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 IEEE 802.3ah [9]), 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.

Moreover, it grants the possibility of treating the signal in the C-band, in which the majority of devices, like lasers and EDFAs, works.

The experimental set-up is reported in Figure 45. The signal from the OLT (AN5116-03 ePON FiberHome), with a power of 0.22 dBm, is amplified by a EDFA S-Band (14 dB) and coupled with a CW from a DFB laser (19 dBm): these signals enter in the first SOA (Covega 2385) where the first wavelength conversion based on XGM occurs (XGM1). The XGM1 converts the OLT wavelength from 1490 nm to 1536 nm, near SOA gain peak, and we measured for the converted signal a power of -6.7 dBm. The converted signal is coupled with a second CW from an ECL (External Cavity Laser, P=21 dBm): these signals enter into the second SOA (Alcatel M18) performing the latter XGM (XGM2). The power of the converted signal XGM2 was equal to -6.9 dBm.

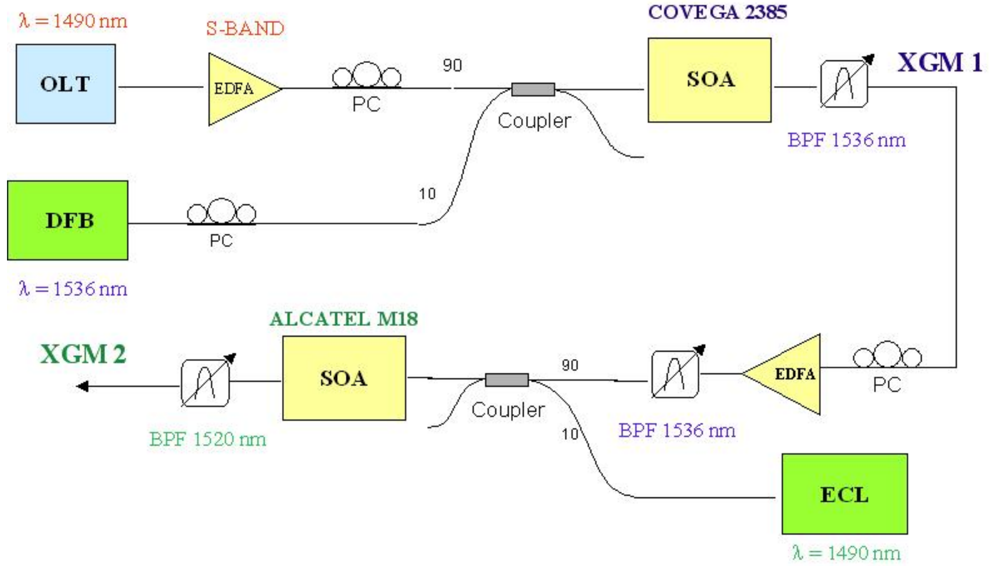


Figure 45: Experimental set-up for AOWC based on SOA. PC polarization control

In XGM1, the signal is logically inverted, in XGM2 there is a second logical inversion that brings back the signal to its original shape (Figure 46). The results are taken using a real time oscilloscope (Tektronix DSA 602). The double XGM induces a very weak signal degradation.

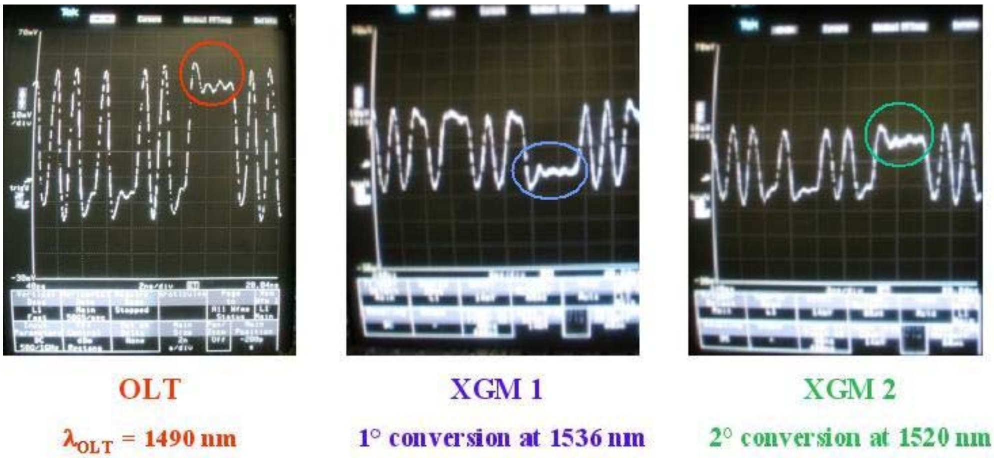


Figure 46: Signal conversions with double XGM

The transmission performance of the SOA AOWC of Figure 45 was tested by means of a traffic analyzer (ANRITSU MD1230B), locating the transmitter in the OLT position and the receiver (with optical attenuator) at XGM2 output; in Figure 47, we report the BER versus the received power at 1 Gbit/s. It has to be pointed out that the instrument was not able to detect a BER higher than 10^{-8}. The results show good performance of the AOWC device and, compared with the back-to-back case, only a small penalty is present. In fact the communication between OLT and ONUs (AN5006-05 ePON FiberHome) was without any degradation also with the inclusion of the AOWC.

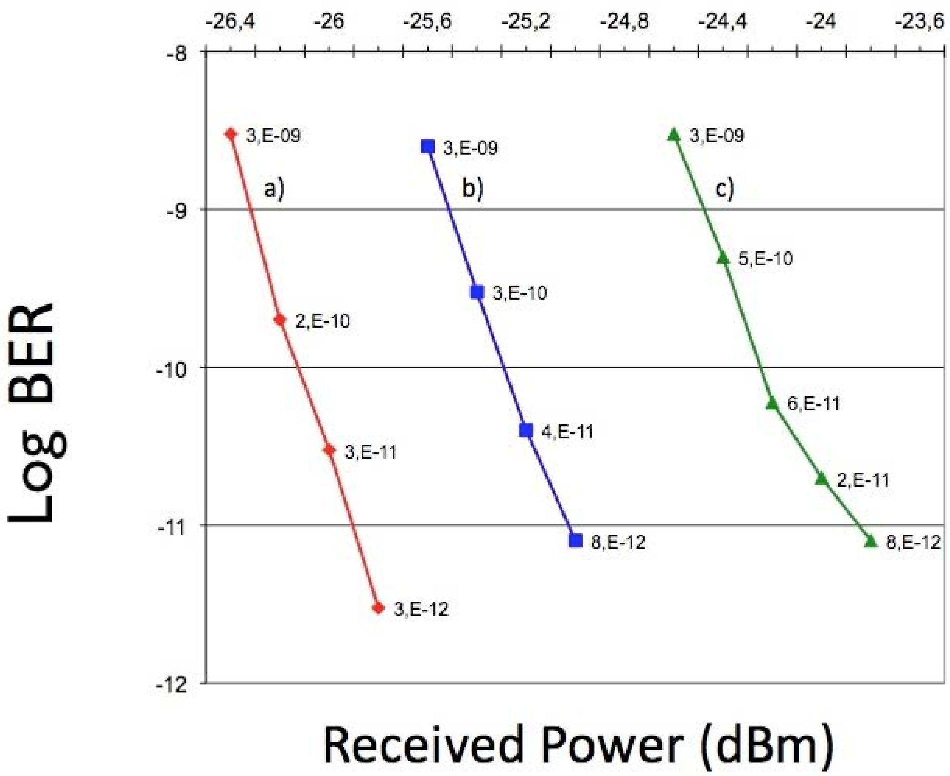


Figure 47: BER vs received power: a) back to back; b) AOWC with double XGM; c) ASE noise modulation and XGM

We also tested the latter method that guarantees optical wavelength conversion, and it is based on the modulation and subsequent filtering of the ASE SOA spectrum, as reported in Figure 48.

The noise modulation set-up is similar to the Figure 45 set-up, and the only difference is the absence of the DFB branch, so the amplified OLT enters into the SOA saturating its gain. In this case, after the first conversion (ASE MOD), the signal power was equal to -16.3 dBm and after the latter conversion the output power was equal to -7.2 dBm.

Performance get worse because the signal on the converted “1s” is much noisier; however the second conversion reconverts and cleans the signal, permitting, as shown in Fig. 8 in case c), only a higher power penalty; as a result, OLT and ONU can communicate without degradation.

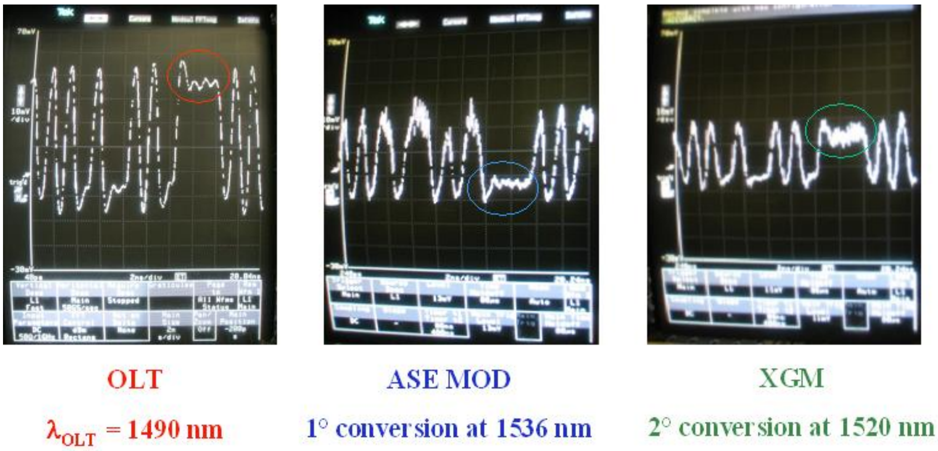


Figure 48:Signal conversions with noise modulation and single XGM

To conclude our tests, in Figure 49 we show two pictures taken from MPEG2 HD TV streaming at ONU2 output, that was sent from the server, crossing the whole VPLS&VLAN network, when the SOA AOWCs were included in the EPON. In such a way, we show that the VPLS&VLAN Tagging can operate in the whole core-access network, including the presence of AOWC process also in the access.

Figure 49:Two pictures taken from MPEG2 HD TV streaming at ONU2 output with SOA AOWC in the access. On the left the AOWC is based on double XGM, on the right on noise modulation and single XGM

1.6.3 Control Plane for EPON based access networks

An EPON based optical access network architecture consists in (1) an Optical Access Multiplexer located at the central office which presents multiple Optical Line Termination

(OLT) cards and (2) remote Optical Network Units (ONUs) that deliver broadband voice, data, and video services to subscribers. While downstream traffic is broadcast by each OLT card to all ONUs controlled by this OLT, the access of upstream traffic to the fiber has to be arbitrated in order to avoid collisions. Static sharing is very inefficient since the relatively small number of ONUs (16, 32, or at most 64) precludes efficient statistical multiplexing. Dynamic sharing is achieved by designing both a Dynamic Bandwidth Assignment (DBA) that shares bandwidth opportunities between customers, and an intra-ONU scheduling policy, which is used by customers to take advantage of the allocated bandwidth opportunities. The DBA and the settings of the intra-ONU scheduling policy are part of the control plane of the optical access network.

The control plane of an optical access network typically implements many functions. Some of them are related to Operation Administration and Maintenance (OAM) procedures that are used to initialize a new OLT card, to insert new ONUs for an existing EPON, to provide synchronization in the system, etc. The present contribution concentrates on the traffic management functions addressed by the control plane. These include:

- **Connection Acceptance Control (CAC)** that accepts or rejects the establishment of a new connection;
- **Conformance Checking** that consists in enforcing the traffic description negotiated in SLAs;
- **QoS Control** that dynamically allocates resources in such a way that the QoS levels negotiated in the SLAs are delivered and the non committed resources are fairly shared.

Thanks to various configurations of the control plane, an operator can support different types of services. Indeed, the offer for broadband access is not identical over all network operators: some operators offer only a best effort access; others operators already support streaming services such as Video on Demand, and interactive services such as VoIP. In the near future, it is fairly likely that some operators would like to support Committed Bandwidth services (especially for SME or SOHO customers) similar to the well known Frame Relay services that specified a Committed Information Rate (CIR) and an Excess Information Rate (EIR). Other could wish to support several Classes of Services, implementing either relative priorities between classes or enforcing some kind of access control on some Classes. An operator could also wish to support different types of services for different market segments (e.g. best effort access for residential customers, but committed bandwidth services for SME/SOHO customers). Lastly, service offers have to regularly evolve in order to support new applications and/or to avoid churn.

In the present contribution we show how to build a versatile control plane for EPON based optical access networks that can be configured to support either a classless Best Effort network, or several relative Classes of Services, or a mix of committed bandwidth and Best Effort services. This control plane includes a framework for enforcing Service Level Agreements, and fairly sharing available resources. Moreover, the impact of the EPON architecture on delivered QoS in terms of transfer delay is assessed, which directly impacts on CAC policies. Our contribution also points out how the CAC interacts with the DBA enforced by the OLT. These results have been published in [10].

The key element for this control plane is DBA-TCM described in [11] which integrates traffic conformance checking (TCM) functions to dynamic bandwidth assignment (DBA).

- **A control plane for supporting different service offers**

Our contribution is first illustrated in a simple case, in which the operator supports a classless, Best Effort service. For the operator, the issue is twofold: first ensure that users are fairly served (e.g. avoid that one group of users starves another group), and secondly ensure that resources are efficiently used (e.g. serve as much users demands as possible). The configuration of DBA-TCM is simple in this case: each ONU is allocated an equal share of available capacity that is slightly smaller than *C/O* (*O* is the number of ONUs) in order to account for transmission overhead; we assume here that the OLT allocates 60.0*Mbps* to each of the 16 ONUs. All traffic is handled as *bandwidth guaranteed* traffic; transmission opportunities are first allocated to conforming traffic whereas DBA-TCM also allocates resources to non-conforming traffic as long as the QoS offered to conforming traffic is not degraded. We compare below the performance delivered by an EPON using static Time Division Multiplexing (TDMA), IPACT-LSQoS (which behaves here as IPACT-LS) and our proposed scheme DBA-TCM.

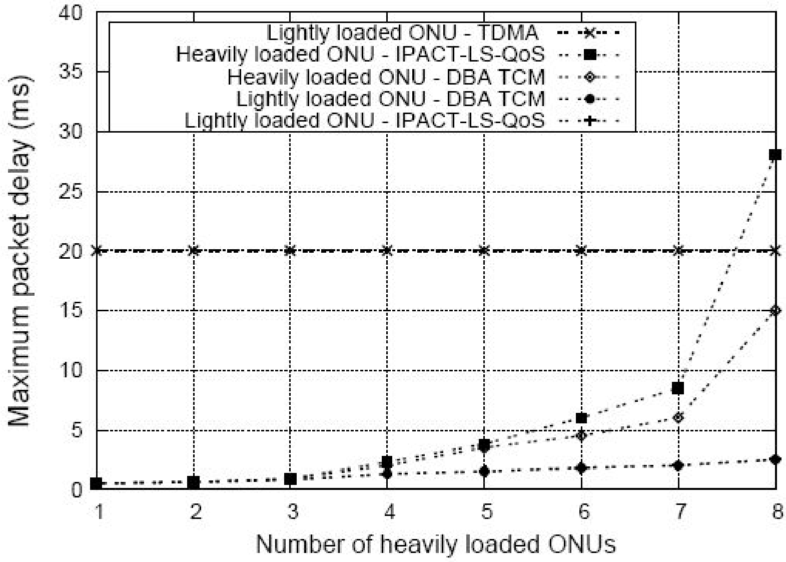


Figure 50: Supporting Best Effort Traffic with DBA-TCM

In the scenario illustrated in Figure 50, we consider unbalanced traffic offers, and wish to assess whether heavily loaded ONUs can use unallocated resources without degrading the performance offered to lightly loaded ONUs. We consider 8 lightly loaded ONUs (*Ra*=25*Mbps*, *Rp*=70*Mbps*) and a varying number of heavily loaded ONUs (*Ra*=60*Mbps*, *Rp*=120*Mbps*). Fig. 10 shows the maximum packet delay performance for the two types of sources, versus the number of active heavily loaded ONUs. The performance delivered by TDMA for heavily loaded sources is not shown on Figure 50 because it is very bad (500*ms*). TDMA behaves badly compared to the 2 dynamic DBAs for both heavily and lightly loaded sources. IPACT-LS-QoS and DBA-TCM behave similarly for lightly and heavily loaded sources; both protect lightly loaded sources, and efficiently share resources amongst heavily loaded sources. Furthermore, Figure 50 also shows that DBA-TCM behaves significantly better towards heavily loaded sources than IPACT-LS-QoS when the number of heavily loaded sources is large. In particular, we see that the QoS offered to heavily loaded ONUs by DBA-TCM is even better than the one offered to lightly loaded ONUs by a static TDMA.

However, even for DBA-TCM, the delay experienced by a heavily loaded ONU (which presents a high proportion of non conforming traffic) is rather high (15ms).

This is why some operators choose to offer multiservice support. For illustration purposes, we assume that 3 classes of traffic are now supported: Real Time Traffic (T0), Guaranteed Bandwidth Traffic (T1) and Best Effort (T2). For a Multiclass Service Offer, the operator should be able to ensure that each class receives the negotiated QoS levels; in the considered scenario, the delay for T0 traffic should be less than 3ms, whereas the delay for for T1 traffic should be less than 30ms.

The configuration of DBA-TCM in case of multiservice offer is as follows: each ONU is allocated a share of available capacity computed according to its SLA. In each ONU, each traffic class has its own traffic profile (and possibly dynamically modified depending on CAC decisions). We assume that each traffic profile is known by the OLT. Traffic Conformance Control is activated.

We wish to assess and compare the QoS supports offered by DBA-TCM and IPAC-LS-QoS. We investigate a scenario where some ONUs require Committed Bandwidth services while others require only a “Best Effort” access. This scenario could represent an OLT serving both residential and SOHO/SME customers; it also corresponds to a scenario where only part of the ONUs request committed bandwidth services at a given time. In a first set of 6 ONUs, each ONU send T0 traffic at an average rate of 20Mbps and T1 traffic at an average rate of 40Mbps. The 10 ONUs in the second set send only T2 (BE) traffic. Fig. 11 shows the maximum packet delay performance for T0 and T1 traffic versus the load offered by T2 traffic. The QoS delivered to T2 is not shown since it is actually very bad (but there is no actual commitment on it).

A first comment on Fig. 11 is that both IPACT-LS-QoS and DBA-TCM offer different levels of QoS to T0 and T1 traffics. However, their respective reactions to the increase in T2 traffic load significantly differ. For DBA-TCM, the QoS delivered to T0 and T1 traffics is not impacted by a large T2 traffic load. This is because in DBA-TCM, the OLT, knowing all demands, first attempts to satisfy T0 traffic demands, then T1 traffic demands and lastly T2 traffic if there are some remaining resources.

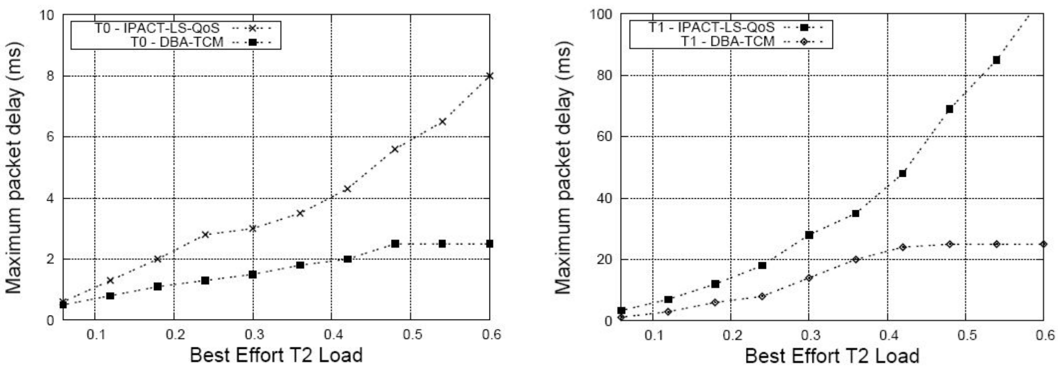


Figure 51: Delay offered to T0 traffic (left) and to T1 traffic (right)

The curves for DBA-TCM indeed become flat (i.e. the delay performance is not degraded) for T2 traffic load of (roughly) 0.4 because then, the frame size is systematically limited to 1.5 ms. This is not the case for IPACT-LS-QoS which cannot efficiently protect T0 and T1 traffics from T2 traffic: the delay performance delivered to T0 traffic is as bad as 8ms, which is much too large for real time service. We observe on Figure 42 that the target delay values for T0 and T1 traffics (respectively 3ms and 30ms) are enforced by DBA-TCM.

- **Supporting CAC in an EPON based access network**

Let us now address the relationship between CAC and traffic management in an EPON based Optical Access Network.

First of all, we note that the EPON standard does not support CAC: Ethernet being connectionless, it does not recognize “calls”, “connections” or “virtual circuits”. However, the access network can recognize this type of objects and implement CAC functions. Then, the Optical Access Multiplexer can directly interact with the OLTs by dynamically modifying the traffic profiles for each ONU. DBA-TCM is particularly well suited to such an interaction since it centralizes conformance control within the OLT and does not distribute it between the ONUs and the OLT.

Another aspect to address is the impact of the DBA controlled access on CAC design. A huge literature addresses the design of CAC in broadband networks using Point-to-Point links; on the other hand, very little effort has been deployed for adapting these CAC procedures to Optical Access networks or more generally to access networks where scheduling policies avoid contention between competing users. This is the point that we address in the following.

For illustration purposes, we consider homogeneous, independent ON-OFF sources with exponential ON and OFF distribution and with Peak Rate Rp =10Mbps. The number of active sources at time t is obviously a continuous time Markov Chain. We consider that the system is “congested” when M (here, M=100) or more sources are in the ON state. Let **e** be a target upper value for the congestion probability. A small target value for **e** (i.e. smaller than 0.01) is applied for T0 traffic, and a larger value for **e** (i.e. between 0.05 and 0.3) is accepted for T1 traffic. This is admittedly rather naive, but it conveniently models the fact that for T0 traffic, there should be minimal queuing whereas T1 traffic is allowed to queue in the system. Let us then consider the following CAC for homogeneous sources: the number of admissible sources is the maximum N for which the congestion probability is smaller than **e**.

We consider scenarios with a single class of traffic (either T0 or T1). Figure 52 compares the delay performance versus target congestion rate achieved respectively by Point-to-Point and EPON systems when we apply the same CAC to the 2 systems.

The left hand side diagram in Figure 52 considers T0 traffic (**e** is smaller than 0.01). We consider 2 cases, corresponding to different ON-OFF period durations. We first see that the delay performance achieved by the Point-to-Point system is excellent and not sensitive to **e**, regardless of the ON-OFF period duration. This is however NOT the case for the EPON system: the performance is significantly worse and degrades when **e** increases, and it also depends on the ON-OFF period duration. This is due to the impact of polling: although the cycle time is limited, all traffic has to wait at least a cycle time, and more if there is significant buffering in the ONUs. This is why the delay performance can be as bad as 3.5ms (a bit more than twice the maximum cycle time) for **e** = 0:01. We see that, in order to limit the packet delay of T0 traffic to 3 ms in the present case, the congestion rate should be limited to less than 0.005. This implies that designing a CAC for T0 traffic in an EPON is not straightforward, since it is necessary to explicitly take account of the polling behavior.

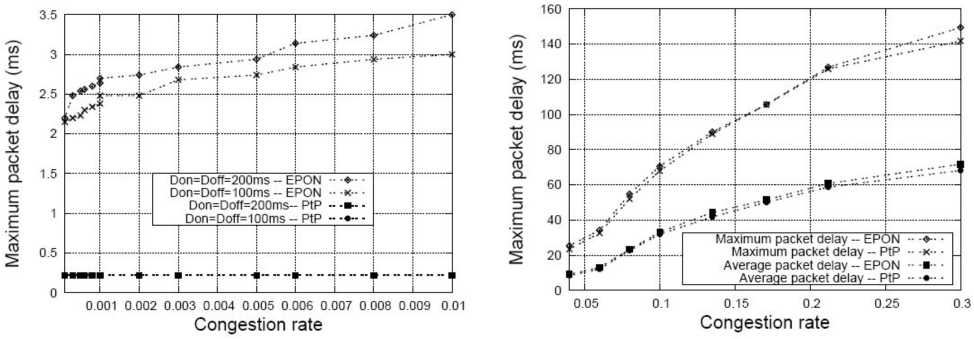


Figure 52: Delay offered to T0 traffic (left) and to T1 traffic (right) for a given CAC

On the other hand, as observed on the right hand side diagram in Figure 52, the delay performances for both Point-to-Point and EPON systems are very similar when the CAC is applied to T1 traffic. Indeed, the impact of the polling delay is negligible compared to the queueing time in the ONU. The practical consequence is that any classical CAC designed for a Point-to-Point system is likely to directly apply to an equivalent EPON based optical access network.

- **Conclusion**

This contribution shows how a simple priority based DBA with a Traffic Conformance checking Module (DBA-TCM) is a major building block for an EPON control plane. Although DBA-TCM is fairly simple in its principles, this paper shows that it easily supports different service offers, and is capable of delivering Committed Bandwidth services with stringent QoS guarantees whereas the well known IPACT-LS-QoS (IPACT with limited Service and QoS support) is slightly less efficient and cannot support stringent QoS guarantees.

We have also addressed the important problem of the integration of CAC into an EPON control plane. DBA-TCM in itself does not implement a CAC procedure because the MAC for EPON does not support the necessary mechanisms. However, any CAC implemented in the optical access multiplexer where the OLT is located can directly interact with DBA-TCM through the OLT (e.g. by dynamically modifying the traffic profiles associated to an ONU). The present paper argues that while any CAC designed for Committed Bandwidth services with no stringent delay requirements can be directly used for EPONs, this is not the case for services with stringent delay requirements. In this particular case, the polling procedures adds a delay which can be as large as several milliseconds. It is thus necessary to be more stringent with EPONs than with a classical Point-to-Point access architecture.

In the recent past, several authors advocate in favor of decentralizing traffic management procedures by giving more autonomy to ONUs. The present approach does not follow this trend, in order to keep ONU design as simple as possible and to delegate all major decisions to the OLT. The OLT is indeed clearly under the control of the network operator, whereas ONUs, as DSL or cable modems, are distant and less easily managed.

- **TCP Preformance in EPON**

In 2009 the research group of University of Modena and Reggio Emilia (UNIMORE) has continued to investigate the performance of optical access networks.

TCP performance have been evaluated when high speed Ethernet over Passive Optical Networks are interconnected by means of a core optical network based on the Optical Burst Switching paradigm.

The inter-working unit, or edge node, between these two networks has properly studied and discussed. A time-based assembly algorithm has been employed, analyzed and designed for operating with a EPON, characterized by some parameters such as the cycle time for managing the upstream transmissions.

This hybrid network has been evaluated through simulations by means of the ns2 simulation tool.

Figure 1 shows the average TCP throughput as a function of assembly time T_{max} for burst loss $=10^{-3}$ and different values of the congestion window.

It is evident to observe that the throughput remarkably improves by increasing the congestion window from 64 to 256 segments. This is due to the fact that each TCP source can send more segments during its time interval $T_c\backslash N$. Even more interesting is that the performance have different point of maximum for the three curves.

In conclusion, the best value for setting T_{max} depends on the TCP congestion window and it should be 0.5 ms, 2 ms and 3 ms, respectively for a congestion window of 64, 128 and 256 segments.

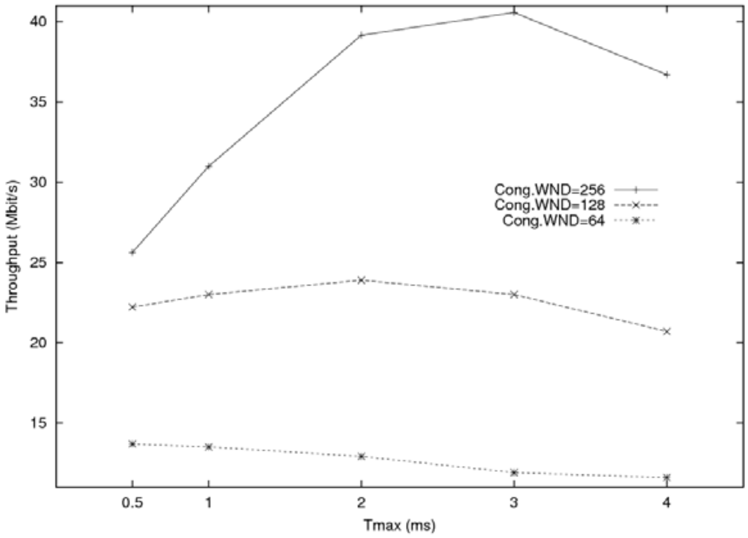


Figure 1 Average TCP throughput vs. T_{max} for burst loss $=10^{-3}$ and different values of the congestion window.

- **References**

1. S. J. Park, H. Chang, L. Ki-Tae, J. J. Park, J. G. Ahn, and K.H. Song, “Fiber-to-the-home services based on wavelength-division-multiplexing passive optical network”, J. of Lightwave Technol. 22, 2582- 2591 (2004)

2. G.Kramer, and B.Mukherjee “Ethernet PON (ePON): Design and Analysis of an Optical Access Network”, Photonic Network Commun. 3(3), 307-319 (2001).

3. A.V. Tran, C.J. Chae, and R.S. Tucker. “Bandwidth-Efficient PON System for Broad-Band Access and Local Customer Internetworking”, IEEE Photonics Technol. Letters, 18, 670-672 (2006)

4. L. Rea, S. Pompei, A. Valenti, F. Matera, C. Zema, and M. Settembre, “Quality of Service control based on Virtual Private Network Services in wide area Gigabit Ethernet test bed”, Fiber Integr. Opt. 27, 301-307 (2008)

5. F. Matera, L. Rea, A. Valenti, S. Pompei, G. M. Tosi Beleffi, F. Curti, D. Forin, G. Incerti, S. Di Bartolo, and M. Settembre, “Network Performance Investigation in a Wide Area Gigabit Ethernet Test Bed adopting the All Optical Wavelength Conversion”, IEEE Photonics Technol. Letters, 20, 2144-2146 (2008)

6. A. Banerjee, Y. Park, F. Clarke, H. Song, S. Yang, G. Kramer, K. Kim, and B. Mukherjee “Wavelength-division-multiplexed passive optical network (WDM-PON) technologies for broadband access: a review”, J. of Opt. Networking, 4, 737-758 (2005)

7. M. Suzuki, “Optical Networks for Broadband fixed and Mobile Services”, presented at the 33rd European Conference on Optical Communications, Berlin, September 16-20, 2007.

8. D. P. Shea, J. E. Mitchell, “Architecture to Integrate Multiple PONs with Long Reach DWDM Backhaul” J. on Selected Area in Communications, 27, 1-7 (2009).

9. IEEE 802.1 ah Standard. "Virtual Bridged Local Area Networks - Amendment 7: Provider Backbone Bridges", IEEE, August 14 (2008)

10. NGO Minh Thanh, GRAVEY Annie. “A Versatile Control Plane for EPON-based FTTX Access Networks”, NGI 2009 : 5th Euro-NGI conference on Next Generation Internet, 01-03 July 2009, Aveiro, Portugal, 2009

11. NGO Minh Thanh, GRAVEY Annie. “Traffic conformance issues in passive optical networks: challenges and solutions”, International journal of communication networks and distributed systems (IJCNDS), January 2009, vol. 2, n° 2, pp. 260-280

4.5 Joint Activity – Techniques for Colourless ONUs

4.5.1 Members

UNIROMA3, UCL, UPC, ISCOM

4.5.2 Objectives

The overall objective of this JA is to consider optical processing techniques to reduce transmitter and receiver requirements in next generation PONs.

4.5.3 Research Topics

Colorless sourceless OCDMA-base PONs

4.5.4 Collaborations/Joint Experiments and Mobility Actions

UNIROMA3 and NICT are performing field-trial experiments of OCDMA-based systems that do not require laser source at the ONUs.

UPC-ISCOM: Victor Polo, PostDoc at UPC, hosted by ISCOM.

4.5.5 Impact

- G. Cincotti, N. Kataoka, N. Wada, K.-i. Kitayama, "Sourceless colorless OCDMA-PONs", 14th OptoElectronics and Communication Conference (OECC) HongKong, Cina 2009.
- G. Cincotti, N. Kataoka, N. Wada, X. Wang, T. Miyazaki, K.-I. Kitayama, "Demonstration of asynchronous, 10Gbps OCDMA PON system with colorless and sourceless ONUs," European Conference on Optical Communication (ECOC), Vienna, Austria 2009.

4.5.6 Research Contribution

- **Colorless sourceless OCDMA-base PONs**

The commonly held view is that the evolution of the next generation access network (NGAN) will be directed toward wavelength division multiplexing (WDM) passive optical network (PON) systems, that can provide symmetric multi-gigabit fiber to the home (FTTH) services. However, recent research activities have been demonstrated that the optical code division multiple access (OCDMA) technology is a valid alternative for the NGAN, with enhanced flexibility and a reduced cost equipment. Like WDM-based systems, an OCDMA-PON can simultaneously provide contentionless gigabit-class up- and downlink bandwidth to end users, offering additional advantages of optical layer security and larger spectral efficiency. In addition, it is possible to extend the overall system capacity by integrating OCDMA and WDM technologies. Among the many research topics, one of the main key issue is the development of 'sourceless' (without a laser source) and 'colorless' (non-wavelength specific) optical network units (ONU), where a centralized broadband signal is distributed from the optical line terminal (OLT) to all users for re-modulation and upstream retransmission, to reduce the installation, operation and maintenance costs. UNIROMA3 and NICT have demonstrated for the first time a full-duplex, asynchronous, 10-Gbps OCDMA system on the same wavelength, in a 'colorless' and 'sourceless' configuration, i.e. without any laser source in all the identical ONUs. Both up- and down-link error-free transmissions (BER<10-9) have been successfully achieved, using differential phase shift keying (DPSK) modulation.

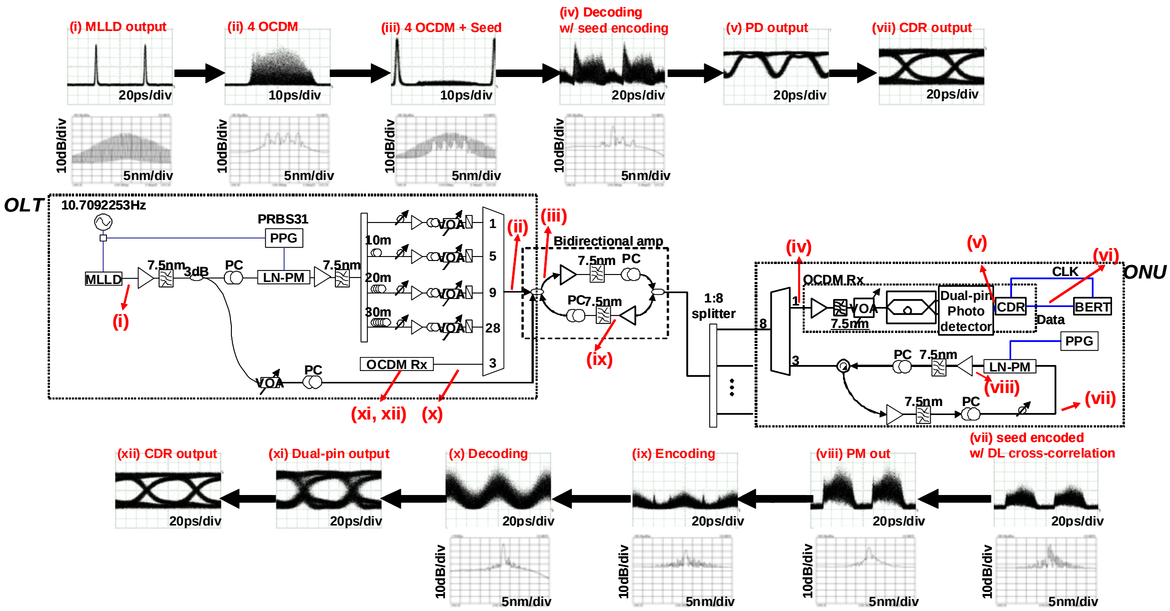


Figure 53: Experimental setup and results of a colorless and sourceless OCDMA-PON

Figure 53 shows the setup of the a full-duplex, 10 Gbps, DPSK-OCDMA system: at the OLT, a 31-port E/D is used and two codes, i.e. two E/D ports, are assigned to each user for the downlink and uplink transmission, respectively; therefore, with a 31-port device we could accommodate 15 different users. At the OLT, a 10.7 GHz 1.8 ps seed pulse train generated by a mode locked laser diode (MLLD) (Figure 54 (i)) is divided into two parts by a 3dB coupler, t to be modulated by the LiNbO3 phase modulator (LN-PM) and to become the seed pulse train that is used at the ONUs for re-modulation and uplink retransmission. The phase modulated signal launched into 4 different input ports of the 31-port E/D to generate 4 OCDMA signals in a worse case scenario with equal power, random delays, and random bit phases (Figure 54 (ii)). The OCDMA signal is asynchronously combined with the seed pulse train by using another coupler to become the downlink transmission (Figure 54 (iii)). This signal is then amplified by a bidirectional amplifier, which consists of a set of EDFAs, polarization controllers (PCs), optical band pass filters (OBPFs) and couplers. All the ONUs are identical and consist of a 31-port E/D and an OCDMA receiver (Rx): each subscriber simply selects this two assigned E/D ports ('colorless' architecture). At the ONU, the received downlink signal is sent into the input port of a 31-port E/D, and at the matched port, the decoded signal (Figure 54 (iv)) is DPSK detected by a fiber-based 1-bit delay line and a dual-pin photodetector (PD) (Figure 54 (v)). For BER measurements, the detected DPSK signal is recovered by the clock-and-data-recovery (CDR) circuit (Figure 54 (vi)) and forwarded to the BER tester (BERT). On the other hand, all the other unmatched E/D output ports simultaneously generate encoded signals (from the seed pulse train) overlapped to cross-correlation signals (from the 4-OCDMA signal), that correspond to the MAI noise (Figure 54 (vii). The signal at the output port 3 is modulated by the LN-PM for the upstream transmission and loop-backed to E/D by a circulator (Figure 54 (viii)). The clock recovery for the uplink is manually adjusted. Figure 2 (ix) shows the encoded waveform and spectrum of the uplink signal. The uplink signal is amplified by the bidirectional amplifier and sent into the input port of the 31-port E/D in OLT. Finally, the decoded signal is detected at the matched port (port 3) by the DPSK detector and CDR. Figure 54 (x-xii) show the waveforms of the 31-port E/D, PD, and CDR outputs, respectively. Figure 54 show the BER performances in case of (a) down-link and (b) up-link: error free (BER<10^{-9}) transmission has been achieved for all the users, for both cases.

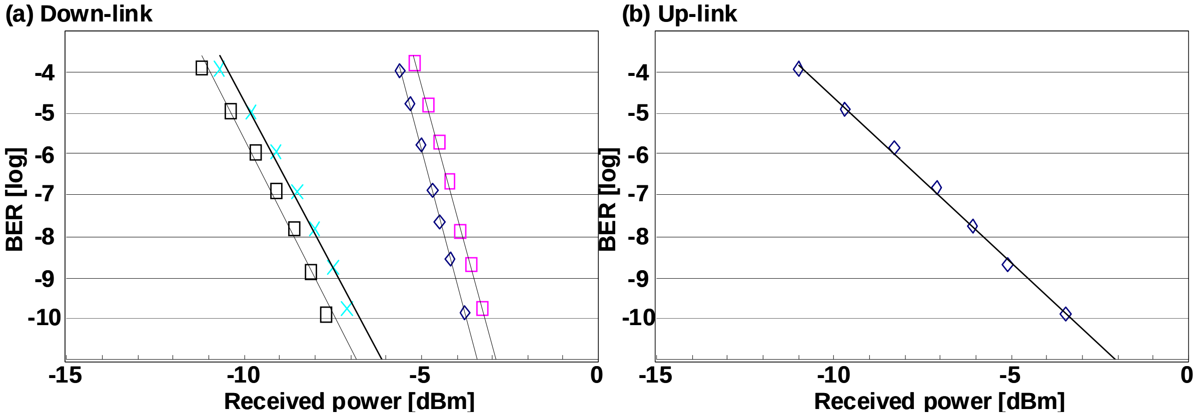


Figure 54: BER measurements.

- **Resilient pump strategies for extended PON architectures**

In order to test the resilience in a Passive Optical Network (PON) using remote amplification, a set-up including a Central Office (CO), 50 km of real deployed fibre (Rome-Pomezia-Rome), two Remote Nodes (RN1 and RN2) and one Optical Network Unit (ONU) was implemented. Each RN includes two 15 m EDFs for remotely amplification of the downstream and the upstream signals, in order to increase the reach of the network.

Resilience was tested by changing the direction of the signal. Normal operation is set by going directly from the CO to the desired RN, while resilience mode path goes through the other side of the ring, crossing the other RN and 5km of SMF as can be seen in Figure 55:

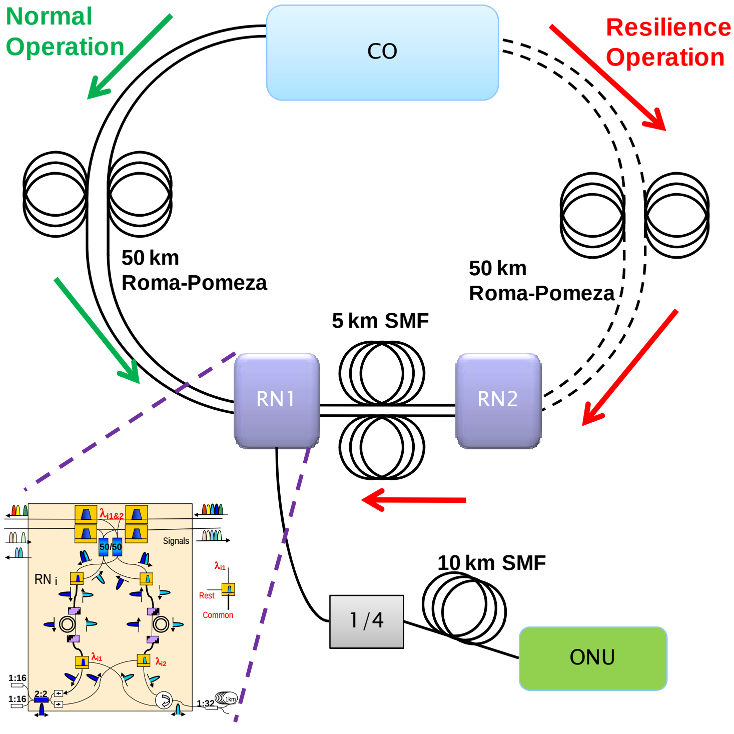


Figure 55: Network Test-bed.

The ONU was connected to the RN1, through a ¼ splitter and 10 km of SMF as drop fibre.

The CO and ONU were composed by:

10G-CW OLT TX
- **out: 0dBm**
- **DFB laser**
- **MZM modulator**
- **Booster EDFA**

OLT RX
- **PIN (2.5GHz)**
- **Preamplifier EDFA**

2.5G-CW ONU TX
- **out: 0dBm**
- **DML laser**

ONU RX
- **PIN (10GHz)**
- **Preamplifier EDFA**

Downstream signal wavelength was set at 1550.12 nm, while upstream signal wavelength was set at 1550.40 nm.

In normal operation mode, Downstream signal was sent from the west, going through 50 km of deployed fibre between Rome-Pomezia-Rome, and dropped in the RN1 using add/drop filters. In the RN the signal was amplified in 15m of HE980 EDF to increase the PON reach.

For distributing the pump power between the RNs, two pump distribution modules, shown in Figure 56, were built. As can be seen in Figure 56, fifty per cent of the pump power coming from I (west side for RN1) is dropped, while 99% of the pump power coming from II (east for RN1) is dropped.

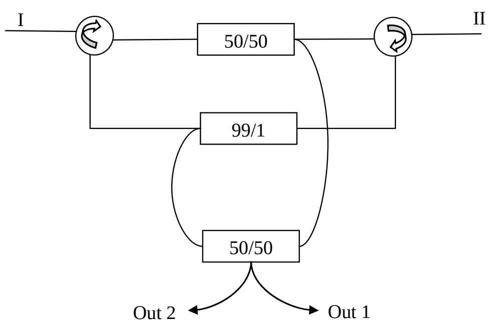


Figure 56: Pump distribution scheme.

Due to the lack of high pump power at 1480 nm, the pumps were connected directly to the RNs, avoiding the 50km fibber attenuation, but maintaining the pump distributors and the 5 km of SMF fibre between RNs. Pump lasers where set to 17 dBm, simulating a pump laser at the CO of 31 dBm.

A preamplifier and a PIN diode were used as ONU receiver. The following figure shows the BER curves for downstream normal operation and resilience mode.

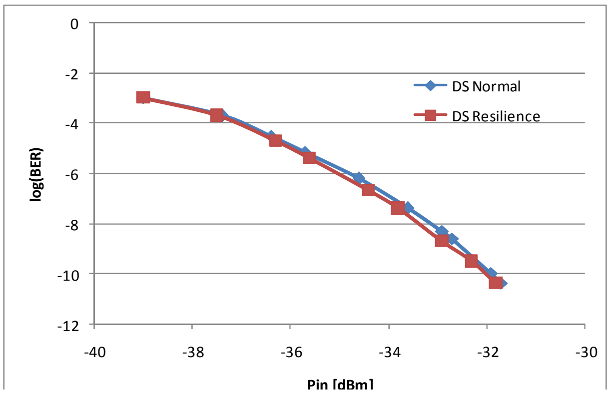


Figure 57: Downstream BER measurements.

As can be seen, no penalty due to the resilient mode can be appreciated, showing that the network can perform in resilient mode.

The following figure shows the upstream measurements. A preamplifier and a PIN were used as OLT receiver.

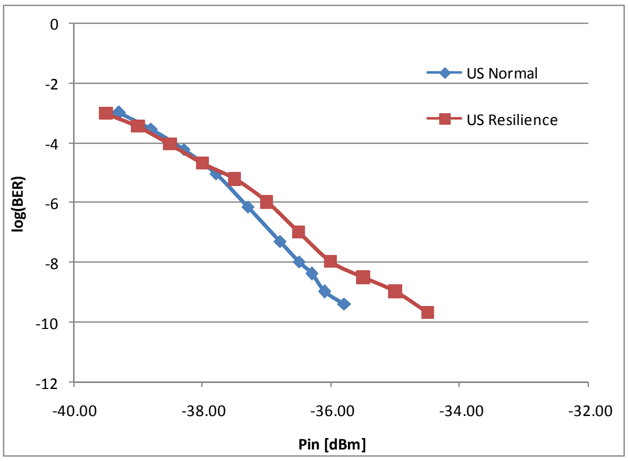


Figure 58: Upstream BER measurements.

No major penalties, less than 1.5 dB, can be seen from the experimental results comparing the normal operation and the resilience mode.

- **SOA burst equalisation**

In the PON networks, optical amplification is usually achieved by using EDFAs or SOAs. While EDFAs are ideal for broadcast type downstream transmission because of its high gain and low noise figure, the upstream direction however requires something different. In the upstream direction, the data is transmitted from several ONUs in a series of bursts to the OLT, in order to avoid noise funnelling, the optical amplifiers need to be gated, which mean it is only switched on for 125μs at each burst of data. SOAs have many benefits for this particular type of operation, including high gain and fast gain recovery time at typically 280ps.

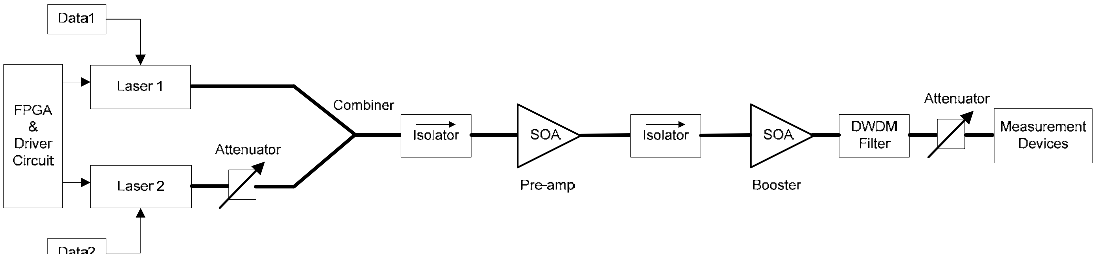


Figure 59: Burst equalisation experiment configuration block diagram

The test system configuration is shown in Figure 59. Two lasers were gated by two outputs from a Field-programmable gate array (FPGA) to simulate the burst from ONUs. Each packet is 125µs long, modulated by a data signal from a 10Gb/s Pseudo random bit sequence (PRBS) generator, 500ns guard time between the two bursts was used to prevent overlapping. A 5dB optical attenuator was placed after one of the laser output to simulate the optical path loss of a distant ONU, thus providing the power difference between the two ONUs. The two signals merged at the splitter/combiner just like they would in a real PON. The isolator before each SOA was there to prevent noise from the SOA travelling back to the laser. As described in theory, an optical filter was used to remove the energies of the “0s” from the received signal. In a real network the filter can be custom made or picked therefore it would have been optimised for the network condition. A 10dB attenuator was place before the Digital Communications Analyser (DCA), because the power from the output of the SOA was too high for the photodetector in the DCA.

The aim of the system is to level the bursts and reduce the non-linear distortions in the signal, therefore being able to maintain or even improve the Extinction ratio at the output is desired. Selecting the optimal filter cut-off frequency for the best ER is required. Since the AOC tech DWDM filters used in this experiment have a fixed filter characteristic and cut-off frequency, the filter is not frequency tuneable. By changing the laser diodes’ control temperature with-in a reasonable range (25°C ± 20°C), we can tune the laser wavelength linearly to find the best ER near the cut-off of the optical filter, that wavelength (frequency) will be the optimal for our system.

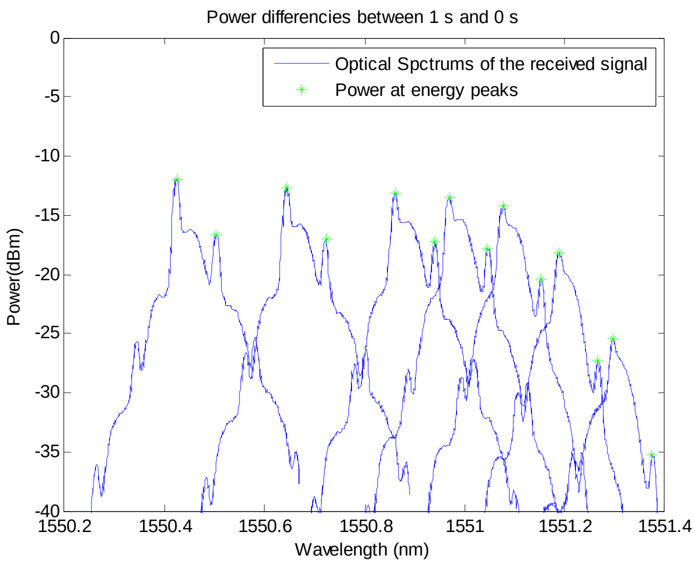


Figure 60: Power Spectrums of the amplified signal, energy of the “1s” and “0s” highlighted

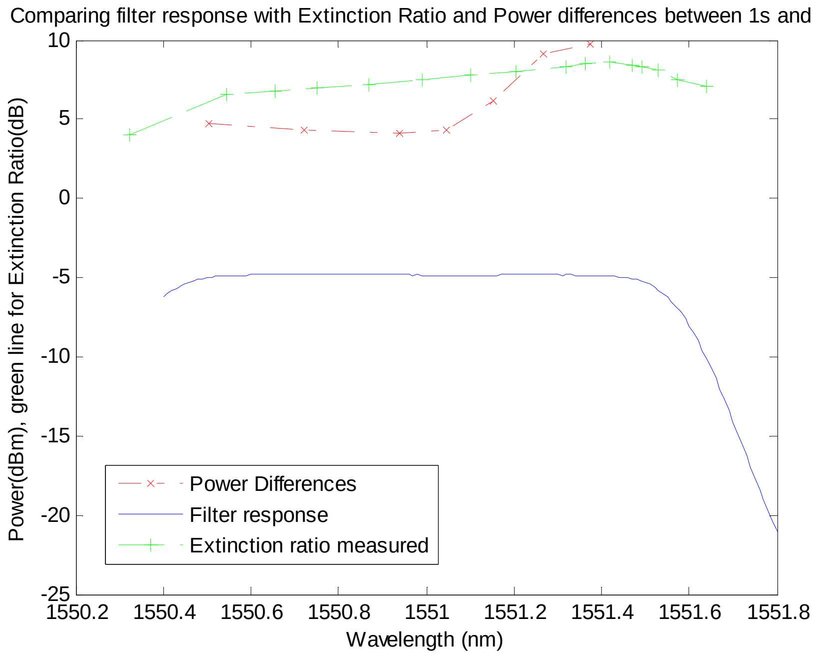


Figure 61: Comparison of filter response with ER and Power differences as wavelength of the signal is detuned to near the filter edge

The results in Figure 60 are spectrums of the output optical signal measured by a spectrum analyser as the wavelength of the laser is tuned towards the optical filter edge. The difference between the energies of the "1s" and the energies of the "0s" is increasing towards the filter edge. A quantitative analysis of this data provides us with Figure 61, it compares the power differences and extinction ratio measured from the DCA with the measured filter response.

From Figure 61, it can be seen that the Extinction Ratio increased by 2dB near the edge of the filter cut-off at about 1551.5nm. The Extinction Ratio then decreases because of the wavelength has move further into the filter cut-off resulting in the data being filtered, causing a reduced Extinction Ratio. The power difference is plotted as the X in the figure showing a significant rise of the difference in power near the filter edge.

In this experiment we tested the idea of using SOA as a limiting amplifier to level the bursts that had a 5dB difference in input power, which translates to about 25km of fibre distance between two ONUs assuming we used a 0.2dB/km loss single mode fibre. The dynamic range of the system at 5dB is still not high enough, considering the split loss and fibre loss of a real PON network can be as high as 12dB or more. The method that uses sharp optical filter to reduce the effect of spectral broadening caused by the non-linear effect in SOA was suggested and tested in the experiment, it showed 2dB increase in Extinction Ratio near the filter edge.

A SOA model was developed, two possible mathematical description of the saturate SOA were compared, it was found that the model was proposed in [1] gave more precise sample based simulation of the saturation and chirp. Further analysis is required to produce a successfully model that simulate the nonlinear effects as well as the identical gain saturation characteristics of the real device. By using a SOA model in OptSim we hope to test a PON access network in simulation with the implementation of the burst equalisation mechanism in place.

---

[1] A. Mecozzi and J. Mork, "Saturation effects in nondegenerate four-wave mixing between short optical pulses in semiconductor laser amplifiers," *Selected Topics in Quantum Electronics, IEEE Journal of,* vol. 3, pp. 1190-1207, 1997.

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					