SEVENTH FRAMEWORK PROGRAMME

Final report on integration activities

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Abstract:

This final report details on the activities, integration and network in the BONE workpackage 13 - Virtual Centre of Excellence on Access. It details the joint activities that have been undertaken specifically in the third year and and thoughout the project highlighting the research achievements. It also outlines the areas of active research undertaken by partners within the VCE which has led to integrated of activities. There is more evidence this year of activities that have let to been consolidation of European research efforts in the area of optical access, enabled by the mobility of research staff and resulting in a number of publications in journals and high quality conferences. The workpackage has acted a valuable platform for interaction between partners, resulting in futher research proposals.

Keyword list: Optical Access, Radio-over-fiber, Passive Optical Networks

Disclaimer

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Executive Summary :

The deliverable is the third and final 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 third year of the project, highlighting key research achievements. It also outlines acheivements of the partners within the VCE over the course of the project towards the aims and objectives of the project and the workpackage.

During the first two years of the project six joint activities were 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.

It is within the context of these six activities that the key research contributions have been made and integration activities undertaken within the project.

This workpackage has resulted in the following outputs and activities:

- Over 67 (23 in year 3) joint and 109 (23 in year 3) individual publications acknowledging the support of BONE
- 18 Mobility actions
- Contributions at major international conferences including significant presences at OFC, ECOC, ICTON and ONDM.
- Encouraged collaborations which have led to new projects

1. 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 that we 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 2 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 results for year three of the project. Section 4 presents a summary of the structure of the VCE and the activities over the lifetime of the project. Section 5 presents details of some of the joint activities that have been undertaken in the third year of the project based on areas of critical mass within the workpackage. In the appendices the inventory of expertise of the partners are presented.

2. Integration Strategy and Acheivements

2.1. Introduction

Much integration had already been achieved in the previous e-Photon/One and e-Photon/One+ projects. This workpackage has used the experience gained in these forums as a guide to the potential areas of integration in this activity. A number of integration activities in the first year and second year of the BONE project have already been reported in FP7-ICT-216863/UCL/R/PU/D13.1 and FP7-ICT-216863/UCL/R/PU/D13.2.

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 complementarity 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

At the start of the project a number of areas and mechanisms for integration were proposed. This section discusses these mechanism and describes activities undertaken within the project.

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, and updated throughout the project, 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. 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 some of the key joint research activities conducted and the research topics to be integrated within these activities are outlined in section 5.

New research proposals

One of the key aims of the WP and a clear output to the Amalgamating research agendas is the involvement of WP partners in new research proposals and new projects. Within recent Framework 7 calls, a number of proposals and new projects have been generated by WP13 partners, in many cases extending work supported by the BONE network.

FIVER including Valencia Nanophotonics Technology Center (VPVLC), University of Essex (UoEssex), Instituto de telecomunicações (IT).

FIVER Project "Fully-Converged Quintuple-Play Integrated Optical-Wireless Access Architectures" develops and demonstrates quintuple-play capabilities (IP data, HDTV, phone, home security and control, and wireless services) in an integrated optical and radio network including integrated and simultaneous centralised transmission impairment compensation of the optical path and of the radio path. FIVER objective is to develop an integrated and streamlined network architecture that enables a centralised network management strategy.

OASE including, IBBT, UoEssex, KTH

The OASE Integrated Project is examinating Fibre-to-the-Home (FTTH) within a multi-disciplinary study to provide a self-consistent and coherent set of technological solutions. The project federates partners from all over Europe and is composed of major operators, industrial leaders in FTTH technologies, and European universities.

The aim of the OASE (Optical Access Seamless Evolution) project is the assessment and development of next-generation optical access (NG-OA) network architectures for the "2020" time horizon focused on European requirements. In contrast to other approaches, OASE will not only address architecture-evolution from a technological point of view, but integrates the financial imperative of total cost of ownership (TCO) minimization with the potential for supporting new business models, e.g. co-operative joint-ventures amongst different stake holders within the telecommunications industry, as well as the crucially important aspects of government policy and regulation. The combination of these multiple dimensions - technology, costs, regulation and business models – requires developing NG-OA network architectures with the highest potential of enabling:

- >1 Gbit/s per customer
- > 1000 customers per fiber feed
- > 100 km transmission distance

at economically competitive prices within a well-regulated and open market environment. OASE will achieve the following objectives:

- A thorough study of current and future (through to 2020) requirements for NG-OA networks from economic, business, operational and regulatory Europe-centric perspectives
- Identification of possible network architectures, energy-efficiency metrics and models by which their suitability may be analyzed, as well as the most appropriate migration strategies

- Enumeration of the network technologies that may be employed, as well as identifying cost factors (such as CapEx, OpEx, TCO etc.) and technical factors (such as the number of possible subscribers) which may indicate their suitability in a given environment
- Examine the interactions between businesses in an "open network" marketplace by studying how increased convergence may offer new value chains and business opportunities
- Validate the findings of the comparative merits of the identified network architectures and technologies in a controlled environment through experimental testing

ACCORDANCE including Research and Education Laboratory in Information Technologies (AIT), Universitat Politècnica de Catalunya (UPC) and University of Hertfordshire (Associate Partner).

A Converged Copper-Optical-Radio OFDMA-based access Network with high Capacity and Flexibility: The ACCORDANCE STREP project composed by partners from Estonia, France, Germany, Greece, Spain and United Kingdom, investigates on a new paradigm for the access network: The introduction of OFDMA (Orthogonal Frequency Division Multiple Access) into a Passive Optical Network (PON) architecture offering at the same time optical backhauling for wireless and copper-based networks.

ACCORDANCE introduces a novel high-capacity extended-reach optical access network architecture, based on OFDMA technology, implemented through the proper mix of state-of-the-art photonics and electronics. Such an architecture is not only intended to offer improved performance compared to evolving TDMA-PON (Time Division Multiple Access - Passive Optical Networks) solutions, but also inherently provides the opportunity for convergence between optical- radio- and copper-based access.

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 are given in section 3.2. These mobilities range from long term exchange of junior researchers to short term interaction of senior staff, for example visits to discuss research collaboration or to give seminars or workshops.

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

A number of workshops and joint events have been organised over the course of the project. These are listed in section 2.3

2.3. Integration Activities:

- **BONE Workshops,**
  - Joint technical workshop with WP16 at ECOC 2010
  - **JA2 Technical Workshops**, held with the BONE summer school in Budapest, and at Kista 24-26/02/10
  - 2nd SARDANA-BONE Workshop on Broadband Access at 12th International Conference on Transparent Optical Networks, Munich, June 27 - July 1, 2010
  - **JA 2 workshop in Kraków** with Miroslaw Kantor (AGH), Attila Mitcsenkov (BME) Lena Wosinska (KTH) and Bart Lannoo (IBBT), 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. The workshop was co-organised by the following European projects: ALPHA, BONE, euroFOS, FUTON, GIBON, HECTO, IPHOBAC, ISIS, OMEGA, and UROOF.
  - **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
  - **Special BONE and SARDANA session on Optical Access at the IEEE CONTEL Conference** (8-10 June 2009) held in Zagreb, Croatia.
  - **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

- **Annual WP Conference Calls**

- **Conference Activities**
  - **Four papers presented BONE WP13 results at ICTON 2010 in Munich (including 3 invited)**
  - **BONE WP13 Poster** at ECOC 2010
  - **Networking Session at the ICT2008** on "Next Generation Access Networks" attracted around 35 participants with presentations and a discussion on the future directions for optical access research.

- **Workpackage specific invited presentations**
  - **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

- **Journal Special Issues**
  - **IET Optoelectronics Journal** – The December 2010 issue of the IET Optoelectronic Journal (www.ietdl.org/IET-OPT) was a BONE special issue on ***Next Generation Optical Access*** specifically linked to the BONE Virtual Centre of Excellence on Access.

- **Book Chapters**
  - Chapter on "Free Space Optical Technologies" representing a joint work done between BONE and COST ICO802 in an e-book published by Intech.

2.4. Advisory Board

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

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

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 and ICTON 2010 and planned for ICTON 2011.

2.6. Summary of Research Activities in Year 3

Hybrid Optical Wireless Networks: Frederic Lucarz

Over the last decade, a plethora of new technologies have been proposed and discussed to solve the last-mile bottleneck issue in telecommunication access networks. Thanks to low-cost high-bandwidth and easily deployable connections**, free-space optics (FSO)** solutions now represent a good candidate for short-reach (i.e. hundreds of meters) connections as an **alternative** to fibre-based and/or existing RF network user interfaces. By carefully taking into account atmospheric conditions and controlling light beam misalignments, FSO could be suitable to temporary high data communications in motion network scenarios. Joint activities have been carried out in year 3 to set up an all optical wireless demonstrator to provide a wireless extension to an existing standard Ethernet PON that will serve as a basis for further collaboration to assess this alternative solution.

Managing Quality of Service (QoS) in fibre-supported wireless access networks remains a prime issue that has been addressed this year within BONE NoE more specifically for WiMAX coverage with a solution based on MPLS and WiMAX class of Services.

The rapid growth of the smartphones' market is at the origin of a strong increase in the traffic within radio-mobile access systems. Existing Radio Access Network (RAN) architectures are not economically suited to such an evolution. It is today widely admitted that the design of a new generation of RAN (NGRAN) is necessary. Telecom ParisTech (TPT) has pursued its investigations in this matter in proposing an innovative hybrid network infrastructure called GeRoFAN (Generic Radio-over-Fiber Access Network). The GeRoFAN architecture aims to backhaul 4G radio access systems based either on the WiMAX or the LTE technologies. During our preliminary studies, we have proposed an original network architecture based on two key elements: Hybrid Optical Line Termination (HOLT) and Hybrid Optical Network Units (HONU). Each of these two equipments is able to deal with upstream and downstream wireless traffic in adopting Radio over Fiber modulation techniques. Since downstream traffic can easily be broadcasted from the HOLT to the base-stations via the HONUs, we have dedicated the major part of our efforts in order facilitate dynamic radio frequency allocation for upstream traffic.

The first experimental demonstration of AWG cognition using SMF-tailed C-band VCSELs based on commercially available components was demonstrated. The proposed method can be readily extended to hybrid networks to assess radio channel performance which can be advantageously for last-mile service provision.

Techno-economic analysis of access networks – Miroslaw Kantor

In order to handle the emerging demands for broadband services, adequate telecommunication access network designs are crucial for network operators, service providers and equipment vendors. As a number of technical candidates and design options for constructing access networks exist, it is necessary to perform calculations to identify cost-efficient combinations of technologies, functionalities and network structures. For this reason, a large variety of access network architectures have to be checked in order to determine the most appropriate ones for different area types and service demand profiles. An accurate construction of a techno-economic model allows to minimize errors in the network development phase and to calculate intermediate results, allowing an evolutionary development of the network solution.

Such a methodology for performing a complete techno-economic evaluation has been developed within our JA. Based on the proposed approach different alternatives can be compared and tradeoffs of costs vs. performance can be made. Moreover, a proper network design also reflects suitability of a certain network infrastructure to the considered scenario, and therefore it supports the optimal choice among the competing technologies. The methodology starts from determining the scope of the problem and detailing the inputs for the study based on a market analysis. The most important outcomes are indicated by the building blocks services and architectures. They contain all input information necessary for building the techno-economic model in the second step. The proposed model makes a distinction between economic calculations, in which costs and revenues are estimated; and the technical calculations, in which the performance metrics of the proposed network solution are estimates. The final evaluation of the analyzed access network architecture is based on the outcomes – economic and technical – of the calculations step. This step is split between investment analysis and performance analysis.

Fibre to the home (FTTH) has been widely recognized as a future proof solution for access networks due to its capability to meet the increasing bandwidth demand of the end users. On the other hand, the deployment of FTTH networks is very costly and an accurate estimation of the investment cost is crucial for operators. Several models have been developed to estimate the deployment cost of FTTH network, e.g. a number of geometric models. However, these models suffer from the inaccuracy problem in particular when applied to the area with uneven population of users since they consider only the average values. Because the residential areas are typically not very event populated and the fibre trenching is constrained by various local conditions, e.g. parks, railways or highways, the accuracy of the geometrical models is questionable.

To address this problem, a geographic approach to design the FTTH outside plant infrastructure has been proposed. This approach is based on the real and detailed geospatial data in order to accurately estimate the deployment cost. If a realistic network deployment cost estimation for a given network architecture and technology is in focus, the geographic model has an obvious advantage since the absolute cost value can be calculated by summing up cost of components included in the obtained network topology design. In order to handle the uncertainties and uneven character of the parameters describing the considered service area, the network deployment cost calculation is based on geographic information including digital map of the service area, infrastructural data, location and demand of the subscribers.

Secure OCDMA based PONs - Gabriella Cincotti

Although Wavelength-Division Multiplexing (WDM)-PON is considered by most carriers and service providers as the natural evolution of existing current Fiber To The Home (FTTH) systems, in this JA we have demonstrated that OCDMA is a valid alternative for next generation access networks (NGAN) that can outperform WDM-based systems with respect to data confidentiality, bandwidth efficiency, also simplifying the migration from existing PONs. We have made an accurate comparison between these two technologies, evidencing their capabilities but also their limits, as well as the difficulties of their integration with current FTTH systems.

An inline-dispersion-compensation-free long-reach OCDMA-based PON have been experimentally demonstrated: 10Gb/s, 4-user, OCDMA error-free transmission over 59 km fiber link has been successfully achieved. Two multiport encoder/decoders (E/D)s are used at the Optical Line Terminal (OLT) and at the Remote Node (RN) to generate/process four different 16-chip (200 Gchip/s), 16-level-phase-shifted Optical Codes (OC).

The confidentiality of OCDMA transmission based on block ciphering is much larger with respect to standard bit ciphering schemes, presenting two layers of confidentiality: physical security, because an adversary should be able to correctly detect the OC, and computational security, since he or she does not know which sequence of bits corresponds to a given OC. We have demonstrated a secure 2.5 Gbit/s, 50 km-fiber transmission based on 16-ary OCDMA with on-line XOR and true clock data recovery.

Furthermore, Orthogonal Frequency Division Multiplexing (OFDM) schemes can be used to enhance the performances of commercial PON systems. In particular, optical OFDM based on Fast Hartley Transform (FHT) and direct detection (DD) can reduce the cost and the complexity of the OFDM transceivers; due to its simple and efficient scheme in terms of computational complexity and power consumption, the FHT-based optical OFDM architecture can be easily adopted in commercial GPON systems.

A code-label recognition processor with recognition time of less than 500 ps has been developed. The code label is generated and processed using low-cost FIR filters. Since the recognition time is basically the transit time of the code label through the matched filter, we found that equivalent results to the previously reported code label processing can be obtained but using high speed FIR filters. These transversal filters have been used to demonstrate ECDMA processing for PON applications. In this case, since each electronic filter tap has a separation Δt of 55 ps, and we use Hadamard codes with Nc =8 chips length, the total label recognition time is about 440 ps. This fast label recognition time, offering comparable recognition times to photonic approaches, is implemented using low cost, low power consumption and flexible FIR filters.

Millimeter-wave radio over fiber – Mike Parker

Various novel aspects to mm-wave RoF technologies have been examined in this JA of WP13 over year 3 of the BONE project. One innovative aspect has been performed by UCL, where they have investigated improved sideband suppression using an optical single sideband (OSSB) modulation with non-linear harmonic upconversion. In the reported work, experiments using an OSSB generator were able to achieve >50 dB sideband suppression of a WiMax (narrowband OFDM) transmission signal.

UPVLC has been investigating the management of RoF signals, with particular regard to the linearization for highly-linear applications, especially suited for RoF transmission of wireless signals in coexistence contexts. In addition, UPVLC has also continued to research the polarization-multiplexed distribution of ultra wide-band (UWB) signals in RoF transmissions and photonic analog-to-digital conversion architectures for wideband spectrum monitoring. As part of an experimental demonstration, a photonic generation system of impulse radio UWB signals targeting high user density for in-flight communications with simultaneous ranging capabilities in the 60-GHz radio band has also been investigated.

In an important aspect to RoF research, which is the understanding of the performance of within-building multi-mode fibre (MMF) infrastructure, UC3M has tested different MMFs to test the possibility of deployment of RoF based on legacy MMF links. In this regard, the temperature influence on the behaviour characteristics was investigated in a joint action with UC3M, FPM, UDE, and UPVLC. In particular, the radio frequency (RF) transfer function of a MMF link based on the electric field propagation method has been analyzed, in order to evaluate the conditions upon which broadband transmission is possible in RF regions far from baseband. Special attention to source parameter influence has also been analysed and experimentally tested. Novel monitoring techniques for access networks have also been analysed.

Future access networks will integrate diverse services and provide a versatile platform for broadband access to hundreds of fixed, mobile and nomadic users, with optical fibre clearly being the transmission medium of choice since it can support such an integrated network due to its immense bandwidth and low loss. To realize such a network, many challenges also need to be considered at the different network layers. During this JA, AIT has also been focusing on the physical layer showing how divergence in the sensitivity of the receivers of different signal types can affect the performance of an integrated transmission system and thus the network design. The example of a ring/bus network that integrates mm-wave and baseband services has been investigated, showing that the selection of the multiplexing and demultiplexing techniques, as well as the power budget of the network depend on the value of the baseband and mm-wave receiver sensitivities. For such access applications, the selection of the system hardware and related technologies is strongly dependent on the trade-off between cost and complexity.

Quality of Service in PONs – Francesco Matera

After the investigation of the previous years to manage the QoS in PON, in Year 3 the main activities were focused on QoS tests to certify the effective quality of the broadband available with PONs. This activity follows the Italian strategies on the QoS certification that Italian Agency for Telecommunications (AGCOM, www.agcom.it) is carrying out for QoS measurements of wireline broadband accesses according to document DEL 244 2008. In particular for such a task FUB implemented an Italian network to carry out user measurements and the details of such measurements will be shown at the ONDM 2011 conference (P. Bolletta et al, Monitoring of the User Quality of Service: Network Architecture for Measurements, role of the User Operating System with consequences for optical accesses). Starting from the experience for such a task, in this year FUB made QoS measurements in PON networks and in particular they have shown the limitations in the bandwidth exploitation for GPON users due to the computer operating systems.

They considered a specific QoS evaluation technique, based on the ETSI EG 202 057, using File Transfer Protocol (FTP) probes. In such assumption, the Transmission Control Protocol (TCP) plays a key role in evaluating performance, since it directly regulates the flow of data. The choice of a TCP dependent technique tries to keep QoS evaluation as closer as possible to the end-user effective experience of broadband access services.

The results reported in this contribution show the dependence of the QoS on the operating systems and in particular the differences due to the operating systems increase with user bit rates.

Therefore, it means that users could be strongly limited in the exploitation of the bandwidth, and such limitation is much relevant in case of optical access networks that should permit very wide bandwidth. As a consequence, we believe that a testing scenario for

FTTx accesses needs to be described not only according to the physical parameters, but also paying attention to software implementation factors that could affect the testing results.

Another activity regarded the management of the QoS for wireless systems connected to PON. This is an important aspect since ONUs will be used to feed Base Station for broadband wireless service as in the case of WIMAX and LTE systems. In particular with this activity it was shown how to use the same QoS procedures that are implemented in wireline architectures, for instance with labeling at MPLS level, in WIMAX and LTE accesses. The demonstration is based on OPNET simulations.

Finally, some experimental investigation on WDM-PON networks were carried out.

Techniques for colour-less optical network units – John Mitchell

Within this joint activity a number of further developments have been made to enable the implementation of colourless ONUs at the user site.

The use of reflective technologies are attractive as they allow the wavelength of operation to be defined at the central office. However, a number of issues arise when such technologies are used. For example, as single fibre working is common in PON networks Rayleigh backscattering becomes a serous concern as the same wavelength must propagate in both directions in such a network. Work conducted recently has demonstrated a novel method that shifts the incoming wavelength at the ONU in order to avoid the overlap of the spectrums while maintaining the new wavelength inside the same array waveguide grating (AWG) channel. A method is investigated that uses serrodyne frequency shifting of optical signals to shift the optical spectra and reduce the impact of the backscattering.

A demonstration is give of a reflective PON system with phase adjustment at OLT and an RSOA of 1.2 GHz of BW and high chirp been used to transmit a bit rate of 10.3Gb/s with a power budget of 23dB and at 5Gb/s with a power budget of 30dB. Conclusions

An experimental, proof-of-concept, of an all-optical wavelength conversion system for integrating multiple CWDM PONs into a long-reach DWDM backhaul at 10Gbit/s has been demonstrated. The BER performance over 20km, 40km and 60km backhaul distances were compared, and an error free total transmission distance of 80km was achieved.

Recent work in “Athermal Colourless C-band Optical Transmitter for Passive Optical Networks” a new control algorithm with reduced mode-hopping for uncooled WDM C band channel generation from a DS-DBR laser with 100GHz spacing and low thermal drift up to 70°C. A 10Gb/s external modulation with transmission over a 25km link was achieved. A summary of this work was presented in the European Semiconductor Laser Workshop 2010 in Pavia, Italy.

3. Summary of VCE Activities

3.1. Membership of the VCE

Coordinator: John Mitchell, UCL.

Joint activity leaders:

Hybrid Optical Wireless Networks: Frederic Lucarz (GET)
Techno-economic analysis of access networks: Miroslaw Kantor (AGH)
Secure OCDMA based PONs: Gabriella Cincotti (Uniroma3)
Millimeter-wave radio over fiber: Mike Parker (UoEssex)
Quality of Service in PONs: Francesco Matera (FUB)
Techniques for colour-less optical network units: 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

Mobilities actions within the third year are highlighted (in bold).

Security in OCDMA based networks
Valentina Sacchieri, PhD student at UniRoma3, hosted by IT from 21/01/2008 to 31/07/2008

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

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

Mitigation of Group Velocity Dispersion in Optical CDMA using Electronics
Miguel Pimenta, PhD Researcher at UCL, hosted by IT from 18/10/2008 to 17/11/2008

Optical CDMA
Izzat Darwazeh, Professor at UCL, hosted by IT from 22/10/2008 to 25/10/2008

Photonic-ADC experimental demonstrator
Tiago Alves, Ph.D Student at IT, hosted by UPVLC from 14/12/2008 to 19/12/2008

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

RoF Information Exchange
John Mitchell, Senior Lecturer at UCL, hosted by GET from 18/09/2009 to 18/09/2009

Preparation of framework for techno-economic analysis of PON architectures
Miroslaw Kantor, Research Assistant at AGH, hosted by KTH from 23/02/2010 to 26/02/2010

Investigation of novel wavelength shifting techniques for next generation networks
Mireia Omella, Phd student at UPC, hosted by FT from 08/03/2010 to 05/06/2010

Techno-economic framework with geometric and geographic models
Miroslaw Kantor, Research Assistant at AGH, hosted by BME from 12/05/2010 to 14/05/2010

Techno-economic analysis of fiber access networks
Lena Wosinska, Professor at KTH, hosted by BME from 12/05/2010 to 13/05/2010

Techno-economic analysis of fiber access networks
JiaJia Chen, Postdoc at KTH, hosted by BME from 12/05/2010 to 13/05/2010

Novel approaches for monitoring drop fibres in TDM-PON and WDM-PON systems
Kivilcim Yuksel, Research Assistant at FPMs, hosted by UC3M from 26/07/2010 to 31/07/2010

OFDM for future access networks
Kivilcim Yuksel, Research Assistant at FPMs, hosted by FT from 15/11/2010 to 19/11/2010

3.3. Joint Papers

Year 3 - List by publication date (25)

1) K. Ennser (USWAN), S. Mangeni (USWAN), S. Taccheo (USWAN), S. Aleksic (TUW), *Techno-economic feasibility studies for Solar powered Passive Optical Network*, SPIE2011/PhotonicWest : Broadband Access Communication Technologies V conference, San Francisco, California United States., January 2011. (with WP14 WP21)
2) A. Mitcsenkov (BME), M. Kantor (AGH), K. Casier (IBBT), B. Lannoo (IBBT), K. Wajda (AGH), J. Chen (KTH), L. Wosinska (KTH), Geographic Model for Cost Estimation of FTTH Deployment: Overcoming Inaccuracy in Uneven-populated Areas, IEEE/OSA/SPIE Asia Communications and Photonics (ACP) Conference and Exhibition, Shanghai, China, December 2010
3) M. Svaluto Moreolo (CTTC), V. Sacchieri (UniRoma3), G. Cincotti (UniRoma3), G. Junyent (CTTC), *Trigonometric transforms for high-speed optical networks: all-optical architectures and optical OFDM*, Journal of Networks, Vol. 5, No. 11, pp. 1248-1253, November 2010. (with WP15)
4) T. Kodama (Osaka University), N. Kataoka (NICT), N. Wada (NICT), G. Cincott (UniRoma3), X. Wang (Osaka University), T. Miyazaki (NICT), K. Kitayama (Heriot-Watt University), *High-security 2.5 Gbps, polarization multiplexed 256-ary OCDM using a single multi-port encoder/decoder*, Optics Express, Vol. 18, No. 10, pp. 21376-21385 , October 2010. (with WP14)
5) M. Omella (UPC), P. Chanclou (FT), J. Lazaro (UPC), J. Prat (UPC), *RSOA as a Sawtooth Generator for Rayleigh Backscattering Effect Mitigation*, Proceedings of ECOC 2010, Torino, September 2010. (with WP15)
6) M. Thakur (UCL), J. Mitchell (UCL), T. Quinlan (UEssex), M. Parker (UEssex), S. Walker (UEssex), *First Demonstration of Secure, AWG Performance Interrogation using OFDM Edge-tones on WDM Access Networks*, ECOC 2010, September 2010.
7) Sotiria Chatzi, Jose A. Lazaro, Josep Prat and Ioannis Tomkos, "AQuantitative TechnoeconomicComparison of Current and Next Generation Metro/Access Converged Optical Networks", ECOC 2010, We.8.B.2
8) M. Milosavljevic (HERTS), M. Thakur (UCL), P. Kourtessis (HERTS), J. Mitchell (UCL), J. Senior (HERTS), *A Multi-Wavelength Access Network featuring WiMAX Transmission over GPON Links*, ECOC 2010, September 2010.
9) N. Stol (Norwegian University), C. Raffaelli (UNIBO), M. Savi (UNIBO), G. Cincotti (UniRoma3), *Optical codes for packet detection in the OpMiGua switch architecture*, Photonics in Switching (PS), Monterey, California, July 2010. (with WP14)
10) N. Kataoka (NICT), G. Cincotti (UniRoma3), N. Wada (NICT), K. Kitayama (Osaka University), *100km transmission of dispersion-compensation-free, extended-Reach OCDMA-PON system with passive remote node*, 15th OptoElectronics and Communication Conference (OECC) , Sapporo, Japan, July 2010. (with WP14)

11) G. Cincotti (UniRoma3), N. Kataoka (NICT), N. Wada (NICT), K. Kiatayama (Osaka University), *Next generation access networks: CDMA- vs WDMA-based PONs*, International Conference on Optical Transparent Networks (ICTON), Munich, Germany, June 2010. (with WP14)

12) G. Cincotti (UniRoma3), N. Kataoka (NICT), N. Wada (NICT), K. Kitayama (Osaka University), *Future passive optical networks: can CDM beat WDM?*, Future Network & MobileSummit 2010, Florence, Italy, June 2010.

13) M. Omella (UPC), P. Chanclou (FT), J. Lazaro (UPC), J. Prat (UPC), *10-GPON Using High Gain RSOA as ONU Transmitter and Optical Phase Adjustment at the OLT*, Proceedings of OSA ANIC Topical Meeting, Karlsruhe, June 2010. (with WP15)

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

15) M. Giuntini (FUB), J. Morabito (FUB), A. Valenti (FUB), F. Matera (FUB), V. Carrozzo (ISCOM), S. Di Bartolo (ISCOM), *Integration Of Optical Telecommunications and Radio Access Networks to Assure Quality of Service*, IEEE ICTON 2010 Conference, June 2010.

16) M. Kantor (AGH), K. Wajda (AGH), B. Lannoo (IBBT), K. Casier (IBBT), S. Verbrugge (IBBT), M. Pickavet (IBBT), L. Wosinska (KTH), J. Chen (KTH), A. Mitcsenkov (BME), *General framework for techno-economic analysis of next generation access networks*, IEEE International Conference on transparent Optical Networks ICTON, Munich, June 2010.

17) N. Kataoka (NICT), N. Wada (NICT), X. Wang (Heriot-Watt), G. Cincotti (UniRoma3), K. Kitayama (Osaka University), *Flexible, long-reach, OCDMA-PON system with passive remote node using single multi-port encoder/decoder without dispersion compensation*, Conference on Lasers and Electro-Optics and The Quantum Electronics and Laser Science Conference (CLEO/QELS, San Jose, California, May 2010. (with WP14)

18) V. Sacchieri (UniRoma3), F. Venturini (UniRoma3), M. Svaluto Moreolo (CTTC), G. Cincotti (UniRoma3), *Applicazione della trasformata Hartley in un sistema di trasmissione OFDM ottico*, Convegno Nazionale sulle Tecniche Fotoniche nelle Telecomunicazioni (FOTONICA), Pisa, Italy, May 2010. (with WP14)

19) M. Svaluto Moreolo (CTTC), G. Cincotti (UniRoma3), *Fiber Hartley transform and optical indirect computation of discrete cosine transform*, IEEE Transactions on Communications, Vol. 58, No. 5, pp. 1338 - 1343 , May 2010. (with WP15)

20) N. Kataoka (NICT), N. Wada (NICT), X. Wang (Heriot-Watt), G. Cincotti (UniRoma3), K. Kitayama (Osaka University), *Demonstration of 10Gbps, 4-user, OCDMA transmission over 59km single mode fiber without inline dispersion compensation*, Optical Fiber Communication Conference (OFC), San Diego, California, March 2010. (with WP14)

21) B. Charbonnier (FT), F. Lecoche (FT), M. Weiss (UDE), A. Stöhr (UDE), F. van Dijk (FT), A. Enard (FT), F. Blache (FT), M. Goix (FT), F. Mallecot (FT), D. G. Moodie (UCL), A. Borghesani (), C. W. Ford (), *Ultra-wideband radio-over-fiber techniques and networks*, Optical Fiber Communication Conference, OFC 2010, San Diego, USA, March 2010. (with WP16 WP23 WP25)

22) N. Kataoka (NICT), N. Wada (NICT), X. Wang (Heriot-Watt), G. Cincotti (UniRoma3), K. Kitayama (Osaka University), *10Gbps-Class, Bandwidth-Symmetric, OCDM-PON System* *using hybrid multi-port and SSFBG en/decoder*, Conference on Optical Network Design and Modelling (ONDM) , Kyoto, Japan, January 2010. (with WP14)

23) T. Kodama (Osaka University), N. Nakagawa (Osaka University), N. Kataoka (NICT), N. Wada (NICT), G. Cincotti (UniRoma3), X. Wang (Heriot-Watt), T. Miyazaki (NICT), K. Kitayama (Osaka University), *Secure 2.5Gbit/s, 16-ary OCDM block-ciphering with XOR using a single multi-port en/decoder*, IEEE/OSA Journal of Lightwave Technology, Vol. 28, No. 1, pp. 181-187, January 2010. (with WP14)

24) Sim Heung Lee, Adrian Wonfor, Richard Penty, Ian White, Giacinto Busico, Rosie Cush, Michael J. Wale, "Athermal Colourless C-band Optical Transmitter for Passive Optical Networks", European Conference on Optical Communication , ECOC, 2010, Torino, paper Mo.1.B.2.

25) A. Wonfor, S. H. Lee, R. V. Penty, I. H. White, G. Busico, R. Cush, M. Wale "Uncooled tuneable lasers for passive optical network applications", European Semiconductor Laser Workshop 2010, Pavia, Italy

Year 2 - List by publication date (24)

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.

24) E. Zouganeli (TELENOR), K. Bugge (TELENOR), S. Andres (TID), J. Fernandez (TID), A. Elizondo (TID), *Drivers for Broadband in Europe*, Broadband Access Networks, Springer, June 2009

Year 1 - List by publication date (23)

1) B. Huiszoon (TUE), J. A. Hernández (UAM), H. de Waardt (TUE), G. Khoe (TUE), J. Aracil (UAM), T. Koonen (TUE), *Performance Evaluation of an Optical Transparent Access Tier Based on PON and Spectral Codes*, Journal on Selected Areas in Communications, Vol. 27, No. 2, pp. 143-155, February 2009. (with WP16 WP24)

2) C. Arellano (VPI Systems), K. Langer (Fraunhofer), J. Prat (UPC), *Reflections and multiple Rayleigh backscattering in WDM single-fiber loopback access networks*, IEEE Journal of Lightwave Technology, Vol. 27, No. 1, pp. 12-18, January 2009. (with WP16)

3) J. A. Lázaro (UPC), F. Bonada (UPC), V. Polo (UPC), A. Teixeira (IT), J. Prat (UPC), *Extended Black Box Model for Fiber Length Variation of Erbium-Doped Fiber Amplifiers*, IEEE Photonics Technology Letters, Vol. 20, No. 24, pp. 2063-2065, December 2008. (with WP15)

4) M. Huchard (FT), P. Chanclou (FT), B. Charbonnier (FT), F. van Dijk (FT), M. Weiß (UDE), A. Stöhr (UDE), *60 GHz Radio Signal Up-conversion and Transport Using a Directly Modulated Mode-Locked laser*, International Topical Meeting on Microwave Photonics (post deadline paper), pp. 333-335, Gold Coast,Australia , October 2008. (with WP16 WP23)

5) I. Papagiannakis (University of Patras), M. Omella (UPC), D. Klonidis (AIT), J. Kikidis (Analog Integrated Electronic Systems S.A), A. N. Birbas (University of Patras), I. Tomkos (AIT), J. Prat (UPC), *Upstream Transmission in WDM PONs at 10Gbps Using Low Bandwidth RSOAs Assisted with Optical Filtering and Electronic Equalization*, ECOC 2008, Brussels, Belgium, September 2008. (with WP15)

6) R. Llorente (UPVLC), M. Thakur (UEssex), M. Morant (UPVLC), S. Walker (UEssex), J. Marti (UPVLC), *Performance comparison of radio-over-fibre UWB distribution in SSMF and MMF optical media*, ECOC 2008, Vol. 34, pp. Tu3E2, Brussels, September 2008

7) J. Chen (KTH), L. Wosinska (KTH), M. Kantor (AGH), L. Thylén (KTH), *Comparison of Hybrid Passive Optical Networks with Protection*, ECOC2008, Brussels, September 2008.

8) M. Weiß (UDE), A. Stöhr (UDE), M. Huchard (FT), S. Fedderwitz (UDE), B. Charbonnier (FT), V. Rymanov (UDE), S. Babiel (UDE), D. Jäger (UDE), *60GHz Radio-over-Fibre Wireless System for Bridging 10Gb/s Ethernet Links*, European Conference and Exhibition on Optical Communication, Brussels, Belgium, September 2008. (with WP16 WP23)

9) B. Charbonnier (FT), P. Chanclou (FT), D. Jäger (UCL), J. Marti (UPVLC), V. Polo (UPVLC), R. Sambaraju (UPVLC), A. Stöhr (UDE), M. weiß (UDE), *Photonics for broadband radio communications at 60 GHz in access and home networks*, Int. Topical Meeting on Microwave Photonics, pp. 5-8, GoldCoast, Australia, September 2008. (with WP16 WP23)

10) M. Weiß (UDE), M. Huchard (FT), A. Stöhr (UDE), B. Charbonnier (FT), S. Fedderwitz (UDE), D. Jäger (UDE), *60GHz Photonic Millimeter-Wave Link for Short to Medium-Range Wireless Transmission up to 12.5Gb/s*, Special Issue of the IEEE Trans. Microw. Theory Tech. and J. Lightw. Techn (invited), Vol. 26, No. 15, pp. 2424-2429, August 2008. (with WP16 WP23)

11) A. Stöhr (UDE), D. Moodie (UCL), D. Jäger (UDE), A. Seeds (UCL), M. Weiß (UDE), V. Rymanov (UDE), S. Fedderwitz (UDE), *Optical Millimeter-Wave Generation using 1.55µm Photodiodes with and without Integrated Antennas*, 2008 URSI General Assembly, Chicago, Illinois, USA, August 2008. (with WP16 WP23)

12) M. Huchard (FT), M. Weiß (UDE), A. Pizzinat (FT), S. Meyer (FT), P. Guignard (FT), B. Charbonnier (FT), *Ultra Broad Band Wireless Home Network based on 60GHz WPANs cells interconnected via RoF*, Special Issue of the IEEE Trans. Microw. Theory Tech. and J. Lightw(Invited), pp. 2364-2372, August 2008. (with WP16 WP23)

13) E. Duca (UniRoma1), S. Di bartolo (ISCOM), D. Forin (ISCOM), S. Betti (UniRoma1), A. Teixeira (IT), *Modulation Effect Induced by Continuous Wavesin Semiconductor Optical Amplifiers*, ICTON 08, Vol. 1, No. 1, pp. 278-281, ATHENS, July 2008. (with WP15)

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18) F. Matera (FUB), L. Rea (FUB), S. Pompei (FUB), A. Valenti (FUB), C. Zema (CORITEL), M. Settembre (CORITEL), *"qualità of Service Control based on Virtual Private Network Services in a Wide Area Gigabit Ethernet Optical Test Bed"*, Fiber and Integrated Optics, Vol. 27, No. 4, pp. 301-306, Amsterdam, June 2008. (with WP11)

19) F. Matera (FUB), S. Pompei (FUB), A. Valenti (FUB), C. Zema (CORITEL), M. Settembre (CORITEL), *Qualità of Service Control in Access Networks Based on Virtual Private LAN Services in a Wide Area Gigabit Ethernet Optical Test Bed*, ICTON 2008, Athens June 22-26 2008, Vol. 4, No. 1, pp. 291-293, Athens, June 2008. (with WP11)

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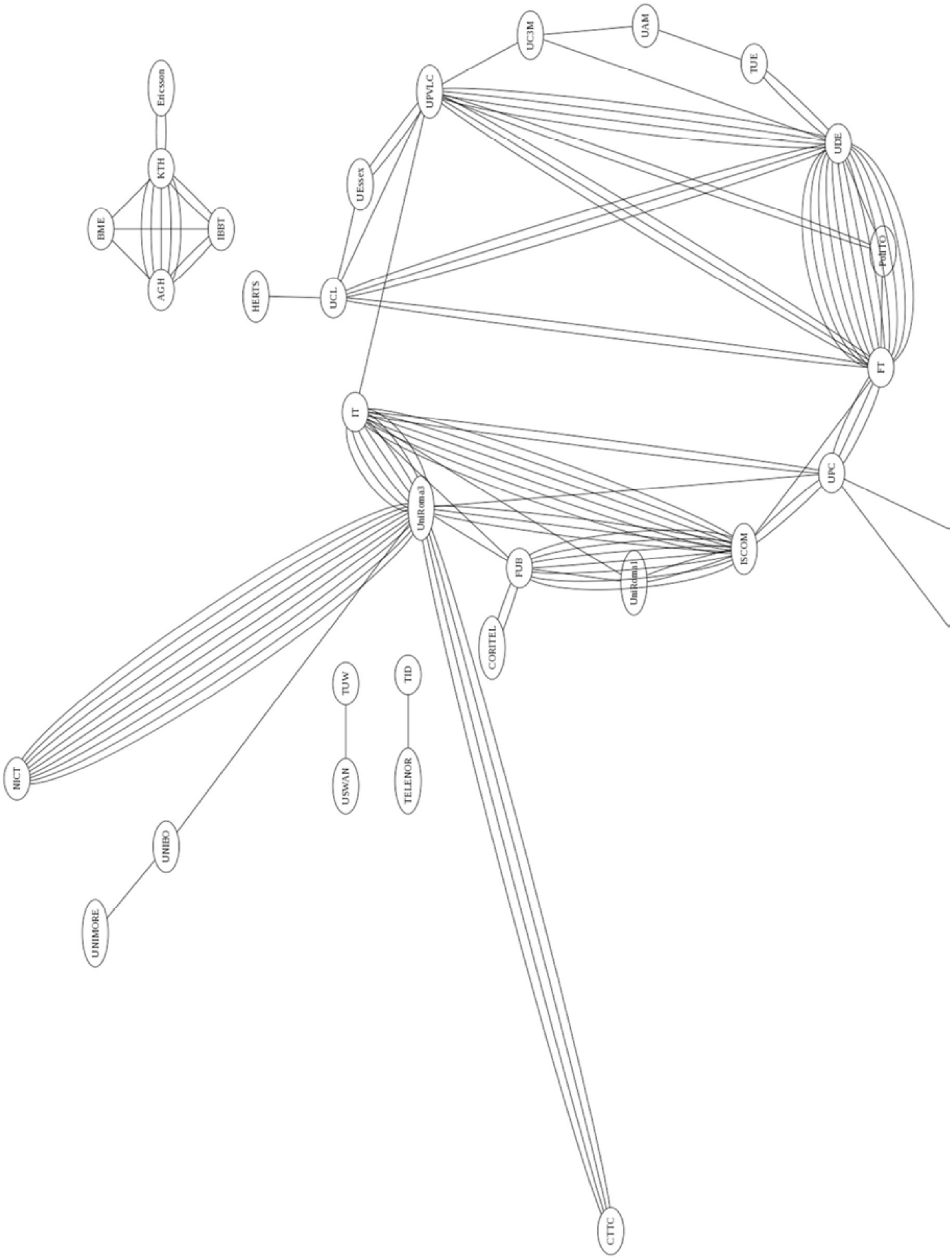
Joint Publications Map



4. Examples of Recent Research Activities

4.1. Joint Activity – Hybrid Fibre Wireless Systems

Members

UoESSEX, UPVLC, UDE, UC3M, UoA, POLITO, IT, GET

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.

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

Collaborations/Joint Experiments and Mobility Actions

Completed Mobility Actions:

- **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.

- **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 the 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 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.

- **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.

- **Milos Milosavljevic, Research Assistant at Herts, Hosted by UCL from 22/03/2010 to 5/04/2010 and 1/12/2010 to 10/12/2010**

An IEEE 802.16-2005 compliant PON architecture with wavelength band overlay is implemented experimentally to demonstrate distributed broadband wireless (DBW) access network following next generation PON requirements. The multi-wavelength overlay is achieved with the slightest modification in network hardware by the application of dense AWG in the OLT and VCSEL arrays in remote base stations. The frequency division multiplexing (FDM) approach is utilised to address individual BSs sharing a single wavelength over splitter-PON. Significantly, the overlapping radio cell/sector concept is also proposed for enhanced network resilience and dynamicity. Experimental results at remote receivers have confirmed EVM below -29 and -23 dB for 25.2 and 18.9 Mbps, downstream and upstream WiMAX channels respectively over maximum transmission distances of 40 km. In addition, $1E^{-11}$ GPON bit-error-rates (BERs) have been also readily achieved over the combined optical and wireless architecture. Finally, the modelling results for the transmission over overlapping radio sector have displayed minimum $1E^{-4}$ BERs bidirectional, over faded 330m overlapping micro-cells circumference without any error coding or relay techniques

Publications

2010

- A book chapter about "Optical Wireless" has been published on Intech Web Publisher.
- M. Omella, P. Chanclou, J. A. Lázaro , J. Prat "RSOA as a Sawtooth Generator for Rayleigh Backscattering Effect Mitigation" in proc. ECOC'10, Torino (Italy), 19-24 Sept 2010, paper Mo.1.B.5 .
- M. Omella, P. Chanclou, J. A. Lázaro , J. Prat "High Gain RSOA as 10G ONU Transmitter and Optical Phase Adjustment at the OLT" in proc. ANIC'10, Karlsruhe (Germany) 21-24 June 2010, post-deadline paper AThD2
- M. Milosavljevic (HERTS), M. Thakur (UCL), P. Kourtessis (HERTS), J. Mitchell (UCL), J. Senior (HERTS), A Multi-Wavelength Access Network featuring WiMAX Transmission over GPON Links, ECOC 2010, September 2010
- Giuntini, M.; Morabito, J.; Valenti, A.; Matera, F.; Carrozzo, V.; Di Bartolo, S.; "Integration of optical telecommunications and radio access networks to assure quality of service," *12th International Conference on Transparent Optical Networks 2010 (ICTON)*, vol., no., pp.1-4, June 27 2010-July 1 2010 doi: 10.1109/ICTON.2010.5549109.
- B. Charbonnier (FT), F. Lecoche (FT), M. Weiss (UDE), A. Stöhr (UDE), F. van Dijk (FT), A. Enard (FT), F. Blache (FT), M. Goix (FT), F. Mallecot (FT), D. G. Moodie (UCL), A. Borghesani (), C. W. Ford (), Ultra-wideband radio-over-fiber techniques and networks, Optical Fiber Communication Conference, OFC 2010, San Diego, USA, March 2010

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- 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.
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- 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.

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- R. Llorente (UPVLC), M. Thakur (UEssex), M. Morant (UPVLC), S. Walker (UEssex), J. Marti (UPVLC), *Performance comparison of radio-over-fibre UWB distribution in SSMF and MMF optical media*, ECOC 2008, Vol. 34, pp. Tu3E2, Brussels, September 2008

Research Contributions

Free-space Optics as an alternative to fibre-supported RF

The test bed based on an FSONA 1.25 GEthernet wireless system has been purchased by ISCOM and mounted on its roof as reported in Figure 1.

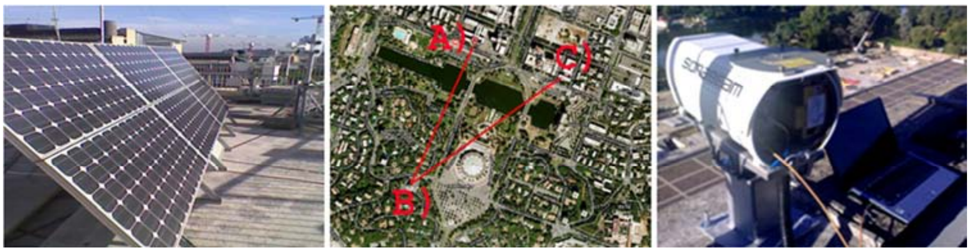

Figure 1. *Wireless Set Up: Photovoltaic Station to supply the FSO Heads [Left], Test Bed Area [Center] (A and C are ISCOM premises while B is a Tower 60m tall also called "the mushroom", The FSONA FSO system [Right]*

This test bed will be in the next months connected, from the ISCOM roof via monomode fibers, with the GePON test bed present in the Optical Communications Labs. In these labs different activities are in process like for example wavelength conversion in standard ePON systems, WDM PON testing via colourless ONUs (R-SOA based) and compatibility between ONUs from different vendor systems. The latest results on WDM PON is reported in Figure 2.

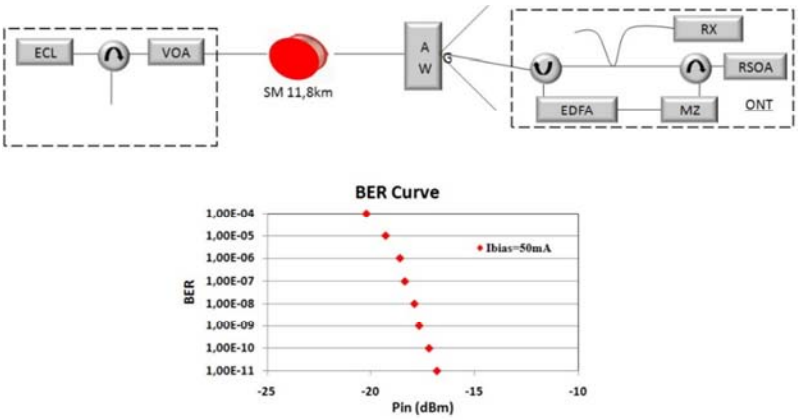

Figure 2. WDM PON BER Measurements at ISCOM labs

Coming back to the Wireless test bed, the overall set up coverage area is around 1.5 km. The propagation faces the effects of an artificial lake, a traffic line and a small vegetation park. Thus fog, humidity and extreme scintillation effects can be studied. In Figure 3 we report some test regarding the alignment process.

Name	Unit1:2:1 Current	Unit1:2:1 Accumulated
Transmitted Bit Rate (bit/s)	761,912,696bit/s	761,912,643bit/s
Transmitted Bit Rate (%)	76.19%	76.19%
Transmitted Rate (%)	100.00%	100.00%
Transmitted Byte	95,239,087	571,434,482
Transmitted Frame	1,488,111	8,928,664
Transmitted Frame (fps)	1,488,111fps	1,488,111fps
Transmitted IPv4 Packet	1,488,110	8,928,663
Transmitted IPv4 Packet (pps)	1,488,110pps	1,488,111pps
Transmitted ARP Reply	0	0
Transmitted ARP Request	0	0
Transmitted Ping Reply	0	0
Transmitted Ping Request	0	0
Transmitted Test Frame	0	0
Received Bit Rate (bit/s)	761,912,536bit/s	761,912,616bit/s
Received Bit Rate (%)	76.19%	76.19%
Received Rate (%)	100.00%	100.00%
Received Byte	95,239,067	571,434,462
Received Frame	1,488,111	8,928,664
Received Frame (fps)	1,488,111fps	1,488,111fps
MAC Control Frame	0	0

Figure 3. Preliminary Results with statistics on the traffic sent between the FSO heads

Future Work

Once everything will be deeply studied and exploited the two systems, wired and wireless, will be merged in order to obtain a standard Ethernet PON infrastructure with a wireless trunk (or one arm after the splitter). All the above work has been carried out in the framework of WP13 also in collaboration with WP23 on Access and the people involved consider it relevant also for possible new project submissions (FP7/FP8). In any case, the measurements will be sustained by internal projects at ISCOM and continuous exchange of measurements and data will be made between the involved partners which have their local activities running at local or national level.

Quality of Service (QoS) in Radio-over-Fibre Networks

Fondazione Ugo Bordoni and Istituto Superiore delle Comunicazioni e Tecnologie dell'Informazione contributed to the management of QoS in FTTx-WIMAX-LTE networks. They showed how to control a Quality of Service in optical networks integrated with WiMAX access radio by means of the MPLS and WiMAX Class of Services, even in condition of traffic congestions. Three possible scenarios for integration of WiMAX in the optical telecommunication networks have been studied to ensure the QoS of specific services by working both directly in the cell WiMAX and before of the same with techniques MPLS/VLAN tagging. It can be concluded that solutions with this type of integration can be used to provide the necessary bandwidth to services that require it.

GeRoFAN: a Generic RoF Access Network

Figure 4 recalls the global architecture of the GeRoFAN system. Several remote Radio-Access Units (RAU) also called HONUs (Hybrid Optical Network Unit) are connected by means of an all-optical loop to the head-end node. The head-end node is called "Hybrid Optical Line Termination" (HOLT). The deployment of such an architecture could stand at the metropolitan scale where several optical loops are envisioned. Each of these loops is intended to cover a specific district of the metropolitan area.

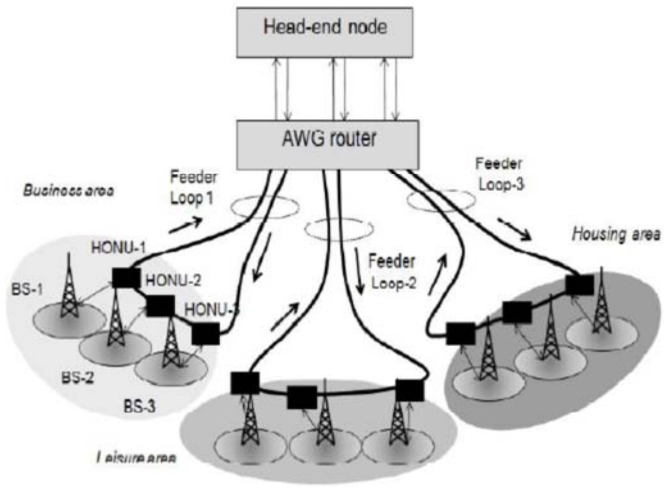

Figure 4: GeRoFAN system Architecture

Each RAU (or HONU) is supposed to serve a 4G radio-mobile cell (LTE/WiMAX). Thanks to RoF technique, all the radio frequency signal processing operations and associated devices are deported to the HOLT. The HOLT located by the central office concentrates the intelligence of the GeRoFAN network by means of its original control plane. The objective of our investigation is to design this control plane. Thanks to radio-infrastructure concentration at the HOLT, our control plane is supposed to acquire a global view of the load activity of all the base-stations connected to the different optical loops. Our main motivation is then to offer the possibility to shift radio resources from one loop to one another in case of macroscopic traffic fluctuations. At a smaller time and geographical scale, our control plane also aims to proceed to radio frequency balancing between the various RAUs connected to a same optical loop. In practice, the GeRoFAN control plane has to manage RoF modulators and tunable laser sources at the HOLT. The dynamicity of the system is provided my means of an Arrayed Waveguide Router (AWG) and of tunable optical transceivers. At the RAU, this dynamicity is achieved through the tunability of the RoF transceivers and the use of reconfigurable optical add drop multiplexers (ROADM). Although the control plane is located at the HOLT, the remote reconfiguration of the RAUs (reconfiguration of the RoF transceiver, reconfiguration of the ROADM to drop the right optical carrier) is enabled though a dedicated out-of-band signaling optical channel per fiber loop. This signaling channel transports all the information issued by the various HONUs in order to enable the reconfigurability of the RAUs. Within a given optical loop, the different RAUs may access to the signaling channel in a TDMA access mode.

<u>Architecture of the HONUs</u>

One key issue for GeRoFAN involves the choice of the optimal RoF transceiver to equip the different RAUs. We classify all different options into 2 categories:

1. The first category consists in equipping the RAUs by optical light sources which can be used either for direct or external modulation (in conjunction with an optical modulator). The laser diode equipping the RAU may be an expensive, high power

mono-mode laser diode (DFB laser) or a low-cost, relative high noisy multimode laser (FP lasers)

2. The second category relies on the concept of remotely-fed colorless modulators. This innovative solution is attractive from an economical point of view since it entails to deport all optical sources at the HOLT to be mutualized by all RAUs connected on the loop. The RAU is in this case equipped with a colorless external modulator (electro-absorption modulator EAM or RSOA). Innovative solutions rely on REAMSOA that exploits the high bandwidth modulation of the EAM while providing optical amplification through the integrated SOA. In the remaining of our study, only the case of colorless HONUs equipped with REAMSOA is considered.

Two main parameters determine the radio frequencies assignment to the optical carriers by means of sub-carrier modulation (SCM): traffic fluctuations and physical layer impairments. Ideally, the RoF transceivers should rely on a trade-off between cost constraints and quality of transmission requirements.

Dynamic radio frequency allocation and physical layer impairments

In the previous sections, we have implicitly neglected the impact of physical layer impairments on the radio-signal quality at destination. Such a perspective suggests that the optical carrier is considered simply as a neutral high capacity bearer. In this case, the control plane has only to assign radio sub-carriers to optical channels only on the basis of the fact that up to K radio-carriers may be attached to a same optical carrier. In practice, multiple physical layer impairments have also to be taken into consideration in our control plane.

Although the considered frequency bands for 4G systems can be considered less challenging than millimeter-wave frequencies (used generally for indoor applications), some physical layer constraints may severely degrade the signal quality of the radio frequencies carried across the GeRoFAN network. To work out the performance of a RoF link, Spurious-Free Dynamic Range (SFDR) related to the common signal to noise ratio (SNR) constitutes a prime figure of merit. Power constraints related to radio interference limitations between co-channel cells and battery life-time of mobile handsets constitute additional constraints. Thus, the GeRoFAN control plane needs to be Quality-of-Transmission (QoT) aware in taking into account the most severe physical layer limitations. This raises the question of how the different optical impairments influence the choice of the optical channel that would carry a given radio-frequency associated to a given RAU.

The main noise sources inherent to upstream radio traffic

Inter-modulation (IM) products distortion coupled with chromatic dispersion (CD) of the optical fiber may impact severely the SFDR. In standard RoF transmission links, the RoF transceiver (either a laser diode or an external modulator) stands for the main contributor responsible for the emergence of IM products. In sub-carrier modulation (SCM) systems, the inherent non-linearity of such components generates mixing IM products between radio subcarriers which may coincide with a used radio frequency transported by the optical carrier. At some extent, the phenomenon may evolve as a snow ball when IM products interfere among themselves as well as with their engendering frequencies. In other terms, without a special attention on the selection of radio channels at the input of electrical multiplex, IM distortions can overwhelm a designated channel causing the radio subcarrier to be suppressed entirely. To tackle the effects of IM distortions and to better use the capacity of the WDM multiplex, the control plane is expected to optimize the placement of RF over the available optical carriers. Other optical impairments may influence the rationale of the control plane. Such impairments are not restricted only to the RoF transceiver, the optical crosstalk among WDM channels brought by the OADM being another potential cause of physical layer impairments. Actually, an optimal RF placement scheme would target two crossed objectives:

1. Our first objective deals with a more efficient use of the total capacity within an optical loop. As all HONUs must be served, we want to transport all RF subcarriers while using globally the lowest number of optical carriers. By reallocating RF among optical carriers in order to avoid a sparse usage pattern. The extra optical spare capacity can be reused by another optical loop to manage an inter-loop bandwidth balancing.
2. Our second objective addresses the SFDR requirement. Because distortions that arise from inter-modulation between RF subcarriers are strictly dependant on the frequency plan adopted for channels assignment, it becomes necessary for the control plane to choose for each subcarrier the right position at the right wavelength in order to reduce the level of generated distortions. The Golomb Ruler provides an optimal strategy to assign radio frequencies to optical channels in suppressing inter-modulation products occurrence. Unfortunately, such a strategy requires larger bandwidth and result generally in a sparse usage pattern of optical carriers.

Conclusion

The cross-optimization mechanism considered in our study highlights two objectives that may contrast each other. It seems difficult to assign RF subcarriers to optical carriers within a minimal number of optical carriers while removing the risk of high inter-modulation distortion. The optimal strategy applied by the control plane would rise then from a trade-off between the capacity usage maximization and the observation of QoT requirements. In summary, GeRoFAN offers an innovative solution to federate remote RAUs for 4G system. Thanks to its control plane, GeRoFAN is able to allocate dynamically bandwidth resources from one cell to another within a same optical loop, or from one optical loop to another optical loop. The success of GeRoFAN system relies on a deep awareness of the main physical impairments of RoF system.

Single-Tone MB-OFDM Interrogation

We reported the first experimental demonstration of AWG cognition using SMF-tailed, C-band VCSELs; all components being commercially available. The basic principles utilised OFDM signal manipulation as described in our previous work [e.g. 1]. Figure 1 shows the experimental set-up. It was comprised of: a 1559 nm VCSEL (Raycan RT3xxx1-F series); 12.7 km single mode optical fibre (SMF); a 1X32 AWG (JDS AWG1M1C32-Z003); a 1X2 optical splitter and a PIN photo-detector (Discovery DSC-R402HR).Wireless connectivity was enabled with two UWB radio hubs (Belkin F5U302) and two UWB antennas (Omron WXA-N2SL).

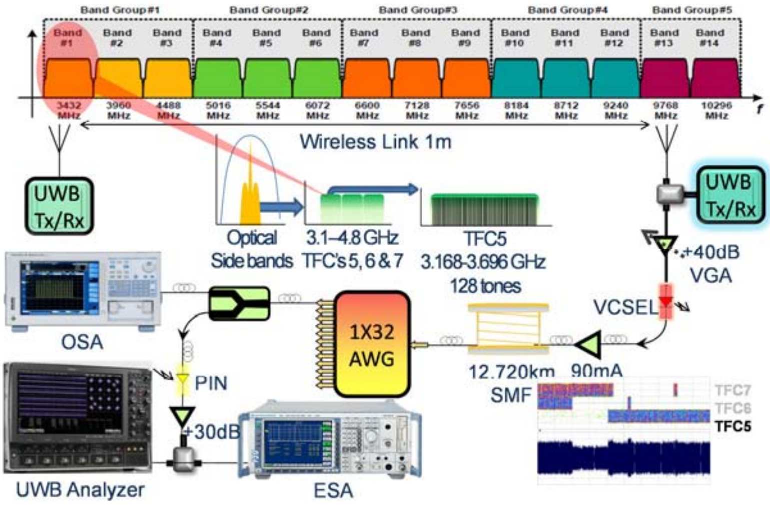

Fig. 5: Performance monitoring system setup in laboratory

After the UWB hub, a split-out electrical signal was fed to the optical channel where a 40dB variable gain amplifier directly modulated the VCSEL. Automation therefore offers varying optical modulation index (OMI) over network life-time. VCSEL also shifts the wavelength in cognition mode; and affects OMI. VCSEL output was boosted for experimental convenience with 10 dB EDFA gain. Table 1 summarises the optical and electrical power levels. An optical splitter facilitated wavelength monitoring after the AWG on an OSA (Ando AQ6317B) and UWB signal analysis (LeCroy "Waverunner"). Here, it should be noted that UWB electrical signal levels are composites over a single 528-MHz bandwidth within a sub-band (TFC5 3.168-3.696 GHz) of band group 1. Signal level calculations were based on measurements with 1 MHz spectrum analyzer resolution bandwidth. The composite power P dBm is given by: P = $P_{measured}$ dBm/MHz + $10\log_{10}(528)$.

Table 1: Optical and electrical powers in link

Optical power after	dBm optical	Electrical power after	dBm/MHz electrical
VCSEL	-5.343	1X2 electrical splitter	-52.76
EDFA	4.57	40dB VGA	-31.61
12.72km SMF	3.1	VCSEL + EDFA + 12.72km SMF + AWG + 1X2 optical 1X2 splitter	-31.13
AWG	-2.76		
1X2 optical splitter	-7.34		

From table 1, it is implicit that VCSEL drive power was -9.38 dBm. Figure 6 shows two reasons for wavelength shift: change in laser characteristics and shift in the AWG port alignment. As may be noted, laser-based perturbations will affect the EVM of two consecutive channels which are identified with no traffic intrusion and minimal overhead by simply monitoring the symmetrical edge-tone EVMs at the point of detection. A date rate of 480 Mbps was used on the overall 528MHz bandwidth. As one band group consists of 128 tones, the use of just two edge signals is not particularly restrictive. Furthermore, the fact that packets are not decoded or analysed shows that the system intrinsically offers personal data security.

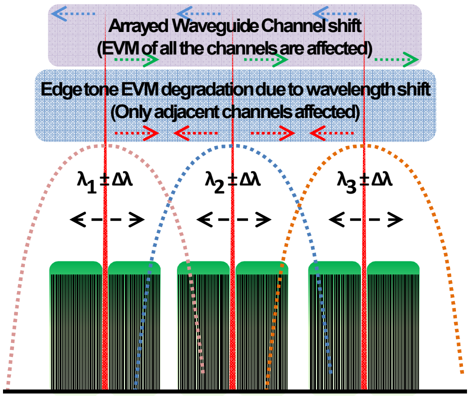

Fig. 6: *EVM of affected edge tones due to wavelength shift*

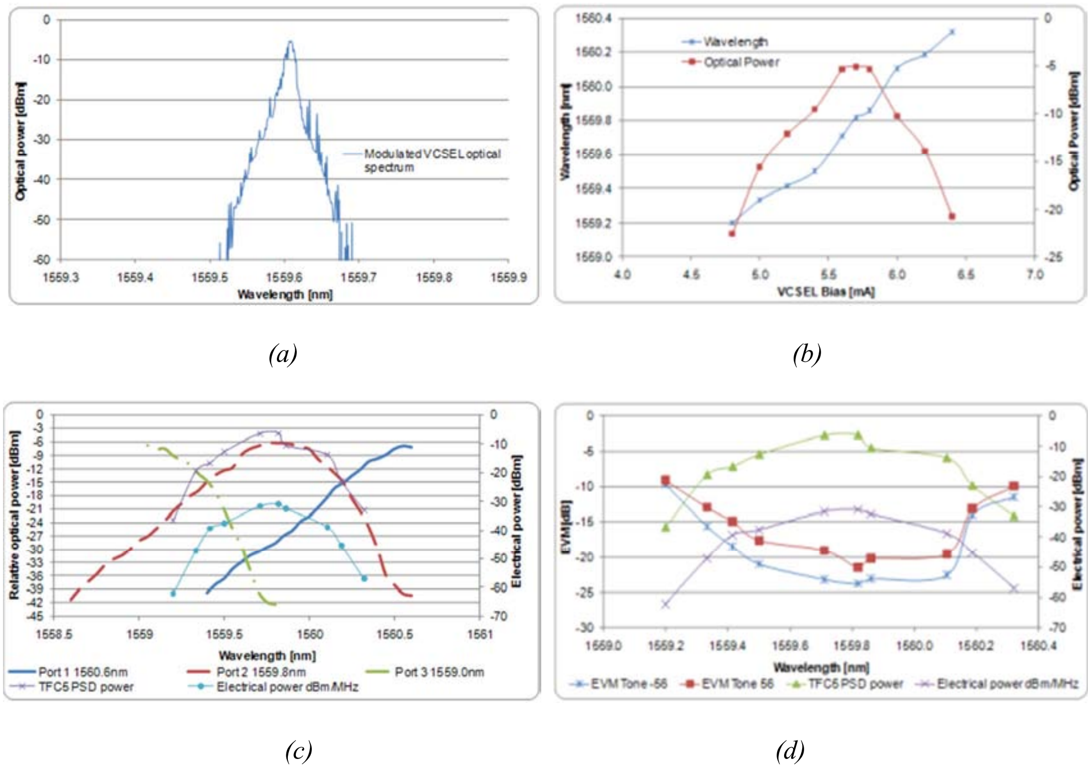

Fig. 7: *(a) Directly modulated VCSEL, FM broadening; (b) VCSEL wavelength shift with bias with AWG port 2 optical power; (c) OFDM electrical power detected with changing wavelength after AWG with ports 1, 2 & 3 optical power profiles; (d) EVM of edge tones ±56 and their electrical powers variation with wavelength on port 2 of AWG.*

Figure 7 above is a composite of the main experimental results and highlights how network cognition can take place with the aid of MB-OFDM tone probes. Figure 7(a) shows the time-averaged FM broadening of the VCSEL. The rms VCSEL signal current is ~ 0.63mA which, from fig. 7 (b), equates to ~0.5 nm rms or ~62.5 GHz rms FM broadening at 1550 nm.

However, the time averaged spectrum shows just 20 pm FWHM (2.5 GHz and instrument limit) due to the 9dB MB-OFDM peak-to-average power ratio. In figure 3 (b), it can be seen that as the optical signal scans across AWG ports 1-3 (1559.0nm to 1560.6 nm), the detected and amplified edge tone power reaches a maximum of -6 dBm as port 2 is crossed. Also in this figure, the VCSEL wavelength sweep across port is evident. Figure 7 (c) shows the close relationship between MB-OFDM, time-frequency code TFC-5 power spectral density and AWG cognition; the band-centre of port 2 being clearly identified. Finally, in fig. 7(d), the key result is presented which is the close rendition of AWG port 2 at 1559.8 nm by EVM variation in the TFC5 edge tone designated as ± 56. The EVM fluctuations over all the tones can be seen in figure 8.

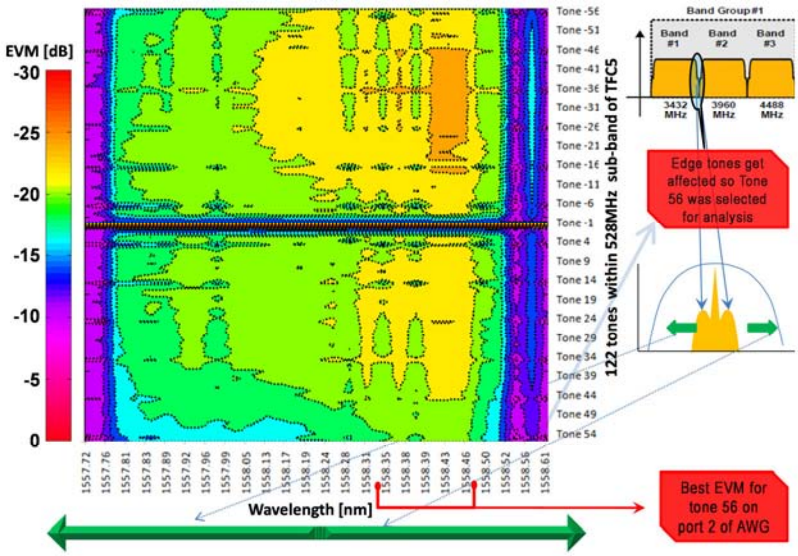

Fig. 8: *EVM fluctuations for all OFDM tones with variation in wavelength.*

Such EVM fluctuations are detected by MB-OFDM firmware and returned to the transmitter via pilot tone modulation as part of the channel set-up and monitoring procedure. Extension of the foregoing technique to multi-variate optimisation is straightforward with iterative methods such as Newton-Raphson as shown previously [2]. This cognitive method is readily extended to hybrid networks where radio channel performance can be assessed and to coherent OFDM systems [e.g.7].

Overall, the technique described above has a clear role to play in the current strongly competitive environment for last-mile service provision.

Demonstration of Transparent WiMAX Transmission over Multi-wavelength GPON

An IEEE 802.16-2005 (WiMAX) compliant PON architecture with wavelength band overlay was implemented experimentally to demonstrate a distributed broadband wireless (DBW) access network over a next generation PON. The multi-wavelength overlay is achieved with the slightest modification in network hardware by the application of dense AWG in the OLT and VCSEL arrays in remote base stations. Frequency division multiplexing (FDM) is utilised to address individual BSs sharing a single wavelength over a power splitting-PON. The use of overlapping radio cells/sectors is also proposed to enhance network resilience and dynamicity. Experimental results at remote receivers have confirmed EVM below -29 dB and -23 dB for 25.2 Mbps and 18.9 Mbps, downstream and upstream WiMAX channels respectively over maximum transmission distances of 40 km. In addition, 10-11 GPON bit-error-rates (BERs) have been also readily achieved over the combined optical and wireless architecture. Finally, the modelling results for the transmission over overlapping radio sector have displayed minimum 10-4 BERs bidirectional, over faded 330m overlapping micro-cells circumference without any error coding or relay techniques.

The proposed network architecture is shown in Fig. 9. The key feature of this topology is the attainable dynamicity, through the application of extended wavelength band overlay [4]. On each wavelength, multiple microwave WiMAX channels are arranged in a FDM window to address individual ONU/BSs. The WiMAX channels are shifted in frequency using a predetermined Local Oscillator (LO) and BPFs in the OLT prior to being combined and modulated onto an optical carrier. At an ONU/BS, only a single LO is required, operating at the same frequency for the specific ONU/BS to downshift the WiMAX channels. Multiple BPFs are needed to select each channel prior to transmission over the air. This approach would significantly simplify the BS design. The same FDM window could be carried on multiple wavelengths, relaxing the bandwidth requirements of optical and electrical devices and simultaneously enhancing the network scalability. The resulting reduction in total FDM bandwidth minimizes the effects of fibre dispersion. This has been demonstrated in the network by the successful transmission of WiMAX channels over 40 km fibre without any dispersion compensation.

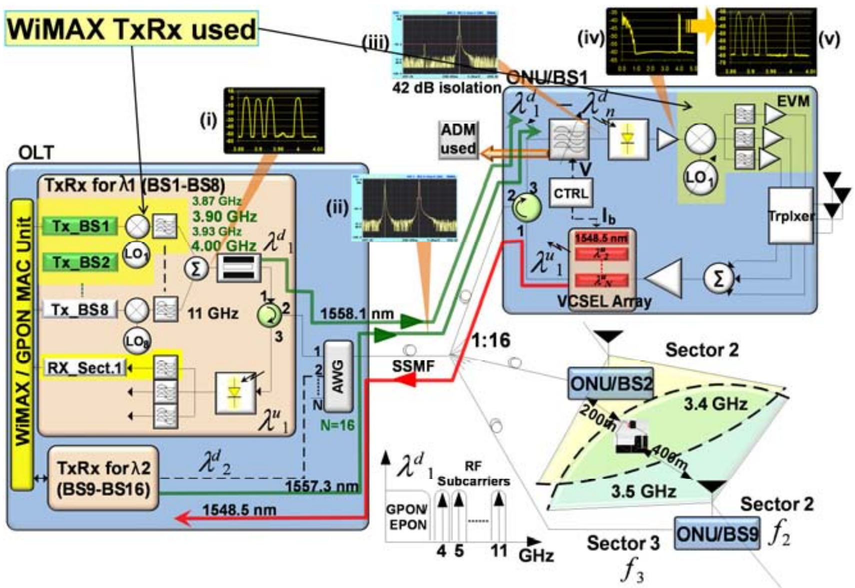

Fig. 9: *WiMAX over multi-wavelength, power splitting PONs.*

In addition, any wavelength can be partly or exclusively assigned to different ONU/BSs, achieving service levels, similar to WDM-PONs. In hardware, this is implemented by the addition of a dense array waveguide grating (AWG) in the optical line terminal (OLT) (adding further capability to support multiple PONs from a single OLT) and tuneable optical filters in ONU/BSs [2]. The centre frequency of the latter can be adjusted by the OLT by means of a control circuit. The distribution network thus remains intact achieving smooth migration towards next generation PONs (NG-PONs) [5].

A noteworthy feature of the proposed architecture is the centralised control, compared to the independent approach in a traditional WiMAX deployment, allowing for the creation of overlapping sectors, e.g. between ONU/BS2 and ONU/BS9 respectively in Fig. 9, operating at different frequency channels. Therefore, the remote radio base stations are able to utilise higher order frequency reuse patterns in order to reduce interference in the overlapping regions. For sectors without overlapping regions, a frequency reuse of 1 is assumed. Users in these overlapping zones can have simultaneous wireless support from multiple ONU/BSs, thus increasing the capacity of the wireless network and providing redundancy in case of fibre failure between a distribution node and an ONU by establishing alternative routes for signal transmission. Another key feature is the use of low-cost long-wavelength VCSEL arrays [11] for the upstream, to demonstrate colourless terminations with simple coupling optics which are not limited by the non-linear effects of the optical fibre. Although RSOAs could be used, Rayleigh backscattering is known to degrade performance [13]. Also, with VCSEL arrays, re-modulation of downstream carriers is not required, therefore avoiding the necessity of reusing upstream wavelengths to transmit downstream simultaneously [13]. VCSEL wavelength selection can be managed by implementing controls similar to tuning the ONU/BS filters. This approach, in combination with TDMA [14, 15] when multiple ONU/BSs are sharing a single wavelength, could also be applied.

To establish accurate signal routing to and from an ONU/BS, received error vector magnitudes (EVMs) for the WiMAX channels and bit error rates (BERs) for the GPON signals were experimentally investigated. EVM gives an indication of transmission quality and a minimum value is often specified in advanced radio systems with complex modulation schemes.

WiMAX over GPON link implementation

For both downstream and upstream, an OFDM-WiMax data region with one burst was used. Three IEEE 802.16-2005 channels, with the specification given in Table. 2, at 3.5 GHz with 30 MHz channel spacing were generated by (Tx_BS2) using an Aeroflex PXI WiMAX Vector Signal Generator/Analyser system. The fourth 3.5 GHz WiMAX channel was generated by Tx_BS1 for transmission measurements. The downstream WiMAX channel

TABLE 2
POWER BUDGET PARAMETERS FOR WIMAX

IEEE802.16e-2005 WiMAX			
Transmitters		**Receivers**	
Power at amplifier output	25 / 20 dBm	SS_antenna gain	17 dB
		SS_cable loss	1 dB
		Noise in BW	-100.1/-104 dBm
		Noise Figure	4 dB
BS_antenna gain	17 dB	SS noise floor	-96.1 / -100 dBm
BS_cable loss	2 dB	SNR_required	24.4 / 18.2 dB
BS_antenna height	30 m	Rx sensitivity for BER=$1e^{-6}$	-71.7/ -81.8 dBm
EIRP	40 / 35 dBm	Shadow margin	8 dB
Propagation Loss with Cat. B [17]	100-120 dB		

transmitter relative constellation error (RCE) was -50 dB, a figure higher than the minimum standards requirement for 64-QAM modulation. Subsequently, the WiMAX channels were frequency shifted to 3.9 GHz (3 channels) and 4 GHz (measurement channel) to address individual ONU/BSs.

As shown in the experimental setup, Fig.9, a MZM was used in the OLT to externally modulate a commercially available distributed feedback (DFB) laser source. The MZM approach offers improved performance in terms of noise and distortion compared to direct laser modulation but with higher cost. However, as it is typically shared by large number of users since it is deployed in the OLT the cost penalty will be shared. Having added the various optical component losses, including 7.75 dB for the MZM, 1 dB for the polarisation controller and 3.76 dB for the AWG, 0.9 dBm optical power was launched into the fibre.

TABLE III
IEE802.16E TRANSCEIVERS PARAMETERS

	Downstream	
FFT size	1024	1024
Modulation	64-QAM	16-QAM
Coding	2/3	3/4
Bandwidth	10MHz	10MHz
RCE	-50dB	-25.8dB
Data rate	25.2Mbps	18.9Mbps

To demonstrate the fixed to mobile convergence, a baseband (e.g. GPON) channel at 1.25 Gbit/s was also introduced. The combined spectrum was transmitted on $\lambda d1$=1558.1 nm, through a 16x1 AWG to an ONU/BS of the corresponding PON, using various lengths of standard single-mode fibre (SSMF) ranging from 23.2 km to 40.7 km. It should be noted that, 1490 nm can also be used to support legacy PONs [16] based on free spectral range of AWG devices. Therefore, a smooth upgrade to NG-PON [5] is still achievable.

An additional un-modulated wavelength at $\lambda d2$=1557.3 nm was employed to investigate interference at the ONU/BS. To account for various splitter loses, an optical attenuator was used after the fibre. At the ONU/BS, a readily available add/drop multiplexer (ADM) was utilised prior to PIN detection (replacement for commercial 50 GHz optical band pass filter). The ADM drop port for 1558.1 nm wavelength had signal to interference ratio of 42 dB. The resulting up-converted WiMAX electrical spectrum was then down-shifted in frequency to get the original WiMAX channels and subsequently amplified by a 30 dB gain amplifier. In order to select the baseband (GPON) signal, a low-pass filter with bandwidth of 900 MHz was utilised.

A single IEEE 802.16-2005, 3.5 GHz channel was generated for upstream to directly modulate a VCSEL, biased at 8.3 mA, with wavelength $\lambda u1$=1548.5 nm and output power level of -0.94 dBm prior to being transmitted over the SSMF. The upstream WiMAX transmitter RCE was -25.8 dB [3]. Assuming a noiseless radio channel, the received RCE at the ONU/BS1 was undistorted. The resulting optical signal was then routed through the corresponding AWG output port to the destination receivers (Rx_Sect.X) in the OLT.

Simulation model

For comparison, a physical layer simulation test-bed was also implemented using the industry standard optical systems simulation package by Virtual Photonics Inc. (VPI) and WiMAX implementation in MATLAB to demonstrate WiMAX transmission over multi-wavelength GPON and overlapping sectors downstream. The same WiMAX and optical parameters, as in the experiment, were used in the simulation. However, this time 20 MHz WiMAX bandwidth was assumed in order to simulate the worst-case scenario over the wireless channel. Additionally, in order to account for range limitations in wireless transmission, data sheet power budget parameters for WiMAX are also considered. These parameters will enable to model distance transmission limitations over the air, which are not accounted for in the VPI. As specified in Table 2, the output power from the non-linear high gain amplifier in the ONU/BS is 25 dBm. Consequently, with the BS antenna gain and cable loss of 17 dB and 2 dB respectively, the effective isotropic radiated power (EIRP) over the air is 40 dBm. The BS antenna height was utilised in an empirical path loss model in order to estimate the maximum transmission distance.

At the WiMAX receiver, the noise power in the 20 MHz bandwidth was calculated to be -100.1 dBm, based on typical -174 dBm/Hz spectral density. The corresponding receiver noise floor is thus -96.1 dBm with 4 dB noise figure. This noise floor was included in the model to limit the received signal-to-noise ratio and consequently maximum transmission distance. Finally, the WiMAX downstream receiver sensitivity for BER of 10-6 was -71.7 dBm.

For the radio transmission, an AWGN and multi-path Stanford University Interim (SUI-4) wireless channels [6] were considered, representing typical sub-urban environment. The subscriber receiver was positioned in the overlapping region between two base stations, as shown in Fig. 5.

Experimental results

The four frequency shifted WiMAX channels generated prior to MZM modulation are shown in Fig. 9 (inset i). As expected the signal to noise ratio at the output of the Aeroflex PXI transmitter was 50 dB. The average power for the measurement channel at 4 GHz was 0 dBm. However, this power was varied in order to observe the effect of intermodulation distortions due to the MZM. After being modulated on the optical carrier and transmitted over the fibre, the spectrum of the combined electrical signal is shown in Fig. 9. The baseband signal extending up to 1.25 GHz could clearly be seen together with up-converted WiMAX channels in 4 GHz spectrum. The power of the received signal before electrical amplification is around -40 dBm. The measured BER with a fixed optical received power of the GPON signal, transmitted over 23.2km fibre, was 10-11, demonstrating error-free transmission for the wired users. For received WiMAX channels (inset V, Fig. 9), the nonlinear distortions introduced by the optical modulator could significantly degrade the network performance. Therefore, EVM characteristics as a function of the MZM RF drive power in the OLT downstream for a 25.2 Mbps channel at 3.5 GHz were measured. As illustrated in Fig. 10, at low RF drive powers the signal is mainly distorted by noise while at high powers, EVM increases due to nonlinear effects. However, an EVM figure of greater than -29 dB for 23.2 km fibre was achieved with +13 dBm RF fed to the MZM, satisfying the WiMAX requirements for 64-QAM 2/3. The measurements were repeated for fibre lengths of 29.7 km and 40.7 km. As displayed in Fig. 10, for lower splits, EVM below -29 dB can be achieved for all fibre lengths without any dispersion compensation techniques. Therefore, the power penalty on longer fibres can be compensated by increasing the launch power.

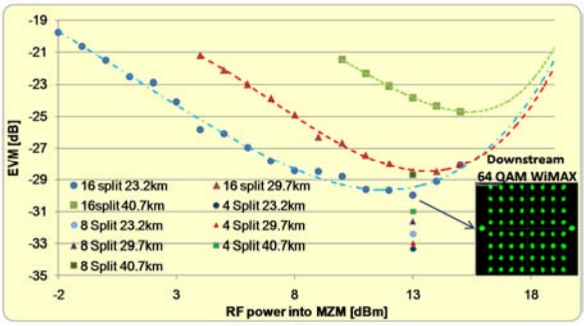

Fig. 10: *Obtained EVM for 3.5 GHz WiMAX channel at remote antenna downstream.*

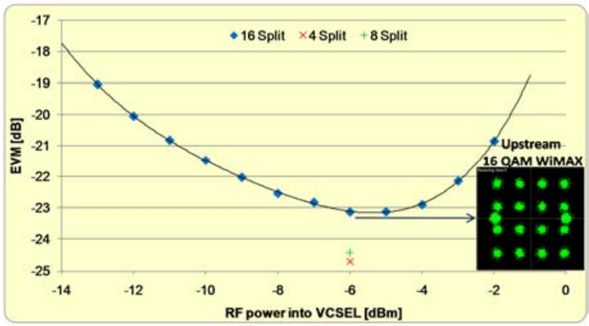

Fig. 11: *Obtained EVM at the WiMAX OLT receiver for 3.5 GHz channel upstream.*

The upstream EVM at the OLT receiver against the RF power into the VCSEL is shown in Fig. 11. An EVM of -23 dB was noted for 23.2 km fibre and 16 split, matching the requirements in the WiMAX standard for 16-QAM 3/4 modulation. The interaction of VCSEL laser chirp and fibre dispersion in analog optical modulation upstream had negligible effect on the received WiMAX channels in the OLT. Longer fibre lengths were not considered due to the VCSEL output power limitation. Similarly for the downstream, at 4 and 8 splits, corresponding to higher received optical power, an EVM below -24 dB was measured. This demonstrates that higher output power VCSEL arrays [7] can significantly reduce the EVM penalties. Hence, it can be concluded, that the proposed optical network provides a transparent channel for standard wireless signal formats transmitted bi-directionally over multi-wavelength power-splitting. The constellation diagrams obtained at the WiMAX receivers after the phase and amplitude corrections are displayed as insets in Figs. 10 & 11.

In the experimentally demonstrated system, the extended wavelength band overlay, following NG-PON requirements, provides for reduced component costs, as the same FDM windows could be utilized on multiple-wavelengths requiring low bandwidth optical and electrical devices. Consequently, 40km downstream transmission without any dispersion compensation was readily achieved.

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4.2. Joint Activity - Techno-economic analysis of access networks

Members

- **AGH, BME, IBBT, KTH, AIT, FUB, PoliTo, UPC**

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.

Research Topics

List of the research topics considered within JA2:

- General framework for techno-economic analysis of next generation access networks
- Accurate cost analysis by topology design for FTTx access network, based on geographic and infrastructural information

Collaborations/Joint Experiments and Mobility Actions

Meetings:

- AGH, BME, IBBT, KTH – Stockholm, 16th February 2010
- AGH, BME, IBBT, KTH – Budapest, 13th May 2010.
- AGH, IBBT, KTH – Munich, 30th June 2010.
- AGH, BME, KTH – Budapest, 8th September 2010.

Mobility actions

- BME→KTH, 14-17 February 2010, Attila Mitcsenkov
- IBBT→KTH, 14-17 February 2010, Bart Lannoo

Miroslaw Kantor, Research Assistant at AGH, hosted by KTH from 23/02/2010 to 26/02/2010

Preparation of framework for techno-economic analysis of PON architectures - The main goal of the mobility action was to discuss with the partners involved in WP13 JA2 the possibilities of preparation of framework for techno-economic analysis of access network architectures. During this mobility action we drafted a possible content of the joint papers and made plan how to proceed. The KTH has also hosted the meeting of WP13 JA2 activity participants.

- **Miroslaw Kantor, Research Assistant at AGH, hosted by BME from 12/05/2010 to 14/05/2010**
- **JiaJia Chen, Postdoc at KTH, hosted by BME from 12/05/2010 to 13/05/2010**

Techno-economic framework with geometric and geographic models and *Techno-economic analysis of fiber access networks* - The main goal of the mobility action was to discuss with the partners involved in WP13 JA2 the preparation of framework for techno-economic analysis of access network architectures for ICTON paper. During this mobility action we drafted a possible content of the journal paper and made plan how to proceed. The BME has also hosted the meeting of WP13 JA2 activity participants.

- **Lena Wosinska, Professor at KTH, hosted by BME from 12/05/2010 to 13/05/2010**

Techno-economic analysis of fiber access networks - According to the aim of the mobility action we discussed a framework for techno-economic analysis which includes geometric and geographic-based models for topology design and evaluation. Two main achievements of our mobility action can be identified:
A)We almost finalized the joint paper for ICTON2010 and
B)We made a plan for a scientific paper to be sent to a respected journal. Below is a summary of our discussions on the joint journal publication.
For the joint the journal submission we first defined a message & main focus.
We'll evaluate reasons for inaccuracy of analytical models compared with geographic calculations. Furthermore we'll try to come up with extensions of existing analytical models in order to make them more accurate.

- **Lena Wosinska, Professor at KTH, hosted by AGH from 03/06/2009 to 06/06/2009**

Reliability analysis of PON architectures - The main goal of the mobility action MA was to prepare a scientific paper on the reliability analysis of different Passive Optical Network architectures and to strengthen collaboration between AGH and KTH in the frame of BONE WP13. The collaboration between AGH and KTH on this topic started within e-Photon/ONe and e-Photon/ONe+ projects. During this mobility action we drafted a possible content of the joint paper and made plan how to proceed. Furthermore, we discussed the final outcome of our Joint Activity, namely the framework for the techno-economic studies of fiber access networks. We explored possibilities to utilize related results from current and past EU projects (e.g. FP4 AC038 BBL - Broadband Loop and TITAN- project 2087 of the European RACE program). Based on the already existing framework for one type of fiber access network architecture we are planning to extend it by including the possibility to evaluate different architectures and different technologies related to fiber access networks. Our aim is to be able to estimate the cost-efficiency of different fiber access network solutions. Furthermore, we are planning to develop cost models for all considered access systems. Moreover, a benchmarking of network element cost will be created in order to be able to perform a comparative study of the analyzed solutions.

Joint experiments:

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

Publications

2010

- A. Mitcsenkov (BME), M. Kantor (AGH), K. Casier (IBBT), B. Lannoo (IBBT), K. Wajda (AGH), J. Chen (KTH), L. Wosinska (KTH), "**Geographic Model for Cost Estimation of FTTH Deployment: Overcoming Inaccuracy in Uneven-populated Areas**", IEEE/OSA/SPIE Asia Communications and Photonics (ACP) Conference and Exhibition, Shanghai, China, December 2010
- Sotiria Chatzi, Jose A. Lazaro, Josep Prat and Ioannis Tomkos, *"**A Quantitative Techno-economic Comparison of Current and Next Generation Metro/Access Converged Optical Networks**",* ECOC 2010, We.8.B.2
- M. Kantor, K. Wajda, B. Lannoo, K. Casier, S. Verbrugge, M. Pickavet, L. Wosinska, J. Chen, A. Mitcsenkov: ***General framework for techno-economic analysis of next generation access networks*,** ICTON 2010, 27th June-1st July 2010, Munich, Germany.
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Research Contributions

General framework for techno-economic analysis of next generation access networks

In order to handle the emerging demands for broadband services, adequate telecommunication access network designs are crucial for network operators, service providers and equipment vendors. As a number of technical candidates and design options for constructing access networks exist, it is necessary to perform calculations to identify cost-efficient combinations of technologies, functionalities and network structures. For this reason, a large variety of access network architectures have to be checked in order to determine the most appropriate ones for different area types and service demand profiles. Moreover, besides technical options, other issues like regulatory and competitive aspects should be taken into account. An accurate construction of a techno-economic model allows to minimize errors in the network development phase and to calculate intermediate results, allowing an evolutionary development of the network solution. The detailed modelling, including offered services, serving area, equipment, operational cost processes, revenues and other related techno-economic elements, assures a significant conformity between techno-economic models and real deployment.

<u>Framework and methodology</u>

Figure 12 gives an overview of the methodology for performing a complete techno-economic evaluation. It starts from determining the scope of the problem and detailing the inputs for the study based on a market analysis. The most important outcomes here are indicated by the building blocks services and architectures. They contain all input information necessary for building the techno-economic model in the second step. Often in a telecom project the network is the central piece and contains most optimization opportunities. Moreover, a proper network design also reflects suitability of a certain network infrastructure to the considered scenario, and therefore it supports the optimal choice among the competing technologies. As such, network design is given a central position in this figure as the link between market analysis and calculations. In the calculations we make a distinction between economic calculations, in which we estimate costs and revenues; and the technical calculations, in which we estimate the performance metrics of the proposed network solution. In the final step, an evaluation will be based on the outcomes – economic and technical – of the calculations step. This step is split between investment analysis and performance analysis. In the first part, we make an estimation of the (expected) profitability of the project. In the second part, we compare different alternatives and make tradeoffs of costs vs. performance. Both results are the final outcome of a well balanced techno-economic study.

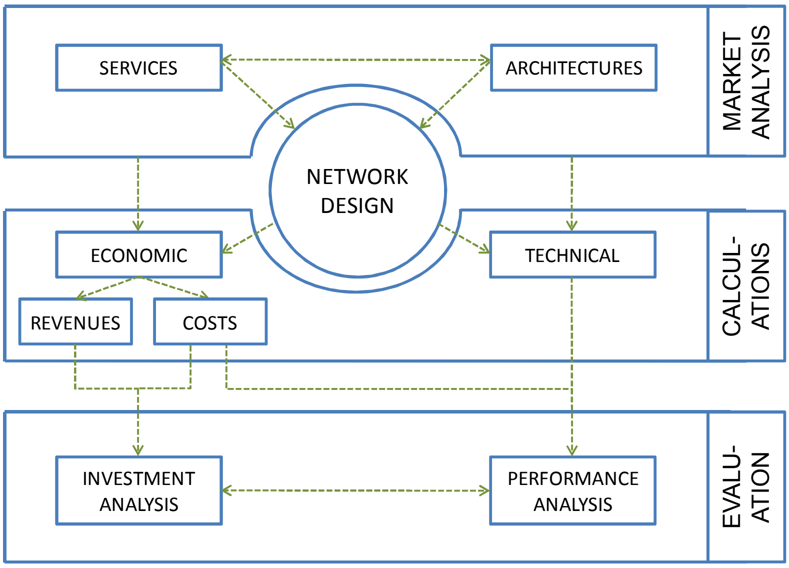


Figure 12: Flow diagram of a techno-economic evaluation

<u>Market analysis for the techno-economic framework</u>

Market analysis related to tariffs, regulations and market shares is a first step in the techno-economic framework. Different tariffs and fees can be assigned to different applications and customer groups. A proper market model should also contain information on the regulatory context, competitive issues, customer preferences, etc.

<u>Services</u>

Demand modelling and broadband forecasts for considered access technologies are essential inputs to all business case analyses. These aspects take into account issues related to customers, applications demands and their characteristics. A number of potential customers has to be described, together with a set of available applications. Each application has to be described by a set of parameters, e.g., bandwidth, usage intensity, quality and resilience requirements leading to engineering rules, and e.g., cost, subscription options and type of service agreement leading to pricing consequences. The service scenario should be prepared defining how many subscribers are connected to a certain service year by year and how much revenue brings one service user for the network operator per year. The penetration of the service, meant as a number of users in time, and the usage of the service also have to be taken into account in techno-economic analysis. These parameters can be estimated from historical data and from forecasts.

Architectures

The description of relevant technologies, systems and architectures to provide the services in the form of selected target access network architectures should be given. In case the access network migration path is considered, also the details related to intermediate scenarios have to be defined. Based on the assumed access network evolution path, the amount of equipment needed in the network and the time when the various components actually are implemented should be indicated.

The cost figures for the network components should be based on comparable input data (with respect to volumes, market, etc.) and collected in an integrated cost database. The cost evolution for the actual components during the study period should also be taken into account, e.g., by applying a learning curve model [1]. Apart from the cost figures, also the technical parameters, such as bandwidth capacity, power consumption, reach, mean time between failures (MTBF), mean time to repair (MTTR), etc. should be provided.

The final step based on the architectures and services should be describing the deployment rules aiming at economically and technically justified network dimensioning and management.

Network design

Network design plays a central role in techno-economic calculations. From the network design, the lengths of fibres, cables and ducts are determined. Additionally, in view of the planned network topology, detailed lists of the necessary network equipment and installation works are available that support accurate, realistic preliminary cost estimations; and also OpEx calculation models are heavily dependent on the network topology itself. On the other hand, designing the access network is impossible without the market analysis described in the previous section, as the chosen network architecture obviously sets constraints on the network topology that has to serve all the customer demand and provide the desired services.

Calculation details

In order to make a techno-economic analysis of the full project, different techno-economic calculations must be performed. At first an economic model will give an estimation of all costs and revenues the project will generate. Additional technical calculations will give more information on the performance of the outcome of the project under consideration. Both parts are discussed in more detail in the following subsections.

In order to cover all costs while building the economic model, it is good practice to start from a life-cycle of the project and perform a gradual cost-breakdown for the costs of the different phases. Figure shows the life-cycle cost for a typical FTTH network rollout [2].

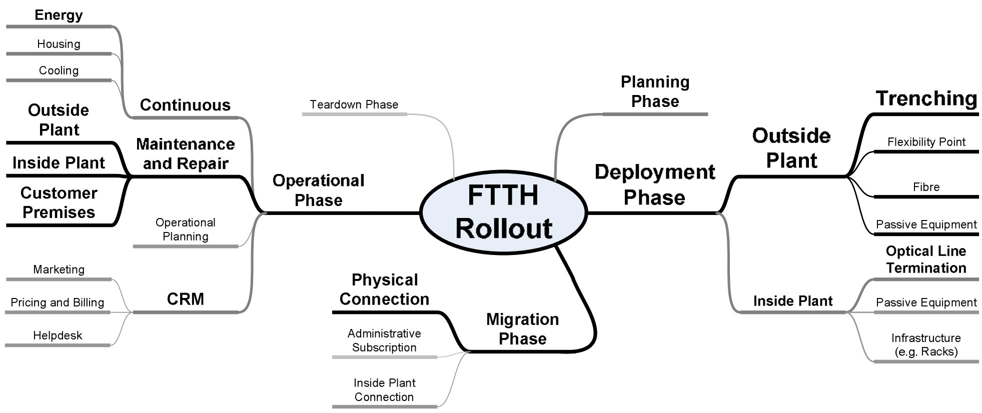


Figure 13: Capital and operational costs for the rollout cycle of an FTTH network [2]

This lifecycle additionally indicates which level of detail to use for the estimation of each part. By providing an (estimative) calculation model for each of the components in this lifecycle a full economic model is built. Finally it is important to note that we make a distinction between infrastructure and operational cost components, based on their origin. This distinction makes sense as both have typically a different structure, information sources and calculation approach. Infrastructure costs are modelled using equipment models and will take specifics of this equipment, such as failure-rates and replacement periods into account. Infrastructure is also typically bundled under Capital Expenditures (CapEx) and can be depreciated. Operational costs are modelled using manpower and operational processes and are typically bundled under Operational Expenditures (OpEx).

In combination with the revenues the economic model is complete. Revenues are typically easier to calculate, based on the subscription rate and a description of the market (market size, service penetrations). The market size in turn is estimated using a so-called customer adoption model [3] or dedicated market research figures.

Based on the input from the market analysis and network design, performance parameters such as capacity, energy consumption, reach, reliability and other technical indicators can be calculated. These technical parameters are then essential for techno-economic evaluation.

One of the most important objectives of NG access networks is to satisfy an increasing bandwidth demand from the end users. Large capacity (more than 1Gbp/s per customer) is a crucial technical criterion for NG access network solutions. Energy consumption by the ICT sector is rapidly growing and becomes an environmental, social and political issue. Therefore, power consumption per bit and per customer in access networks should be minimized in order to contribute to the overall energy saving in communication networks. Extending the reach of access networks from a few kilometres to about 100 kilometres allows for a site reduction and, consequently, gives a potential for lowering the OpEx. However, some technical issues are associated with the reach extension since the power budget needs to be satisfied. Therefore, the maximum distance supported by a given access network architecture is an important parameter. The importance of fault management and reliability performance of access networks increases with the network size and capacity as well as with the new and emerging services. Therefore, network monitoring and recovery mechanisms are essential for the reliable service delivery. Consequently, the reliability performance of candidate access network architectures needs to be evaluated.

Techno-economic evaluation

The techno-economic evaluation incorporates results from both investment and performance analysis with the aim of selecting the most cost-efficient solution for a certain scenario and performance requirements.

Investment analysis

Typical investment analysis will combine all cash flows (costs and revenues in time) and make a decision on the profitability of the investment project. Key performance indicators are Cash balance, Net Present Value (NPV), Internal Rate of Return (IRR) for a given interest rate. As the NPV gives the best view on the economic value of the whole project we typically use this as the deciding metric and use the others as indicative additions.

Performance analysis

Based on the economical and technical calculations, techno-economic performance indicators can be evaluated.

One of the performance parameters is the cost per capacity unit for each user. It can be a more indicative measure than the cost per user as it would allow for a fair comparison of different access technologies. The relation between cost and reliability also should be evaluated. A large variety of reliable network architectures has been developed in the recent years with the aim to offer high service availability in NG access networks [4]. On the other hand, improvement of reliability performance is typically associated with additional investment cost while access network providers need to keep CapEx and OpEx at reasonably low level to be able to offer economical solutions. Therefore, a techno-economic analysis which takes into account the resilience issues helps to select the most cost-efficient approach in respect to the reliability performance of an access network.

Geographic Model for Cost Estimation of FTTH Deployment: Overcoming Inaccuracy in Uneven-populated Areas

A geographic approach is proposed to accurately estimate the cost of FTTH networks. In contrast to the existing geometric models, our model can efficiently avoid inaccurate estimation of the fibre infrastructure cost in the uneven-populated areas. Fibre to the home (FTTH) has been widely recognized as a future proof solution for access networks due to its capability to meet the increasing bandwidth demand of the end users. On the other hand, the deployment of FTTH networks is very costly and an accurate estimation of the investment cost is is of high importance. Several models have been developed to estimate the deployment cost of FTTH network, e.g. a number of geometric models [1]. The geometric models design the fiber infrastructure based on a set of parameters describing the considered area, e.g. average values for population density, distance between end users and central office (CO), and give an input for cost estimation based on the designed infrastructure. However, these models suffer from the inaccuracy problem in particular when applied to the area with uneven population of users since they consider only the average values. Because the residential areas are typically not very event populated and the fibre trenching is constrained by various local conditions, e.g. parks, railways or highways, the accuracy of the geometrical models is questionable.

To address this problem, we propose a geographic approach based on the real and detailed geospatial data to design the FTTH outside plant infrastructure in order to accurately estimate the deployment cost. A case study is carried out and it is shown that there is a significant difference between the results obtained by our approach and the geometric models. In this way we are able to quantify the inaccuracy of caused by the geometric models.

Review of the geometric models

Geometric models make an abstraction of the installation region and parameters and have an algorithmic or mathematical approach for calculating the trenching and fibre length. Typically the abstraction assumes a uniform subscriber population density and recursive area structure. In practice, the areas where FTTH networks are deployed are not evenly populated which is a reason why the geometric models cannot contribute to the accurate estimation of the deployment cost. In this paper we take two geometric models as examples to compare with our proposed geographic model.

Triangle Model (TM): This model is a polygon-based model for the access network [5]. Fig. 14 illustrates the model showing polygonal structure surrounding the hub and representing the distribution area. The dispatching boxes FP1 (boxes B, C and D) and distribution cabinets FP2 (points F) are symmetrically located at the gravity centres of the elementary triangles.

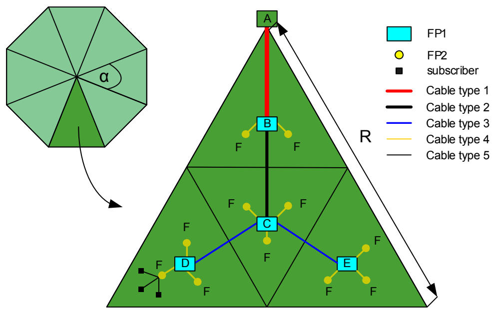


Fig. 14 The Triangle Model (TM)

Length of the cables considered in TM model is calculated using the following formulas:

$$|\overline{AB}| = |\overline{BC}| = (R/3)\cdot\cos(\alpha/2) \tag{1}$$

$$|\overline{CD}| = |\overline{CE}| = (R/6)\cdot\sqrt{1+8\cdot\sin^2(\alpha/2)} \tag{2}$$

$$|\overline{DF}| = R\cdot(0{,}132 + 0{,}336/n) \tag{3}$$

where n denotes the number of fibre cables leaving the hub. The average distance b between the branching box F and building entrance gives the formula:

$$b = \frac{2}{3}\cdot\sqrt{M/\pi d} \tag{4}$$

where M denotes the number of potential users per branching box while d is the number of potential users per km2. The total trenching length and fibre length can be obtained by summing up these for all triangles.

Simplified street length model (SSL): In this model, the potential customer base is uniformly distributed over a squared area (see figure 15). One side of the square contains n houses and the distance between two houses is indicated by l. The CO is always situated in the middle of the square. Equations 5 and 6 express length and fibre length respectively.

The simplified street length analytical model is constructed from highly symmetric graphical models over a uniformly distributed potential customer base. The potential customer base is uniformly distributed over a squared area (see Figure 15). One side of the square contains n houses and the square contains a total of n^2 houses. The distance between two houses is indicated by l. When considering only the connection points of the houses, the longest distance horizontally or vertically between the two most distant houses is $(n\text{-}1)\cdot l$. When considering a house to have a square perimeter separating this from the neighbouring houses and the graphical model to continue beyond the selected square, the longest distance horizontally or vertically is $n\cdot l$. The surface of the square is at most $n^2\cdot l^2$. The central office (CO) is always situated in the middle of the square.

$$l = n \cdot (n-1) \cdot l + (n-1) \cdot l = (n^2 - 1) \cdot l \tag{5}$$

$$F = 4 \cdot l \cdot \sum_{i=1}^{n-1} \left[\min(i, n-i) \cdot (n-i) \right] \tag{6}$$

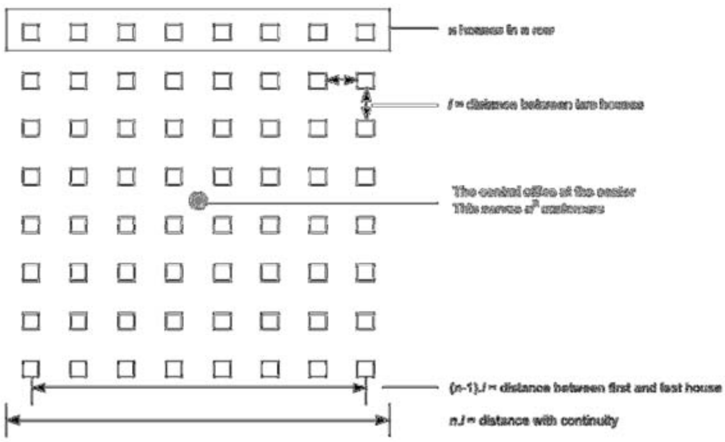


Figure 15: Simplified street length model

<u>Geographic model</u>

It is proposed here to use the real and detailed geospatial data instead of geometric models defined by some average and aggregated parameters.

If a realistic network deployment cost estimation for a given network architecture and technology is in focus, the geographic model has an obvious advantage since the absolute cost value can be calculated by summing up cost of components included in the obtained network topology design.

In order to handle the uncertainties and uneven character of the parameters describing the considered service area, the network deployment cost calculation is based on geographic information including digital map of the service area, infrastructural data, location and demand of the subscribers.

A network topology is then designed based on all the necessary details, i.e. the list of cabling work, network equipment and fibre/cable needed, as well as a complete system design, the location of distribution units (DU), the subscriber-DU assignments and network connections.

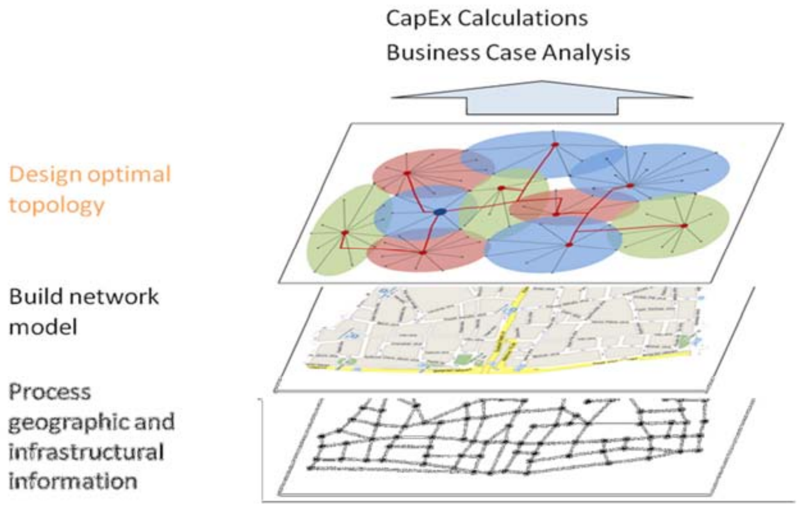


Figure 16: FTTx Designer framework

Our FTTx Designer framework [2] (figure 16) takes the above mentioned parameters into account in order to design accurate access network topology. The topology design process itself is a highly complex mathematical problem that needs formal modeling and properly developed and adapted approximation heuristic techniques. It exceeds the scope of this paper, and paper [2] gives a deep insight of its construction and performance evaluation. This work extends the framework in [2] with an ability to make a realistic cost estimation for a FTTH deployment

Table 4. Properties of the Budapest scenario

Households	Buildings	Area
4239 (902 / km^2)	1079 (230 / km^2)	4,7 km^2

<u>Case study</u>

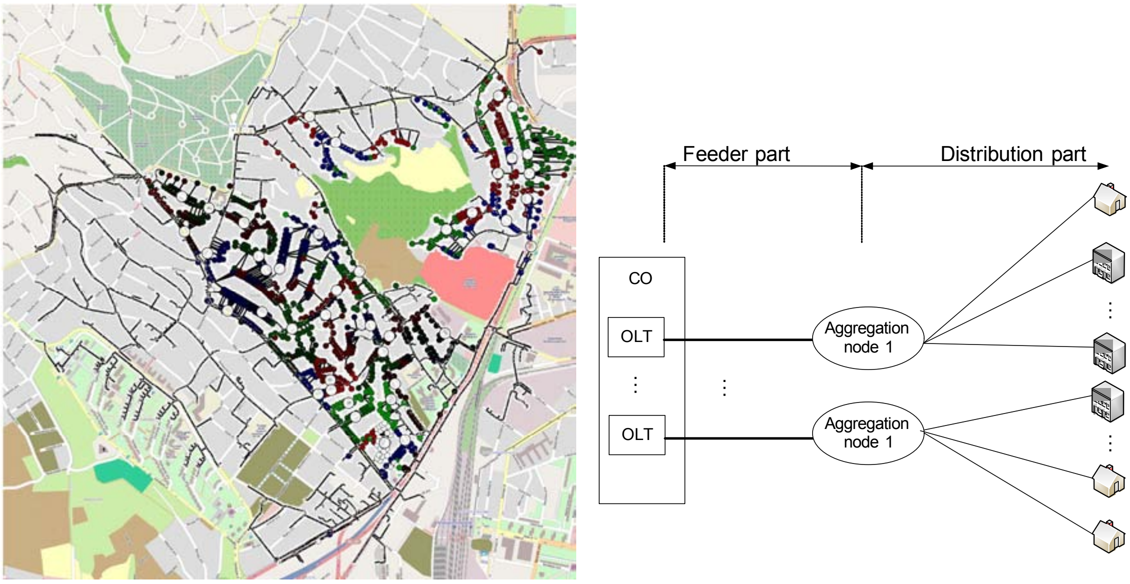
A case study is presented here in order to show a comparison between the considered models.

Scenario description

The complete service area of a CO was chosen as an example, located in Budapest, Hungary. Its uneven population density and irregular street system make it appropriate to show inaccuracy of geometric models and demonstrate the advantage of our approach.

The results are representative in a sense that the chosen scenario is built on real-life data obtained from our industrial partner. Parameters are given in table 4 and the map is shown in figure 16a.

FTTH architecture



(a) *(b)*

Fig. 16 Map of the Budapest scenario and FTTH Architecture

The considered FTTH architecture has been presented in figure 16b. The model consists of CO where all the optical line terminals (OLT) are located, the feeder part of network connecting the OLT with aggregation nodes AG1 (splitting points), and the distribution part from AG1 to the end-users.

Results

The deployment cost estimation based on the topology design obtained by the considered geometric models is compared with the one based on geographic and topology information (table 5).

Table 5. Summary of results

	TM	SSL	GM
# splitters	68	68	73
Feeder trenching	21,7	18,1	14,3
Feeder fiber	56,1	75	204
Distribution trenching	246	69	66
Distribution fiber	966	588	1060

The results immediately show limitations of the various models. The triangle model is not capable of taking the parallel connections along the same street into account, therefore the calculated trenching especially for the distribution segment is useless. On the other hand, this model approximates the distribution fiber usage well, which is probably the most important measure.

In comparison, the SSL model incorporates parallelism that makes sense regarding the calculated trenching requirements, both for feeder and distribution part.

The amount of splitters is determined by a simple division at the geometric models, that gives a proper approximation for PON networks.

Conclusions

The results of this case study indicate how for a representative case study the geometric models do not incorporate the specifics of the area. In comparison with the geographic model, clearly, the uneven population distribution and irregular topology leads to important inaccuracy of the trenching and fibre length estimation.

On the other hand, geographic models consume much more calculation resources, and might be prohibitive in large or recursively refining calculations (e.g. geomarketing), even though our initial results have shown that the methodology is capable of handling services areas of 1000s of subscribers also. Moreover, the necessary input data is hard to obtain which is also a practical difficulty.

As such future research should try to advance on both fields, increasing the reliability of the geometric models by incorporating the most important geographic parameters and increasing speed of the geographic models by relating them to the geometric interpolations.

Techno-economic comparison of current and next generation long-reach optical access networks

A complete study has been performed in terms of capital expenditures (CAPEX) for three long reach optical access architectures. Those are namely metro ring & Gigabit Passive Optical Network (GPON) in the access, metro ring & Ethernet Point to Point (EP2P) in the access and a converged access-metro architecture based on the combination of Wavelength Division Multiplexing (WDM) and Time Division Multiplexing (TDM), called Scalable Advanced Ring-based passive Dense Access Network Architecture (SARDANA). The results show that CAPEX/user range depending on the technology used and that a decrease in the range of 20% can be achieved between EP2P & GPON as well as between GPON and SARDANA. The results may be used as design/cost guidelines for operators, municipalities and policy makers.

Results

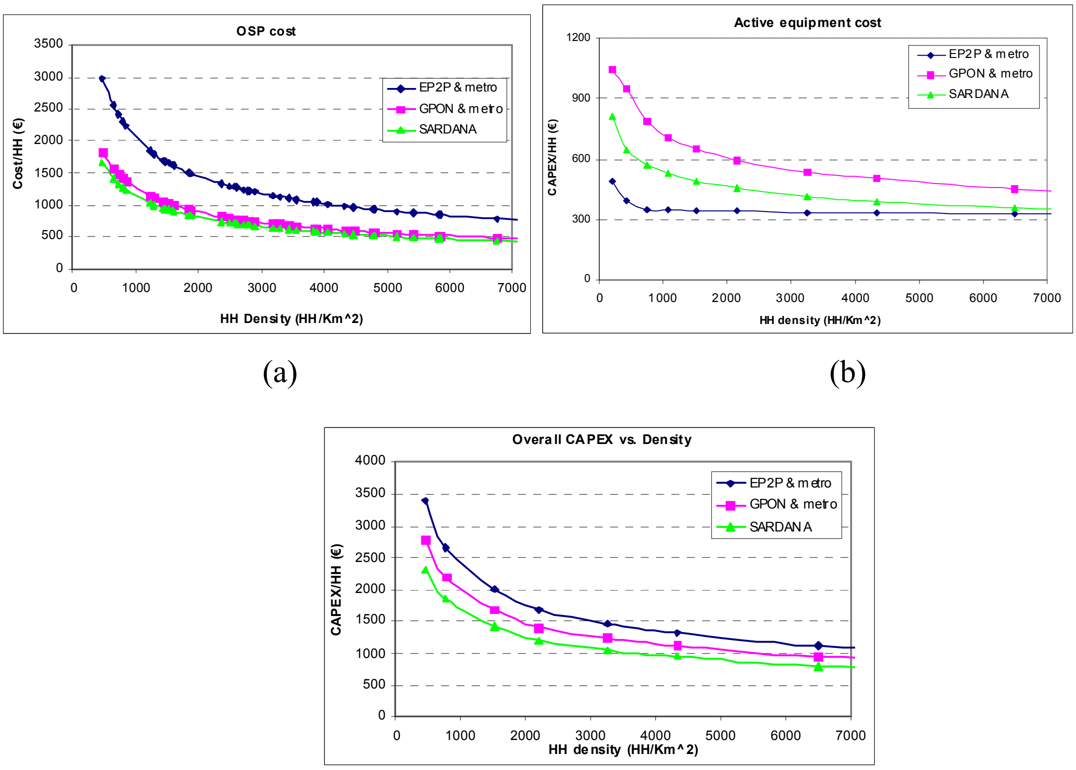
Three metro-access network architectures were examined namely metro ring & EP2P, metro ring & GPON and a metro access rind WDM/TDM PON.

The target was to deliver a symmetrical bit rate of 150 Mb/s per user. In all three cases we considered a 100% take up rate. For the first case in this study the fast Ethernet standard was taken into account. For the second case the ITU-T standard G.984 (Type A) with a splitting ratio of 1:16 was considered. This splitting ratio was chosen for we wanted to achieve a comparable bit rate in all three networks' users. The tree-ring PON was based on the Scalable Advanced Ring-based passive Dense Architecture (SARDANA). SARDANA is designed as a WDM ring for the transport of downstream and upstream information and TDM trees transmitting up to three wavelengths from corresponding operators, sharing a common infrastructure. The WDM ring is implemented by a double fibre ring. Along the ring, passive Remote Nodes (RN) implement cascadable 2-to-1 fibre optical add & drop functions. From the RNs fibers with the drop wavelengths begin, which conclude to the splitters. The central office (CO) centralizes the light generation for the whole network. A stack of lasers is used to serve the different tree network segments on a TDM basis. The optical network unit (ONU) is colourless and implemented with an integrated reflective semiconductor device for upstream remodulation, on the same fibre and on the same wavelength.

For this study an urban deployment scenario was examined therefore 32 λs were considered, 1:64 splitting ratio. The number of end users was therefore 2048 per ring.

For the calculations we have used a potential deployment area with a diversity in HH density varying from dense rural to dense urban. The number of buildings, namely multi-dwelling units (MDU) and single dwelling units (SDU), as well as the number of HH units are estimated. For the calculations of OSP CAPEX the mean distance among buildings was calculated which depends on the HH/buildings density. Every three buildings a Y-branch is being used to separate the individual drop cables from the distribution ones. The splitters of GPON and SARDANA, the RNs as well as the splicing closures of EP2P are placed inside handholes/manholes every several buildings. These are the points where we have the transition from feeder to distribution fibers. The feeder fibers are launched from the OLTs in the COs that are placed in the Points of Presence (POPs). The CO is placed in the POP of the network which consists of a building that houses all active transmission equipment and in the case of EP2P the routers required. In the POP all fibre terminations are managed and the interconnection between the optical fibres and the active equipment is facilitated. For the cases of GPON and SARDANA we consider that each CO will serve up to 100.000 users, while for the case of EP2P this number is appointed to 20.000 due to fiber handling constraints at the CO. For the calculation of CAPEX per user and as far as the OSP is concerned we consider the total length of the different types of trenches, ducts, subduscts and fibre cables, the total number of hand-holes/manholes, splice closure boxes, splitters (for GPON and SARDANA) and y-branches needed, their total cost and the cost of their installation. As far as the active equipment is concerned, the overall cost includes the cost of the Optical Network Units (ONUs) and their parts (for GPON and SARDANA) and the cost of the Customer Premises Equipment (CPE) (for the EP2P case). Furthermore the cost of the OLTs and their individual parts and for the case of EP2P, the cost of the total number of switches as well as of the routers needed. A different maximum reach is considered in each case, based on the networks' standardization. The spot where the manholes are placed derives from this limit, as well as the length of each cable needed in each case.

The cost for the OSP and the active equipment is estimated for each of the three architectures and the results are shown in Fig.17 a) and b). The overall cost comparison is shown in Fig.17 c).



(c)

Fig. 17: *a) OSP equipment CAPEX/user vs. HH density, b) Active equipment CAPEX/user vs. HH density c) Overall CAPEX/user vs. HH density*

The results show diversity in costs depending on the HH density and the technology chosen. A solution focused on a long reach WDM/TDM PON can be adjusted to the needs of each area and each household density and is the most cost effective.

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4.3. Joint Activity - Secure OCDMA-based PONs

Members

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

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.

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

Electronic processed CDMA for PONs

Collaborations/Joint Experiments and Mobility Actions

UNIROMA3 and NICT had technical discussions during the conferences ICTON 2010, ECOC2010 and OFC2010.

- **Valentina Sacchieri, PhD student at UniRoma3, hosted by IT from 21/01/2008 to 31/07/2008**

Security in OCDMA based network. The research during the mobility period has been focused on the emerging topic of optical data security. Optical networks are addressed as the solution for the ever increasing bandwidth demand from private users and enterprises, and physical layer security is a key request from vendors and network operators, to avoid information theft from unauthorized users.

Optical code division multiplex access (OCDMA) is considered an access technique with an intrinsic high level of confidentiality, since signals are encoded at the transmitter side and can be received only using the same code. However the system security presents some vulnerabilities, that have been pointed out in recent studies, and this mobility has been focused on researching new systems that can provide larger data protection in OCDMA networks. A possible solution is to introduce in the optical domain the code scrambling, that has been borrowed from the electronic data criptography. A scrambled signal is fully distorted and the corresponding eye diagram is closed, so that an eavesdropper cannot decipher encrypted data with standard or differential power detection. The technique increases the number of degrees of freedom and therefore the overall system confidentiality is enhanced. Numerical simulations have been performed, considering a chain of two or more optical encoders. In this way, two consecutive encoded bits overlap, and it is impossible for an adversary to determine the code length.

To break the system security, an eavesdropper should test all the possible combinations between all the possible sequences. Furthermore, the technique is simple to implement, by using only off-shelf devices, and it is also compatible with other existing technologies.
To test the performance of the system, BER calculations have been performed, showing a large difference between the matched and unmatched signals; in the last case, BER varies in the range of 10-2 to 10-1, for any transmitted power. Therefore, the eavesdropper is not able to detect the transmitted data, that are correctly received by the intended user.

Publications:
• V. Sacchieri, P. Teixeira, A. Teixeira, G. Cincotti "Secure OCDMA transmission using data pattern scrambling" in Proc. of the International Conference on Transparent Optical Networks (ICTON 2008), Athens, Greece, 22-26 June 2008.
• V. Sacchieri, P. Teixeira, A. Teixeira, G. Cincotti "A novel scrambling technique using OCDMA encoders" in Proc. of the VI Symposium on Enabling Optical Networks (SEON 2008), Porto, Portugal, 20 June 2008.

- **Miguel Pimenta, PhD Researcher at UCL, hosted by IT from 18/10/2008 to 17/11/2008**

Mitigation of Group Velocity Dispersion in Optical CDMA using Electronics - The experimental work carried out in Instituto das Telecomunicacoes, Aveiro demonstrates for the first time electronic GVD compensation in multi-wavelength CDMA. Results show good agreement with theoretical models. Improvements in auto-correlation intensity peak to the maximum cross-correlation level ratio (P/C ratio) exceeding 50% were achieved. These results have been submitted to D13.1

- **Izzat Darwazeh, Professor at UCL, hosted by IT from 22/10/2008 to 25/10/2008**

Optical CDMA A visit took place to IT Aveiro where my PhD student, Miguel Pimenta, was running experiments on OCDMA systems. During the visit, I checked the experimental set up and defined the required measurements. Further,I met with Professors Antonio Texeira and Paulo Monteiro to discuss project progress and future collaboration.

Publications

2010

- Sim Heung Lee, Adrian Wonfor, Richard Penty, Ian White, Giacinto Busico, Rosie Cush, Michael J. Wale, “Athermal Colourless C-band Optical Transmitter for Passive Optical Networks”, European Conference on Optical Communication , ECOC, 2010, Torino, paper Mo.1.B.2.
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Research Contributions

CTTC and UNIROMA3 investigated the suitability of using real trigonometric transforms based processing for access networks [1].

CTTC and UNIROMA3 also investigated the use of OFDM schemes in PON networks [2, 3]. Specifically, an optical OFDM system based on Hartley transform has been studied and designed to reduce the cost and the complexity of the OFDM transceivers. The direct detection (DD) system scheme is depicted in Fig. 18.

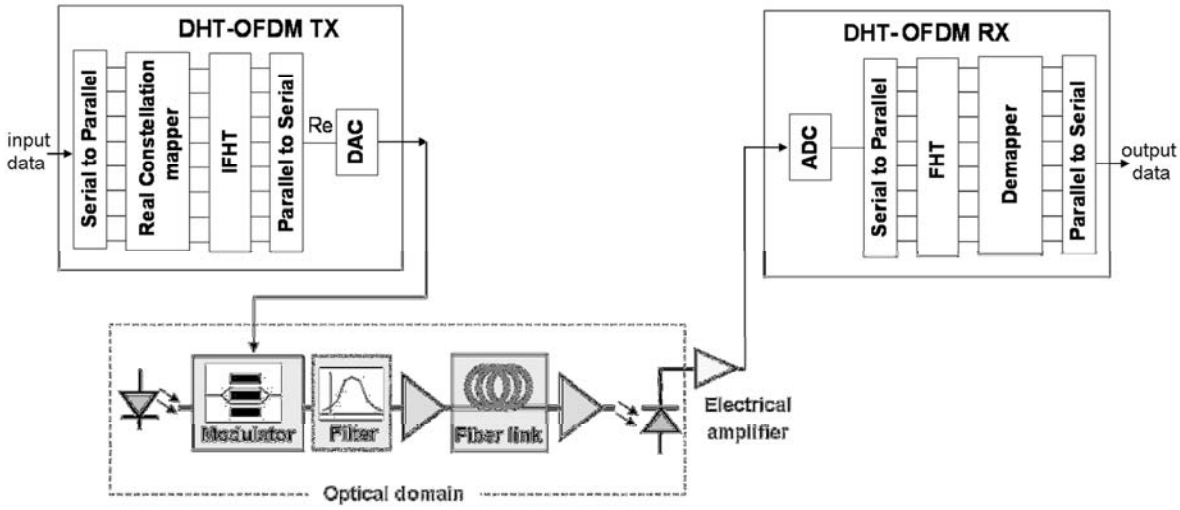

Figure 18. Optical DHT-based OFDM system. The OFDM-modulation and demodulation are performed in the electrical domain by using an N-order inverse FHT and forward FHT, respectively. The optical detection is direct. The components in grey are in the optical domain.

The electrical transmitter and receiver use the fast Hartley transform (FHT) processing for the OFDM modulation and demodulation. Real OFDM signals are simply obtained if the transmitted bit sequence is mapped into a real constellation. Thus, only one single digital-to-analog converter (DAC) and one single analog-to-digital converter (ADC) are required, as in discrete multitone modulation (DMT) systems. DMT is a multi-carrier transmission technique considered a cost-effective OFDM scheme. In fact, the OFDM signals are real-valued and no I/Q modulation at radio frequency (RF) is needed, resulting in an electronic design with reduced complexity. If FFT is used, real-valued OFDM signals are obtained at the expenses of the spectral efficiency, since the input constellation symbols are forced to have Hermitian symmetry. Thanks to the FHT real processing, in the proposed OFDM system, the Hermitian symmetry constrain is not required and the double of input data symbols are supported. Moreover, FHT processing has low computational complexity and the transform is self-inverse, which allows applying the same FHT routine at the transmitter and receiver.

The optical system is very simple: one single Mach-Zehnder modulator is required for transmitting the signal that can be easily recovered by using DD. A simple photodetector is used, which can be modeled as an Avalanche Photo-Detector (APD) standard GPON compliant (0.7 A/W responsivity, multiplication factor of 7, and overall thermal noise value of $10x10^{-12}$ A/sqrt(Hz)), with extended bandwidth. The photocurrent is given by the OFDM signal term and unwanted mixing products, which can be minimized by inserting a guard band between the OFDM signal and the optical carrier. Single-side band (SSB) modulation can be adopted to ensure that the OFDM subcarriers are represented only once by the optical frequencies. If this solution is considered, an optical filter is required to transmit in the fiber channel only one side of the optical spectrum, which is symmetric with respect to the optical carrier. To reduce the ASE noise, another optical filter with narrow band can be added before the photoreceiver.

Due to the simple and efficient scheme in terms of computational complexity and power consumption, the FHT-based optical OFDM architecture that CTTC has proposed results suitable for PON networks. In order to test the system for PON applications, the VPI simulated set-up has been adapted to be XG-PON compliant, according to the preliminary version of the standard.

UNIROMA3 and NICT have investigated the confidentiality of OCDMA systems based on block ciphering and have demonstrated a secure P2P 2.5 Gbit/s, 50 km-fiber transmission based on 16-ary OCDMA with on-line XOR and true clock data recovery (CDR) [4]. A block-ciphering scheme is more secure than standard bit-ciphering one, since it presents two layers of confidentiality: physical security, because an adversary should be able to correctly detect the optical code (OC), and computational security, since he or she does not know which sequence of bits corresponds to a given OC. In addition, the on-line XOR implements the cipher block chaining (CBC) mode, where the optical code depends not only on the bit sequence, but on all the bits of the message processed up to that point. Therefore, the proposed scheme presents a very high level of confidentiality because an adversary cannot even detect data patterns in the message.

To further increase the system secuirty, it would be necessary to increase the M-ary number and, therefore, the number of OCs. To overcome this limitation, UNIROMA3 and NICT have implemented a novel POL-MUX M-ary OCDM system that reduces the number of codes needed. A POL-MUX 2.5 Gbps, 32 (= 16 + 16)-ary OCDM transmission has been demonstrated, using 16 OCs generated by a multiport encoder/decoder (E/D) [5].

WDM-PON is considered by most carriers and service providers as the natural evolution of existing FTTH system, that helps in improving the three main performance metrics: bandwidth, split ratio and reach. However, based on experimental results using field-installed fiber, we have demonstrated that OCDMA is a valid alternative for next generation access networks (NGAN), that can outperform WDM-based systems with respect to data confidentiality, bandwidth efficiency and simplifies the migration from existing PONs. UNIROMA3 and NICT made an accurate comparison between these two technologies, evidencing their capabilities but also their limits, as well as the difficulties of their integration with current FTTH systems, as shown in the following table [6, 7].

Table 6: Comparison between WDM- and OCDMA-based NGAN

	WDM-based PON	***OCDMA-based PON***
contentionless access (unshared bandwidth)	*yes*	*yes*
ONU types	*different, expensive (possible sourceless, colourless)*	*different, low-cost (possible sourceless, colourless)*
migration from existing FTTH systems	*difficult for wavelengths 1310, 1490, 1550-1560 nm already in use*	*easy*
data confidentiality	*no*	*yes*
spectral efficiency	*about 0.1 bit/s/Hz*	*about 0.4 bit/s/Hz*
inline dispersion compensation	*yes*	*no*
further upgrade	*difficult*	*easy (CDM-WDM-based PON)*

UNIROMA3 and NICT have also demonstrated an inline-dispersion-compensation-free long-reach OCDMA-based PON based on the bandwidth optimization of OCs spectrum: 10Gb/s, 4-user, OCDMA transmission over 59 km fiber link has been experimentally demonstrated [8, 9, 10, 11]. Figure 19 show the experimental setup of down- and up-link transmission, respectively. Two multiport E/Ds are used at the OLT and at the remote node (RN) to generate/process four different 16-chip (200 Gchip/s), 16-level-phase-shifted OCs. These experiments demonstrate confirm that OCDMA is a reliable technique for next generation PON systems, with a high level of confidentiality.

Electronic processed CDMA for PONs

In the first part of the WP, we have worked in high speed low-cost ECDM Labels for Optical Label Switching. A code-label recognition time of less than 500ps using low-cost FIR-filters is demonstrated. The electronically-processed label provides a control signal from an auto-correlated label. Error-free electronic code-label switching of an optical 10Gb/s signal is demonstrated.

The label recognition speed in label switched networks is one of the key parameters used to determine the latency in the network. In recent years, much work has been carried out to investigate the use of optical codes for ultra fast label recognition. Fast recognition is typically achieved using a matched filtering process where a code division multiplexed (CDM) label is correlated in a bank of correlators or using a single device which is capable of recognizing several codes simultaneously. The fast label recognition and parallel processing of large number of labels using codes can benefit label switched networks reducing part of the bottleneck, where electronic memory access can be in the scale of several ns. It has been reported that optical code label recognition can result in recognition times as fast as 35 ps, the fastest label recognition time reported to date to our knowledge. Here the labels were implemented using a dedicated optical device to process a 7-chip code using 5 ps pulses. However, the requirement for short pulses, dedicated encoders, several mode-locked lasers and nonlinear thresholders results in a complex design, high cost and high power consumption, rendering this solution unsuitable for commercial applications.

Since the recognition time is basically the transit time of the code label through the matched filter, equivalent results to the previously reported code label processing can be obtained but using recently available flexible and low cost electronic signal processing techniques. Electronic CDM (ECDM) at 18 Gchip/s processing rates is implemented using electronic

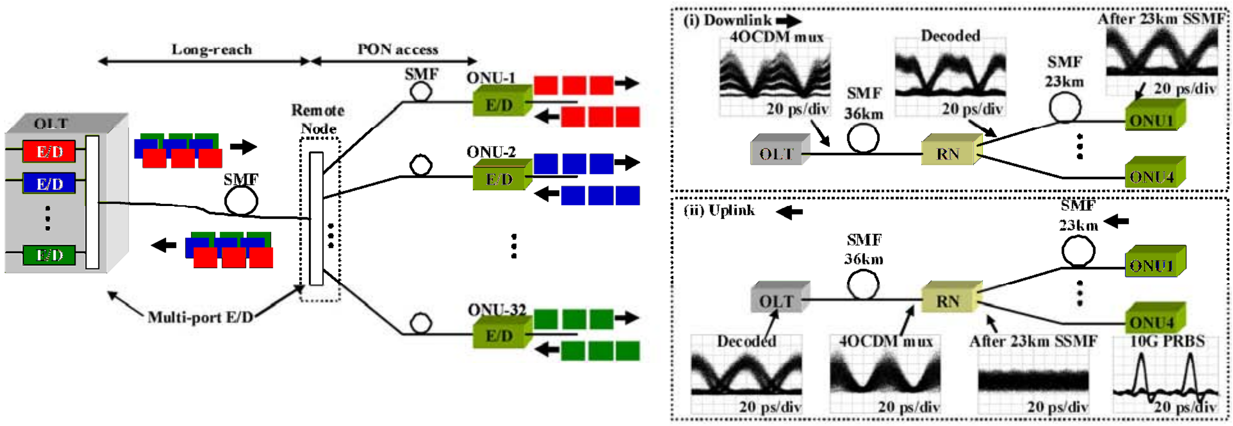

Figure 19. Configuration of the long-reach OCDMA-PON system and experimental setups and results: (i) downlink and (b) uplink.

finite impulse response FIR filters. Since each electronic filter tap has a separation of 55 ps, and used Hadamard codes with Nc=8 chips length, the total label recognition time is about 440 ps. This fast label recognition time, offering comparable recognition times to photonic approaches, is implemented using low cost, low power consumption and flexible FIR filters.

The experimental setup for the optical label forwarding using ECDM label recognition is shown in Fig. 20. A 40 Gb/s pulse pattern generator (PPG) generates a 25 ps pulse that is input into a transversal FIR filter to generate the Hadamard codes at 622 Mb/s rate, the filters being provided by Avago Technologies. Simultaneously a 10 Gb/s PPG generates 10 Gb/s packets of length 204.8 ns with gaps of 256 ns between them. In a real system, the code labels can all be stacked on the same wavelength as the data packets. However, due to experimental convenience here the packets and the labels are modulated on different wavelengths. The codes and the data packets codes are modulated onto 1550 and 1555nm wavelength respectively using LiNbO3 Mach-Zehnder modulators (MZMs).

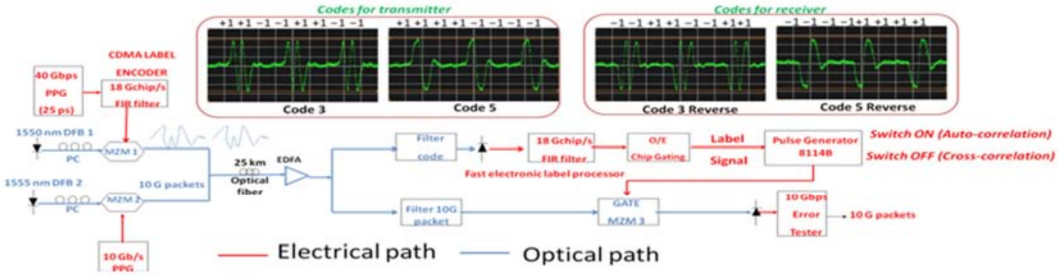

Fig. 20 (a) Experimental setup for the 18 Gchip/s ECDMA label recognition system and optical label forwarding. The codes used are shown (time axis 200 ps/div).

The packets and the code labels are combined using a 2 × 2 optical coupler and then transmitted over 25 km of single mode fiber (SMF). In the forwarding node, a second 2 × 2 optical coupler along and optical bandpass filters are used to separate the ECDM labels from the data. A second FIR filter is set for label recognition by performing autocorrelation or cross-correlation on the received labels. The correlations are gated using a 25ps window time gating opto-electronic subsystem to distinguish the one chip-length correlation peaks. The gated signal is used as a trigger for the packet control signal generator. When the autocorrelation is present, it externally triggers a pulse generator (Agilent 8114B), which generates a 220ns pulse, delayed appropriately, which drives a MZM control gate. Fig. 20 also shows the codes from the Hadamard family set which are implemented using electronic transversal filters, in which the tap weights can be electronically set to +1 or −1 and have a 55 ps tap spacing. The codes used are Code 3 (+1 +1 −1 −1 +1 +1 −1 −1) , Code 5 (+1 +1 +1 +1 −1 −1 −1 −1), Code 3 Reverse (−1 −1 +1 +1 −1 −1 +1+1) and Code 5 Reverse (−1 −1 −1 −1+1 +1 +1 +1). As described in previous papers, codes in reverse order are need at the receiver to perform autocorrelation.

Fig. 21(a) shows the 10 Gb/s packet and the code label after being transmitted together through 25 km of SMF. The 10 Gb/s packet is separated from the label using optical filtering (Fig. 21(b)). The optical code label is also optically filtered and input to a second transversal filter where code auto- and cross-correlations are obtained (Fig. 21(c)). Fig. 21 (d) shows the electrical cross-correlation and auto-correlation signals after gating with a 25 ps window. Although the auto-correlation and cross-correlation peaks are very different, crosstalk occurs from the cross-correlation signal due to size of the window. The trigger level of the waveform generator is set at a level between the peaks of auto and cross-correlation. This difference is sufficient to have a decision point where the auto-correlation signal triggers the waveform generator and allows the optical 10 Gb/s signal (Fig 21(e)) to be transmitted and received. The bit error rate (BER) tester is gated with the pulse of the waveform generator to measure the BER. The gated signals switching are error free (Fig. 21(f)). Conversely, when the electronic FIR filter is set for cross-correlation, it does not trigger the waveform generator and so the packets are not passed through the gate MZM.

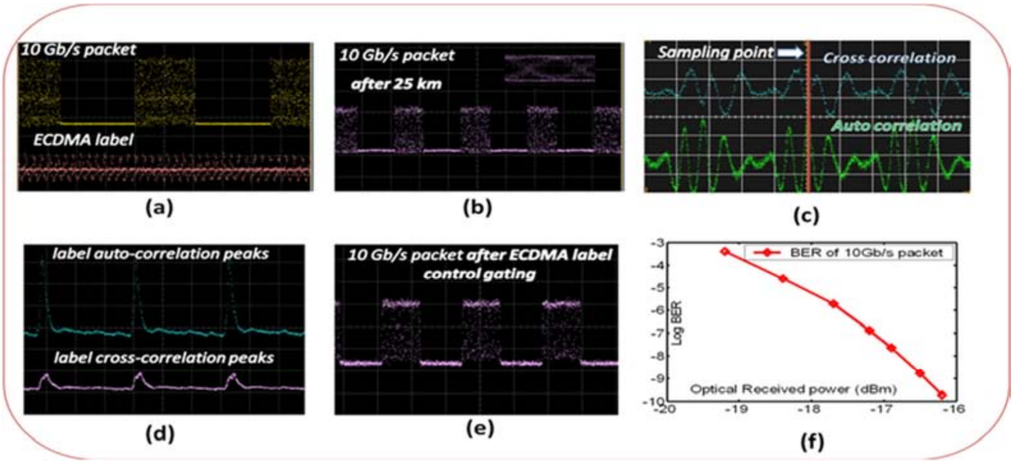

Fig. 21 (a) 10 Gb/s packet and code label after 25 km of SMF (b) 10 Gb/s packets after separation from the label (c) Electrical cross-correlation signal (upper trace) and electrical autocorrelation signal (lower trace) (d) electrical control signal after time gating for the auto-correlated (upper trace) and the cross-correlated label (lower trace). (e) 10 Gb/s packet after ECDM label control gating (f) BER measurement of the forwarded signal Time axis for (a), (b) and (e) 200 ns/div; (c) and (d) 200 ps/div

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4.4. Joint Activity – QoS in PONs

Members

- Fondazione Ugo Bordoni (FUB)
- Istituto Superiore delle Comunicazioni e Tecnologie dell'Informazione (ISCTI)
- Telecom Bretagne (GET)
- University of Modena and Reggio Emilia

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 JA5 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)
- QoS measurements on PON

Research Topics

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

In 2010 the main research topics that will be detailed, illustrated in 1.6 have regarded:

- QoS measurements in PON networks and role of the operative systems in the bandwidth exploitation.
- QoS management in wireless systems connected to PON networks
- QoS Experiments on WDM PON networks

Collaborations/Joint Experiments and Mobility Actions

- **Kivilcim Yuksel, Research Assistant at FPMs, hosted by UC3M from 26/07/2010 to 31/07/2010**

Novel approaches for monitoring drop fibres in TDM-PON and WDM-PON systems. New techniques for individual fibre-attenuation, fault detection and simultaneous remote temperature measurements in PONs were comparatively analyzed. These monitoring systems are based on remote reflective filters and radio-frequency techniques. Fibre Bragg Gratings (FBG) or interferometers can be installed in a demarcation point (DP) and make it possible to simultaneously measure the temperature, thus detecting harmful environmental conditions for the OSP such as freezing or burning of a single FTTx user DP. Temperature measurement functionality which is inherent to the monitoring system at FPMs has been added into experimental set-up at UC3M.

Preliminary measurements realized by means of an optical spectrum analyser demonstrated an easy and efficient applicability of the concept.

Joint Publications:

2010

- M. Giuntini (FUB), J. Morabito (FUB), A. Valenti (FUB), F. Matera (FUB), V. Carrozzo (ISCOM), S. Di Bartolo (ISCOM), *Integration Of Optical Telecommunications and Radio Access Networks to Assure Quality of Service*, IEEE ICTON 2010 Conference, June 2010

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- 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
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- F. Di Vincenzo (UniRoma3), G. Cincotti (UniRoma3), G. M. Tosi Beleffi (ISCOM), D. M. Forin (ISCOM), F. Curti (ISCOM), A. Teixeira (IT), *Remote inline all optical signalling and monitoring in passive optical network scenarios by means of erbium doped fiber amplifier pump modulation*, Conference on Laser and Electrooptics (CLEO) and Quantum Electronics and Laser Science Conference (QELS) , San Jose, California, May 2008
- J. Chen (KTH), L. Wosinska (KTH), M. Kantor (AGH), L. Thylén (KTH), *Comparison of Hybrid Passive Optical Networks with Protection*, ECOC2008, Brussels, September 2008.

Research Contributions

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

QoS tests in PON: dependence of the operative system

Fiber To The x (FTTx) accesses allow users to have at disposal huger and huger bandwidth, even though it has to be well understood if they will be able to exploit such a huge bandwidth in their broadband devices (PC, USB TV,...). This is particularly important especially if we look at large investments that are required to install optical fibers up to the buildings, and therefore we have to avoid all the intrinsic limitations that users can experience in the use of fiber accesses. One of the limitations in the exploitation of the access bandwidth is given by Operating Systems (OS) located in the broadband devices. In particular, an issue to be addressed regards on how much layer 2 bandwidth can be really exploited from upper OSI Layers.

This topic has been already investigated in [1], and in [2] a detailed experimental investigation was shown for accesses based on xDSL, illustrating strong differences in terms of bandwidth exploitation for different OSs (Microsoft Windows XP, Microsoft Windows 7, Linux); moreover, results showed how such differences were stronger at higher bit-rates. Therefore, we foresee that such differences will be wider and wider using optical accesses in FTTx networks.

In this contribution we report an experimental investigation about the role of OSs on Quality of Service (QoS) for Gigabit Passive Optical Network (GPON) [3], i.e. the fiber access technology preferred by many operators. The QoS is analyzed in terms of throughput and then we adopted the method proposed by ETSI in [4].

We consider a specific QoS evaluation technique, based on the ETSI EG 202 057 , using File Transfer Protocol (FTP) [5] probes. In such assumption, the Transmission Control Protocol (TCP) [6] plays a key role in evaluating performance, since it directly regulates the flow of data. The choice of a TCP dependent technique tries to keep QoS evaluation as closer as possible to the end-user effective experience of broadband access services.

Many papers investigate TCP performance and specific implementation behavior focusing in specific network applications, considering for example mobile or satellite environments, (e.g., [7, 8]). On the other hand, in [1] the authors measure the performances of TCP stacks in lossy and congested networks. In this work, we look at the evaluation of protocol performance and at the impact of software implementation, considering an immediate deployment of a QoS evaluation infrastructure and looking forward at the Next Generation Access Networks (NGAN). Our method was already used in different access network scenarios, in terms of access bandwidth and network delay. In particular, in [2, 9] we reported measurements regarding ADSL2+ that is the European most adopted technology in Telco Operators' network.

The network test bed is shown in Fig. 22: the core part is composed of four Juniper M10 routers fully meshed using the fibers deployed in the cable Roma-Pomezia-Roma (50 Km with round trip in Pomezia). Server and GPON Optical Line Termination (OLT) are connected to the core network by means of two edge routers (CISCO 1, 2) using fiber Gigabit Ethernet transmission. The routers were set up according to OSPF (Open Shortest Path First), MPLS and BGP (Border Gateway Protocol) protocols.

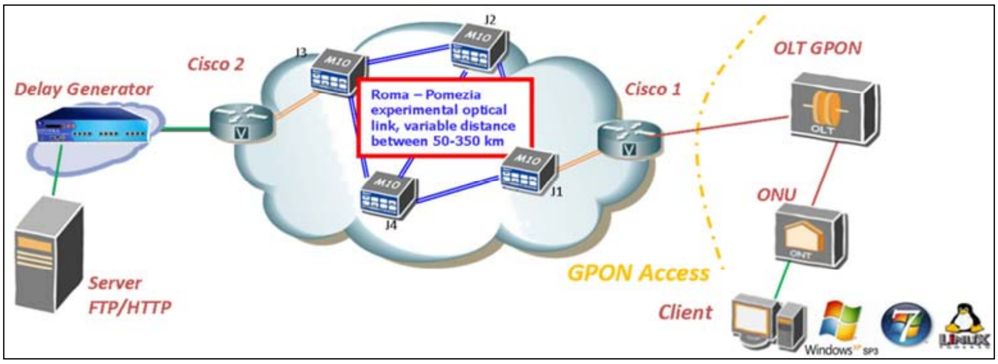


Figure 22 Test Bed Design

In this context, the only parameter taken into account is the network delay, in order to emulate a wide set of network topologies and conditions in terms of geographical extension (simplified as network delay). To achieve this goal a delay generator is used to obtain different Round Trip Times (RTTs) between Server and Client.

In such tests a FTP-based QoS estimation tool is implemented in the three most popular OSs: Windows XP SP3, Windows 7, Linux Ubuntu 9.10. The aim is to outline the impact of TCP implementation in QoS evaluation and bandwidth customer exploitation.

The FTP-based bandwidth evaluation method, as used in our testing activity, measures FTP Throughput, considering data flow between FTP Server process and FTP Client process located in different network portions, respectively provider side and customer side. FTP sessions make possible to estimate data transmission rate and the transmission delay experimented for downloading and/or uploading specified test files several times (50 repetitions) between a remote site and a user's terminal.

In Fig.23 experimental results are reported, average throughput values are represented vs. network delays. We considered two typical bandwidth profiles. In the first one we considered GPON with 128 users, that can provide a physical bandwidth of about 18 Mbit/s. In the second one, a GPON with up to 32 users was used, with a physical bandwidth of about 100 Mbit/s.

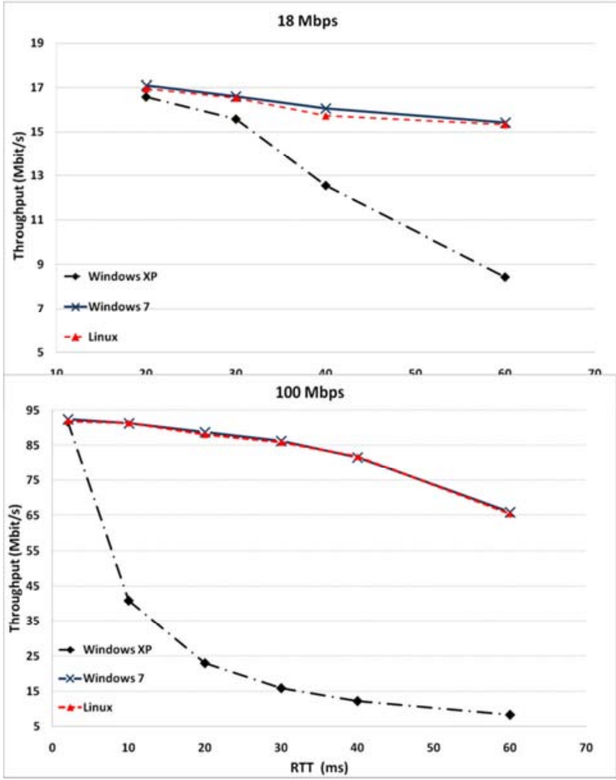


Figure 23 TCP connection Throughput evaluation.

Like other window-based protocols, such as TCP, performances depend on RTT, in particular these results point out that, for specified access conditions, OSs in client host have a considerable impact on FTP performances.

Results reported in Fig. 2 outline the critical impact of network delay and the increasing of bit-rate values considering TCP protocol implemented in MS Windows XP. In particular, we noticed a reduction of throughput, with respect to the nominal one, equal to 50 % for 18 Mbit/s profile, and equal to 90% for 100 Mbit/s profile.

Evident substantial differences between Win XP and advanced OSs (Win 7 and Linux) are due to enhanced TCP algorithm implementation, related to adaptive parameters in the algorithm (i.e. Auto-Tuning of receiver windows size).

Furthermore, it is important to remark that a performance degradation can be observed also considering advanced OSs for high values of network delay. For example, for 100 Mbit/s profile, only 65 Mbps are measured by QoS measurement test when RTT is 60 ms.

In conclusion we have reported an experimental investigation about role of operating system on the bandwidth exploited by GPON users. The results reported in this paper show that the dependence of the QoS on the operating systems and the differences due to the operating systems increase with user bit rates. In particular, we noticed a reduction of throughput, with respect to the nominal one, equal to 50 % for 18 Mbit/s profile, and equal to 90% for 100 Mbit/s profile.

Therefore, it means that users could be strongly limited in the exploitation of the bandwidth, and such limitation is much relevant in case of optical access networks that should permit very wide bandwidth. As a consequence, we believe that a testing scenario for FTTx accesses needs to be described not only according to the physical parameters, but also paying attention to software implementation factors that could affect the testing results

Integration of PON networks with broadband wireless systems (WIMAX-LTE) with assurance of QoS

The integration between broadband wireless systems and PON is one of the possibilities to cover, with broadband access techniques, areas where it is difficult, in economic and deployment terms, to install the optical fibre, e. g. in mountainous zones. In particular, we consider the BS as an Optical Network Unit (ONU) of EPON network (Fig. 3). We dedicate such a contribution to the way to manage the QoS in the wireless broadband access connected to the PONs.

WIMAX case

We start from the necessary to manage the QoS in all network's segments, that is in WiMAX network (by procedures allowed in the standard)[3], in EPON (by definition of VLANs and relative CoSs, dependently on the bases of the service carried) and in the core network (by DiffServ over MPLS technique).

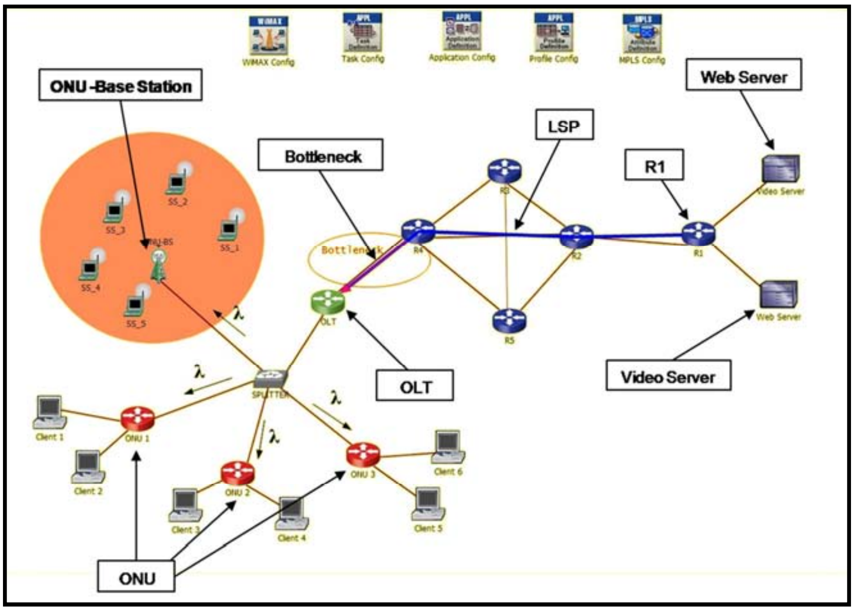


Figure 24 - BS connected to ONU EPON

Several congestion scenarios have been considered, but for sake of brevity we report only the case in which there is saturation before WiMAX network. EPON is simulated in OPNET with a multipoint access network. In this case, QoS is managed by MPLS/VLAN tagging. The congestion starts after 8 minutes and it lasts about 2 mins. Fig. 25 shows the traffic received from the WiMAX terminals. Each Web Flow carries about 5 Mbit/s, whilst the High Priority flow carries multiple Video Streams (about 33 Mbit/s). It can be seen that, when the congestion occurs, the throughput of Best Effort flows (Web Flows) experiences degradation, while the throughput of guaranteed QoS Flow (Video Stream) is not affected.

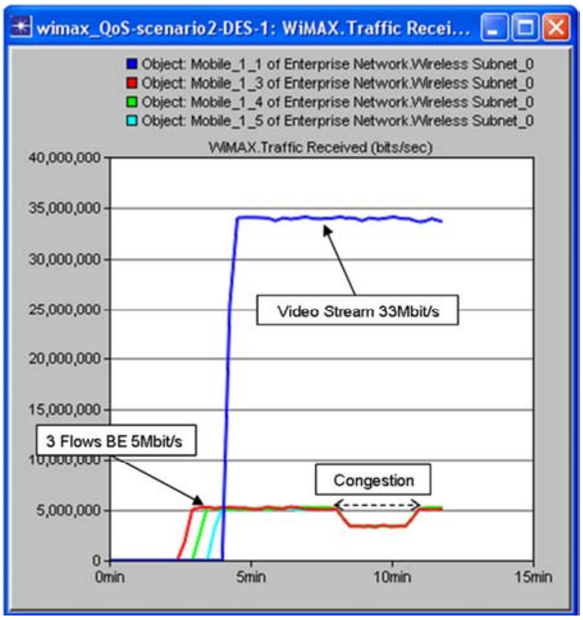


Figure 25 - Traffic received with congestion on the link before WiMAX cell

<u>LTE case</u>

Here, we consider the integration between LTE network and Ethernet PON with the architecture reported in fig. 26. LTE network parameters are set to have a max capacity of about 80 Mbit/s: bandwidth of transmission channel equal to 20MHz and MCS equal to 28. EPON is simulated in OPNET with a multipoint access network. In this case, QoS is managed by MPLS/VLAN tagging. The congestion starts after 6 minutes and it lasts about 1 mins. Fig. 27 shows the traffic received from the LTE terminals and fixed terminal. Two IP Flows to mobile terminals carry about 1 Mbit/s and two IP Flows to fixed terminals carry about 5 Mbit/s, each with CoS Bronze. While the High Priority (with CoS Gold) flow carries Video Streams (about 16 Mbit/s). It can be seen that, when the congestion occurs, the throughput of Bronze flows (Web Flows) experiences degradation, while the throughput of guaranteed QoS Flow (Gold Flow) is not affected.

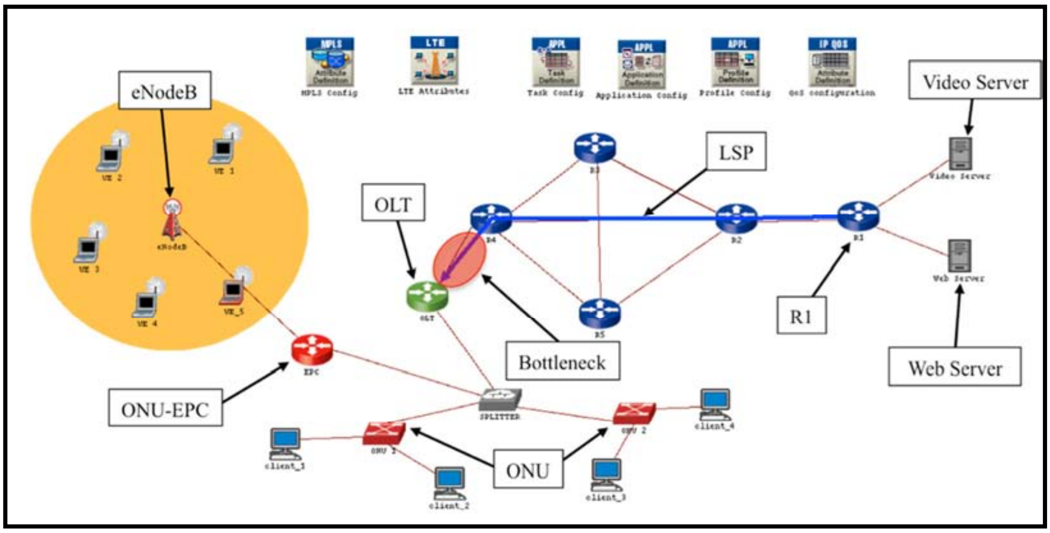


Figure 26. EPC connected to ONU EPON

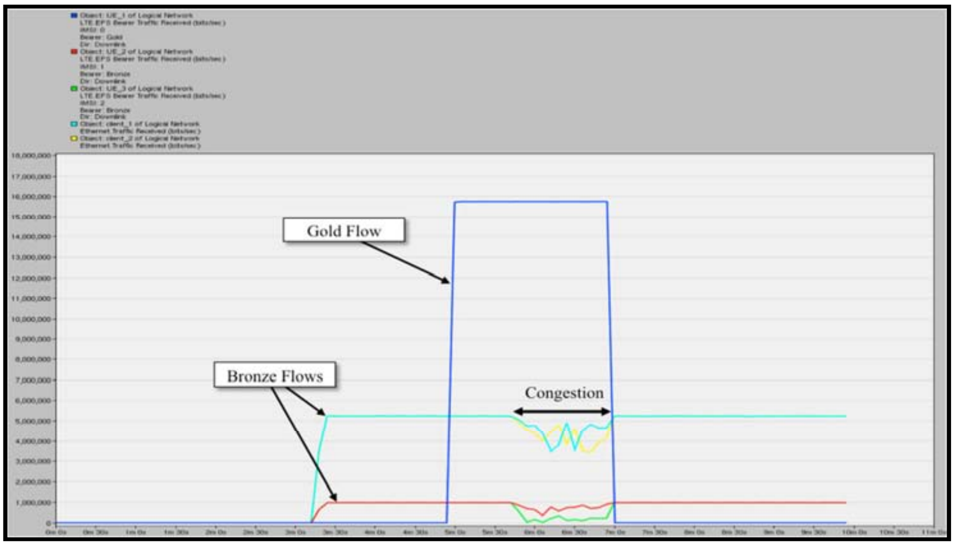


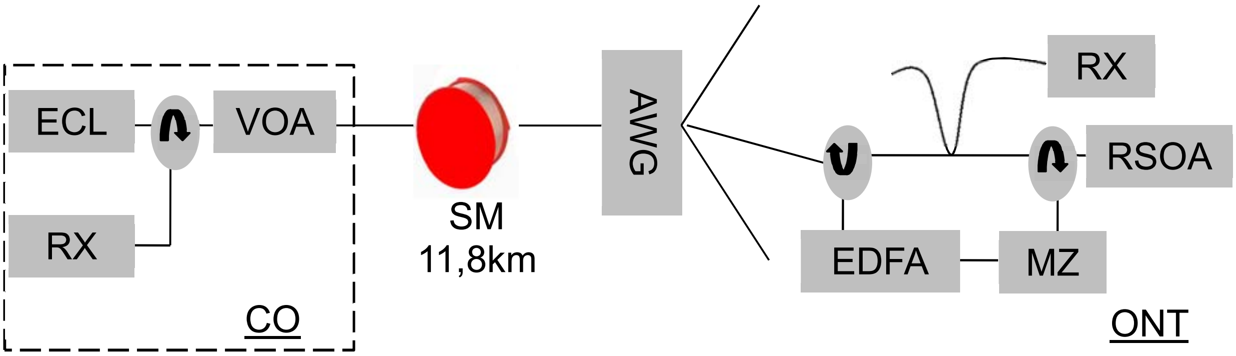
Figure 27. Traffic received with congestion on the link before OLT

Further investigations were carried out in the case of WDM PON and details can be found in [11]. The results confirm the possibility to menage the QoS in broadband wireless accesses, permitting to extend the same procedures used in core-PON access networks based on MPLS/VLAN labelling.

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 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. 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 as reported in the previous section. 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.

This is the reason why in this year we have continued in some experimental investigation on WDM PON networks based on wavelength conversion. In particular we make some preliminary tests on a colourless PON with the scheme reported in fig. 28, where a simple wavelength seed is injected in a reflective SOA to obtain a colourless ONT. The first results have shown an error free transmission on about 12km of SM fiber. The next step will be the direct modulation of the SOAs



Fiure. 28: scheme of the WDM PON

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4.5. Joint Activity – mm-wave Radio Over Fibre Systems Millimetre Wave Radio-over-Fibre

Executive Summary of Activities in Year 3

Various novel aspects to mm-wave RoF technologies have been examined in this JA of WP13 over year 3 of the BONE project. One innovative aspect has been performed by UCL, where they have investigated improved sideband suppression using an optical single sideband (OSSB) modulation with non-linear harmonic upconversion. In the reported work, experiments using an OSSB generator were able to achieve >50 dB sideband suppression of a WiMax (narrowband OFDM) transmission signal.

UPVLC has been investigating the management of RoF signals, with particular regard to the linearization for highly-linear applications, especially suited for RoF transmission of wireless signals in coexistence contexts. In addition, UPVLC has also continued to research the polarization-multiplexed distribution of ultra wide-band (UWB) signals in RoF transmissions and photonic analog-to-digital conversion architectures for wideband spectrum monitoring. As part of an experimental demonstration, a photonic generation system of impulse radio UWB signals targeting high user density for in-flight communications with simultaneous ranging capabilities in the 60-GHz radio band has also been investigated.

In an important aspect to RoF research, which is the understanding of the performance of within-building multi-mode fibre (MMF) infrastructure, UC3M has tested different MMFs to test the possibility of deployment of RoF based on legacy MMF links. In this regard, the temperature influence on the behaviour characteristics was investigated in a joint action with UC3M, FPM, UDE, and UPVLC. In particular, the radio frequency (RF) transfer function of a MMF link based on the electric field propagation method has been analyzed, in order to evaluate the conditions upon which broadband transmission is possible in RF regions far from baseband. Special attention to source parameter influence has also been analysed and experimentally tested. Novel monitoring techniques for access networks have also been analysed.

Future access networks will integrate diverse services and provide a versatile platform for broadband access to hundreds of fixed, mobile and nomadic users, with optical fibre clearly being the transmission medium of choice since it can support such an integrated network due to its immense bandwidth and low loss. To realize such a network, many challenges also need to be considered at the different network layers. During this JA, AIT has also been focusing on the physical layer showing how divergence in the sensitivity of the receivers of different signal types can affect the performance of an integrated transmission system and thus the network design. The example of a ring/bus network that integrates mm-wave and baseband services has been investigated, showing that the selection of the multiplexing and demultiplexing techniques, as well as the power budget of the network depend on the value of the baseband and mm-wave receiver sensitivities. For such access applications, the selection of the system hardware and related technologies is strongly dependent on the trade-off between cost and complexity.

Members

University of Essex (UESSEX), UK

University College London (UCL), UK

Universität Duisburg Essen (UDE), Germany

Athens Information Technology (AIT) Center, Greece

Technological Educations Institute of Athens (TEI), Greece

Universidad Carlos III de Madrid (UC3M), Spain

Universidad Politecnica de Valencia (UPVLC), Spain

Faculté Polytechnique of Mons University (FPM), Belgium

Objectives

Research in this JA has concentrated on millimetre-wave radio-over-fibre technologies with a particular focus on:

- 3.1-10.6 GHz UWB (ultra-wideband) signal distribution
- 60 GHz high data capacity applications
- SMF & MMF implementations
- Within-building and outside deployment
- Distributed antenna systems (DAS)
- Energy efficiency and low carbon footprint designs
- Source parameters influence on bandwidth in RoMMF
- Joint Paper amongst all partners for publication in IET Optoelectronics Journal

Research Topics

- UCL: WiMax transmission by optical up-conversion with improved sideband-OSNR using an optical single sideband modulation with non-linear harmonic up-conversion. Experimental transmission tests have also been performed using 4 × WiMax (narrowband OFDM) signals.
- UPVLC: Investigations of linearization of wireless signals in coexistence for highly-linear applications such as RoF transmission. Research in polarization-multiplexed distribution of UWB in RoF transmissions and photonic analogue-to-digital conversion architectures for wideband spectrum monitoring. Experimental demonstration of a photonic generation system of impulse radio UWB signals targeting high user density in-flight communications with simultaneous ranging capabilities in the 60-GHz radio band. [1-5]
- AIT: Investigations into physical layer of RoF systems showing how divergence in the sensitivity of the receivers of different signal types can affect the performance of an integrated transmission system and thus network design. Research into an example ring/bus network that integrates mm-wave and baseband services showing that the selection of the multiplexing and demultiplexing techniques, as well as the power budget of the network depend on the value of the baseband and mm-wave receiver sensitivities. [6]
- UC3M: RF transfer function of a MMF link based on electric field propagation method, to evaluate the conditions upon which broadband transmission is possible in RF

regions far from baseband. Analysis with special attention to source parameter influence is made and experimentally tested. Novel monitoring techniques for access networks have also been analysed [7,8]

- UESSEX + UPVLC + UDE + TEI + UC3M: Joint Paper describing BONE approach to mm-wave RoF technologies. [9]

Collaborations/Joint Experiments and Mobility Actions

Mobility Actions:

Visit of M. Thakur (UCL) to UEssex, July 2010

Visit of J Mitchell (UCL) to UDE to discuss joint project proposal, 11th June 2010

Tolga Tekin, PD Networkanalysis -> UDE, (23.09.2010)

Vitaly Rymanov, UDE -> TUB (25.11.2010)

Joint Experiments:

Broadband 60GHz Fiber-Extension Demonstration on ECOC 2010 -> UDE, FT

M. Morant (UPVLC) to UEssex, Jun-Aug 2010.

Publications

- R. Llorente (UPVLC), M. Morant (UPVLC), J. Hauden (Photline Technologies), H. Porte (Photline Technologies), N. Grossard (Photline Technologies), “Dual-Parallel Y-Coupled Lithium Niobate Electro-Optic Modulator with 15.2 dB SFDR gain”, 15th European Conference on Integrated Optics (ECIO2010), Cambridge, UK, April 2010.
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- R. Llorente (UPVLC), M. Morant (UPVLC), J. Duplicy (Agilent Measurement Research Laboratory), T. Van Waterschoot (Katholieke Universiteit Leuven), V. Le Nir (Katholieke Universiteit Leuven), M. Moonen (Katholieke Universiteit Leuven), J. Puche (DAS Photonics S.L.), J. Romme (IMST GmbH), “Sensing and fingerprinting of ultra wide band radio in UCELLS Project”, Future Network and Mobile Summit 2010, Florence, Italy, June 2010.
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- A. Stöhr, Photonic Millimeter-Wave Generation and its Applications in High Data Rate Wireless Access, 2010 IEEE International Topical Meeting on Microwave Photonics (MWP 2010), 5-9 October 2010, Montreal, Quebec, Canada

Research Contributions

More detailed aspects of the BONE WP13 mm-wave RoF research contributions are detailed as follows:

WiMax transmission by optical upconversion with improved sideband-OSNR

In order to demonstrate the transmission system, the test bed shown in Figure 1 was implemented. An FPGA based signal generator (Aeroflex) was used as WiMAX (802.16-2005 specification) transmitter and receiver. Multiple modulation schemes (BPSK, QPSK, 16QAM, 64QAM or higher with OFDM or OFDMA in 2-66 GHz spectrum) are defined in the IEEE 802.16 standard to extend broadband wireless access (BWA), from the local area network (LAN) to the metropolitan area network (MAN). In FDD mode, used in this experiment, there are separate uplink and downlink sub-frames which reside on different frequencies. For both downstream and upstream, a data region with one burst was used. Four IEEE 802.16-2005 channels, with the specification given in Table. 7, at 440, 460, 480 & 500 MHz with 20 MHz channel spacing and 10MHz channel width were generated.

TABLE 7
IEE802.16E WIMAX TRANSCEIVERS PARAMETERS

Symbol	DOWNSTREAM	Upstream
FFT size	1024	1024
Modulation	64-QAM	16-QAM
Coding	2/3	3/4
Bandwidth	10MHz	10MHz
RCE	-50dB	-25.8dB
Data rate	25.2Mbps	18.9Mbps

The back-back baseline downstream WiMax channel transmitter relative constellation error (RCE) was -36.7 dB, a figure higher than the minimum standards requirement for 64-QAM modulation. Local oscillator input at 10GHz and 19.5 dBm power, was split using 900 hybrid to be fed to the upconversion mixer and at quadrature to the variable attenuator and phase shifter for optical sideband cancellation at the OSSB generator. Subsequently, the 10GHz RF carrier at the 00 arm, was mixed with the WiMax signal using WJ-M79C-10 mixer.

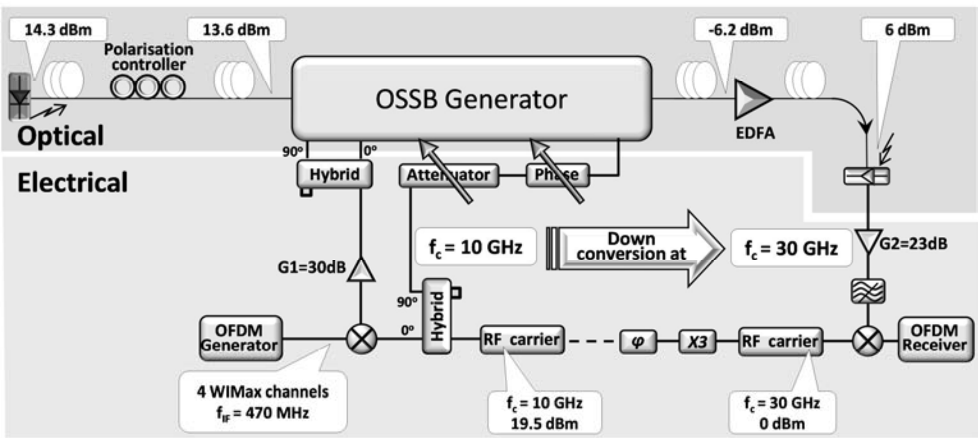


Figure 29. Experimental setup for upconversion

The upconverted WiMax signal at 10GHz was amplified. The OSSB generator was biased at quadrature. Optical CW was generated using a DFB laser, and the power at the OSSB generator input was measured to be 14.3 dBm. An EDFA was used to amplify the optical output (6dBm) of the PM before photodetection using a PIN diode. An Aeroflex receiver was used to demodulate and analyse the WiMax channels.

In the experiments, the bandwidth capability of the developed system was 10 GHz, limited by the modulation bandwidth of the optical components. An RF frequency of 10GHz was used so as to make the down-conversion electrical frequency of 30GHz fall within the bandwidth of receiver amplifier. A penalty of 25 dB was imposed on the SNR of the WiMax signal by the experimental optical channel. The optical power budget of the system can be seen in figure 28.

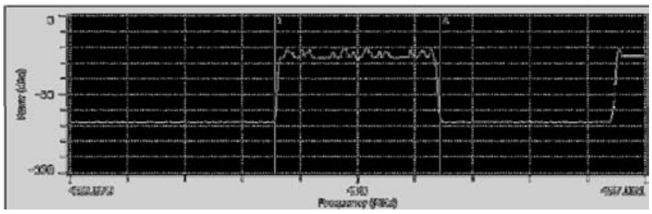


Figure 30. WiMax channels at transmitter

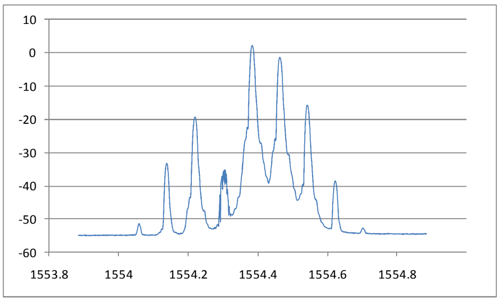


Figure 31. Optical signal after amplification using EDFA, with WiMax modulation signal applied to OSSB generator.

Figure 30 shows one of the 4-channel WiMax signals which was upconverted to 10GHz. The SNR can be seen as being in excess of 45 dB. As shown in figure 31, after the WiMax modulation signal is applied, there is evidence of some modulation signal leakage on suppressed sideband which reduces the relative OSNR by 10dB, to around 40dB, which is still an improvement compared to using a standard OSSB configuration. The electrical WiMax modulation signal power level was determined by the dynamic range of the system (before going in to optics, mixer and amplifier) and its effect on the achievable EVM (RCE).

In figure 33, the constellation for the 4 WiMax channels can be seen, and the recorded RCEs were -19.438 dB, -20.22 dB, -20.033 dB and -20.459dB for WiMax channels at 440 MHz, 460 MHz, 480 MHz and 500 MHz respectively, which can be compared to the back-back Tx-Rx constellation in figure 32, achieving an RCE of -36.726 dB.

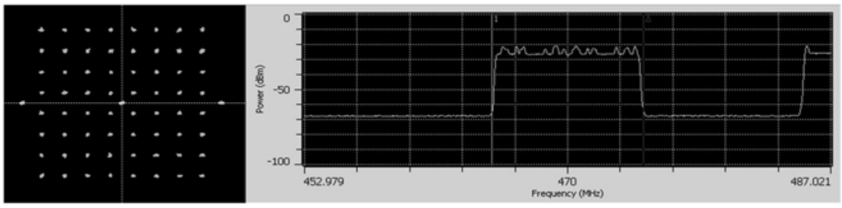
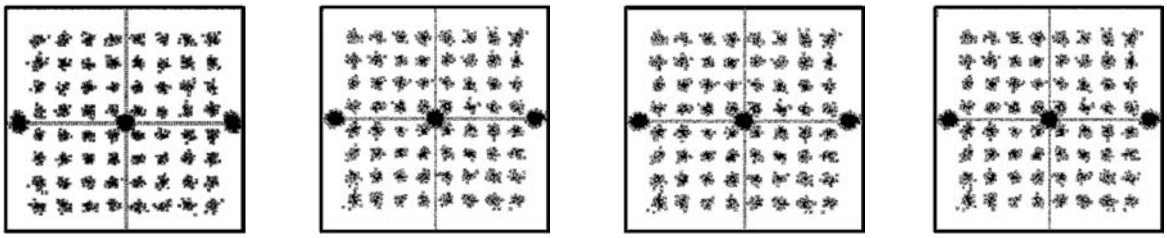


Fig. 32. Measured frequency spectrum and constellation in back-back WiMax Tx-Rx configuration for establishing baseline RCE (-36.726 dB).



(a) 440MHz *(b) 460MHz* *(c) 480MHz* *(d) 500MHz*

Fig. 33. Measured constellation for the 4 × WiMax channels at 440 MHz, 460 MHz, 480 MHz and 500 MHz (RCE measured: -19.438 dB, -20.22 dB, -20.033 dB and -20.459 dB, respectively).

In this work we have reported WiMax (narrowband OFDM) transmission using frequency upconversion by employing an OSSB generator to achieve >50 dB sideband suppression.

UWB distribution using polarization multiplexing techniques, impulse radio UWB signals, & 60 GHz

A dual-parallel linearization architecture of Y-coupled LiNbO3 electro-optic modulators is proposed and evaluated experimentally in Figure 34. Fabricated devices have been characterized in UPVLC exhibiting 15.2 dB SFDR gain over a conventional LiNbO3 Mach-Zehnder modulator and 10.2 dB SFDR gain over a parallel Mach-Zehnder architecture. A paper joint with Photline Technologies was prepared and published in the European Conference on Integrated Optics (ECIO2010) in April 2010.

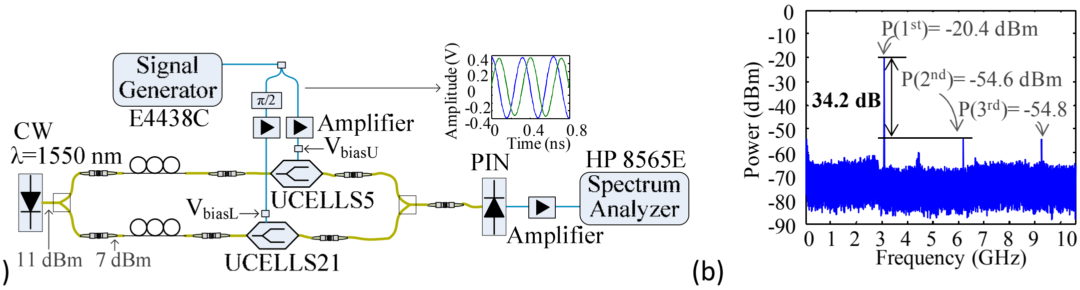


Figure 34: (a) Experimental setup for dual parallel Y coupled linearized characterization, and (b) Measured electrical spectrum for dual parallel Y coupled linearized proposed architecture.

This linearization concept finds application in highly-linear applications like radio-over-fiber transmission of wireless signals in coexistence and photonic-ADC sensing. In this activity, the effect of channel aggregation and inter-channel distortion is evaluated for MB-OFDM

UWB radio-over-fibre transmission using polarization multiplexing. Different transmitter configurations were studied experimentally with commercial standard UWB transmitters. MB-OFDM UWB channels following current regulation of 528 MHz bandwidth at 200 Mbit/s (QPSK modulation) without frequency hopping (ECMA time frequency codes TFC5, 6 and 7) are generated as depicted in Figure 35, covering from 3.168 to 4.752 GHz (low band group #1) [ECMA368].

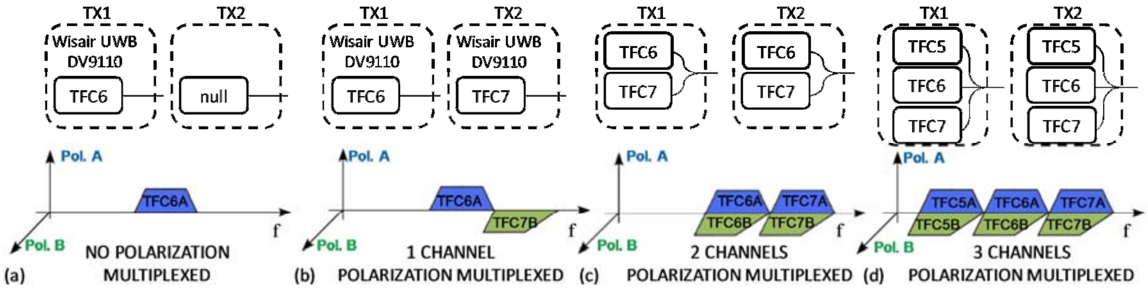


Figure 35: Transmitter configurations and spectrum schemes: (a) without PM, (b) 1 channel PM, (c) 2 channels PM and (d) 3 channels PM

The effect of channel aggregation and inter-channel distortion measured for the center channel (TFC6) is evaluated for different SSMF lengths and the EVM is represented in Figure 36. It can be observed that distortion effects are deeper with longer SSMF transmission. For example, changing from no polarization multiplexing (configuration described in figure 35(a)) to one channel PM (figure 26(b)) induces a maximum distortion of 1.85% in EVM observed in figure 35(c) when transmitting over L=25 km SSMF. Both configurations have a spectral efficiency of 0.3788 bit/s/Hz (=200 Mbit/s/528 MHz). When using 2 channels PM (figure 35(c)) introduces a 2.24% EVM co-channel distortion but doubles the spectral efficiency (0.7576 bit/s/Hz). Finally, adding a third MB-OFDM channel to use the entire low band group #1 (figure 35(d)) has a maximum penalty of 1.2% EVM in the center channel.

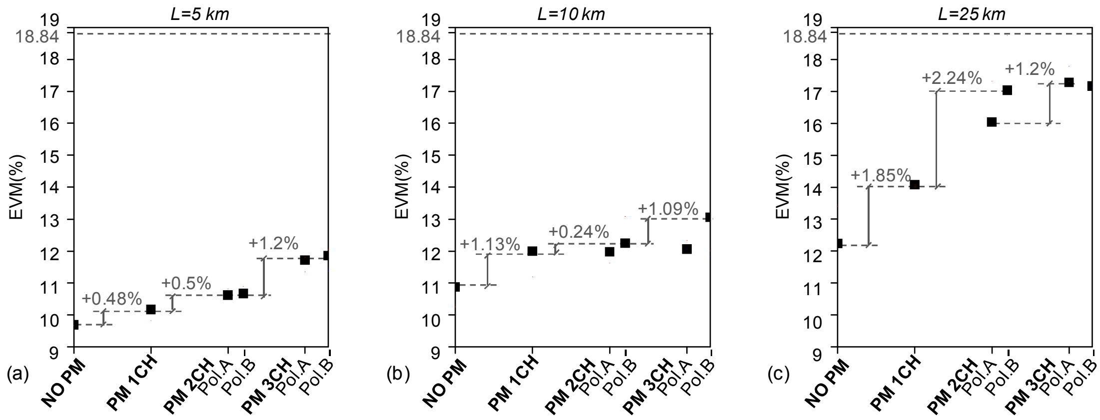


Figure 36: Experimental EVM results in TFC6 for different PM configurations and different FTTH paths: (a) L=5 km, (b) L=10 km and (c) L=25 km

A maximum distortion of 2.24% EVM is observed comparing a transmission of two MB-OFDM channels at different frequency bands multiplexed separately in orthogonal polarizations with a joint two co-channels transmission polarization multiplexed. Using the whole band group #1 (three MB-OFDM channels) with polarization multiplexing induces an increment of 1.2% EVM in the center channel (TFC6) as an effect of the neighbor channels (TFC5 and TFC7). EVM results are placed under the 18.84% ECMA limit for each PM configuration evaluated up to 25 km SSMF transmission, improving the spectral transmission efficiency up to 0.7576 bit/s/Hz. [ECMA-368] ECMA-368 International Standard, “High Rate Ultra Wideband PHY and MAC Standard”, December 2005.

60 GHz high data capacity applications

In the 60 GHz high data capacity application evaluation, the experimental results show that good quality 57-GHz UWB pulses can be obtained with the proposed system after the transmission over a standard single-mode fiber at in-cabin distances up to 100 m. The results have been published in M. Beltrán, and R. Llorente, “60-GHz ultra-wideband radio-over-fiber system using a novel photonic monocycle generation,” IEEE Trans. Microw. Theory Tech., vol. 58, no. 6, pp. 1609–1620, Jun. 2010. The photonic generation with dispersion-tolerant fiber distribution of impulse-radio ultra-wideband signals has been proposed and experimentally demonstrated in the 60 GHz band.

Photonic ADC architectures

UPVLC continued investigating the photonic-ADC architectures for radio sensing applications. A joint publication with UCELLS project was presented in the Future Network and Mobile Summit 2010 in June 2010. A proof-of-concept experiment indicate that the proposed photonic-ADC technology is a suitable approach for sensing ultra-low power UWB radio signals in real-time. The experimental set-up shown in figure 37 permits the sensing -48 dBm sensitivity and with 11.2 dB SNR. This SNR successfully enables the adequate fingerprinting of the UWB signals detected.

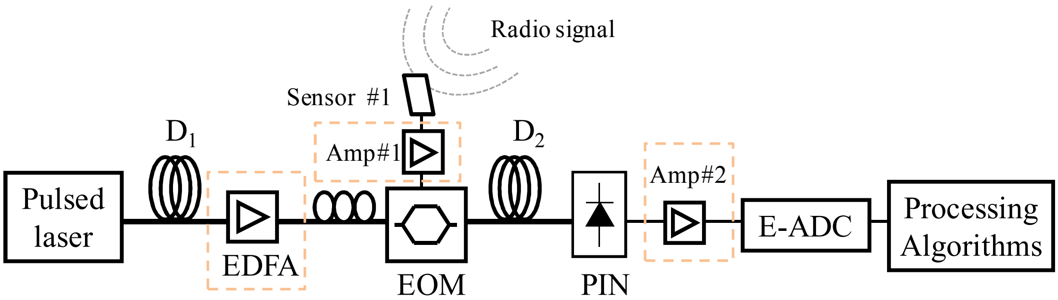


Figure 37: Proposed single-channel Ph-ADC architecture with engineered optical and electrical amplification

The fingerprinting algorithms applied to the sampled data consists in, first, computing an averaged periodogram to give an estimate of the power spectral density of the received sequence, and second, a time domain correlation will confirm the presence of a UWB signal.

The results of the fingerprinting process of the received signal in a single-channel photonic-ADC architecture with UWB input signal using frequency hopping were presented and analyzed. The processing algorithms were able to detect the transmission presence in each band of the frequency hopping and the silent periods as it is shown in the received spectrogram of figure 38.

The time stretching is confirmed observing the spectrum at the output of the system shown in figure 39**Error! Reference source not found.**, where the first UWB band (first hopping band in the sequence of TFC1 (f1, f2, f3, f1, f2, f3) from 3.1 to 4.8 GHz is reduced to 0.91 to 1.41 GHz after the time stretching architecture with M=3.4.

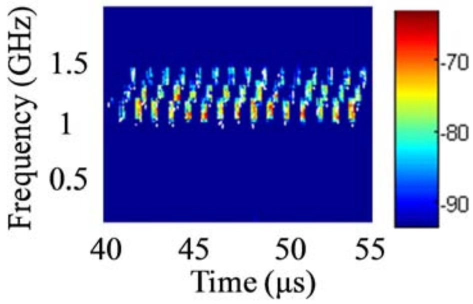


Figure 38: Processed spectrogram of the received UWB signal using TFC1 configuration after photonic-ADC

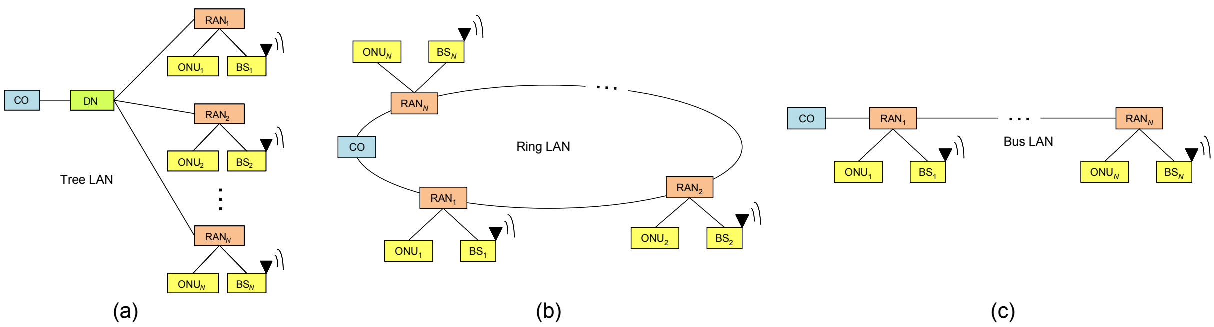


Figure 39: Integrated access network architectures. (a) Tree (b) ring and (c) bus topologies. CO: central office, DN: distribution node, RAN: remote access node, ONU: optical network unit, BS: base station.

RoF Receiver Sensitivity Investigations

The standard architecture of a PON based on time division multiplexing (TDM) is that of a tree, where a central office is connected to several optical network units (ONUs) via a remote (or distribution) node where the TDM signal is passively split to access all ONUs. Wavelength division multiplexing (WDM) PONs often follow the same topology by replacing the passive splitter with a WDM demultiplexer, such as an arrayed-waveguide grating. For large scale networks, where a great number of users (~1000) needs to be served, more complex solutions have been proposed, such as a hybrid WDM/TDM approach based on a WDM ring architecture where at each node of the ring TDM trees are connected [7]. Similarly, for RoF networks, both tree and ring/bus architectures can be applied. Networks that integrate diverse services by supporting simultaneous transmission of baseband (BB), microwave and mm-wave services can have similar topologies [1,2,8]. Figure 40 shows such network topologies integrating fixed and wireless access.

In WDM networks, physical layer reconfigurability allows dynamically allocating different wavelength-channels. This requires colourless access nodes (optical network units (ONUs) and base-stations (BSs) in the case of Fig. 40), i.e. nodes that do not operate in specified wavelengths. The applied mechanisms that enable physical layer reconfigurability depend on the network architecture. For a tree configuration [Fig. 40(a)], a reconfigurable optical router, such as an optical cross-connect, can be used in the distribution node (DN) [2]. In a ring/bus topology, such as the ones illustrated in Figs. 40(b) and 40(c), physical layer reconfigurability takes the form of add-drop multiplexing [1]. Dynamic channel allocation offers a mechanism to adjust the aggregate capacity provided at a local area network (LAN) and facilitates network scalability and maintenance (due to the colorless feature of the access nodes). Especially when several LANs are connected over a main access backbone [7], the bandwidth demand at each LAN will not remain constant throughout a day, as well as in the course of a year. Examples of LANs with such varying bandwidth demand include networks in convention centers, airports, shopping malls, or large residential condominiums and blocks.

The selection of the techniques for multiplexing the different types of signals is also dependent on the network architecture. WDM, TDM, OFDM, wavelength interleaving and polarization multiplexing/demultiplexing (PolMux/Demux) have been proposed [1,2,4,5,7,8], as well as digitization of all types of signals with analog-to-digital converters, yielding an optical system that transmits only BB data [9]. Each approach exhibits advantages and disadvantages that can be evaluated as a trade-off between cost and complexity.

For each type of signal (BB, microwave, mm-wave) in an integrated network, the sensitivity of the corresponding receiver will be different as already explained in the introduction. This will impact the power budget for each signal type, affecting the tolerance of the system to accumulated ASE noise from optical amplification, as well as the impact of cross-talk. Although in current PON standards, optical amplification is not included in the network nodes, in large scale next generation PONs, the transmitted signals can be optically amplified by remotely-pumped optical amplifiers, therefore still retaining the passiveness of the network nodes [7]. In the following section, a transmission system in the context of a ring/bus network that integrates BB and mm-wave (60-GHz) services is evaluated showing the impact of the receiver sensitivity in the system performance and hence the network design.

Simulation Results

In the following, we consider a ring/bus network configuration as the ones shown in Figs. 40(b) and 40(c). We follow the approach proposed in reference [1], where wavelength interleaving and PolMux are used to simultaneously transmit mm-wave (60-GHz) and BB signals. At each remote access node (RAN) of the network, a RoF signal and a wavelength interleaved BB signal are dropped by means of tunable optical filtering. This provides a simplified way of physical layer reconfigurability [1]. The BB signal is interleaved between the carrier (RoFc) and the sideband (RoFs) of the RoF signal. The frequency offset of the BB signal from RoFc as well as the difference ΔPol in the state of polarization (SOP) between the BB and RoF signals affect the requirements for demultiplexing and successfully detecting the two signals.

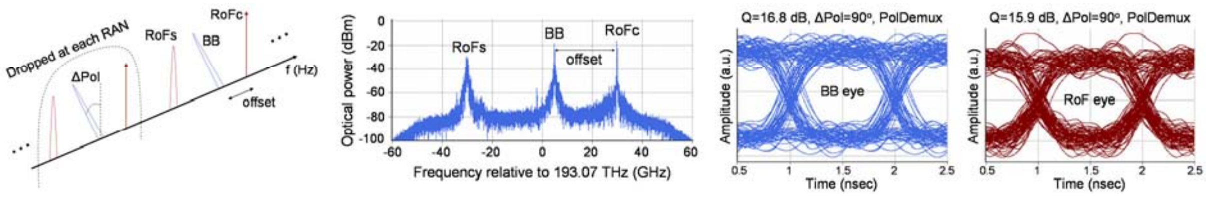


Figure 40: Wavelength division multiplexing and interleaving combined with polarization multiplexing to integrate BB and mm-wave (60 GHz) transmission.

The impact of ΔPol and the frequency offset in the Q-factor of the RoF and BB signals was investigated by simulating the system with VPItransmissionMaker. In particular, a 1-Gb/s BB signal and a 1-Gb/s 60-GHz signal were generated and simultaneously detected in a back-to-back configuration. The 1-Gb/s 60-GHz signal was generated by electrically up-converting a

1-Gb/s 3-GHz DPSK signal with a 57-GHz electrical oscillator and then using an electro-absorption modulator. The optical single-sideband-with-carrier scheme was used by optically filtering out one sideband. This scheme is tolerant to dispersion and by optimizing the carrier-to-sideband ratio around 0~dB, optimal receiver sensitivity can be achieved [10]. For the generation of the BB signal, a Mach-Zehnder modulator was used. The combined signal was split by a 3-dB coupler and at the two output arms of the coupler a BB and a mm-wave detector were connected.

Figure 41 shows the results on the Q-factor evaluation when PolDemux applies by using polarizers (PLZs) at the input of the PIN photodiodes of the two detectors, as well as when PLZs are not used with ΔPol varying from 90^o (orthogonal SOP) to 0^o (same SOP). In Figs. 41(a) and 41(b), the difference in the sensitivity of the BB (-26 dBm) and mm-wave (-23 dBm) receivers is 3 dB. This is because the 60-GHz signal is down-converted and half of the power (which is up-converted to the 120-GHz range) is filtered out. If no PLZs are used, a 1.7-dB degradation from the ~16-dB target Q-factor is observed for the BB signal. This degradation can be overcome by a 1.3-dB penalty in the received optical power of the BB detector (while the RoF-to-BB power ratio is not altered), as shown in Fig. 42(a). For frequency offsets equal to -0 and -60 GHz, there is a strong degradation both for BB and RoF signals, due to in-band beating.

On the other hand, in Figs. 41(c) and 41(d), an extra 12-dB optical attenuation was added at the input of the mm-wave receiver, to emulate a system where the difference in the sensitivities is significant (15 dB). In order to have a power efficient system, the launch power at the transmitters should be determined by the receiver sensitivity and the loss of the link. However, this impacts the RoF-to-BB power ratio. As a result, an 11-dB degradation is observed in the Q-factor of the BB signal, which cannot be overcome even by a 10-dB penalty in the received optical power (while keeping the RoF-to-BB power ratio constant), as shown in Fig. 42(b). At the same time, RoF signal detection only deteriorates for frequency offsets equal to -0 and -60 GHz, especially for small values of ΔPol.

Applying PolMux/Demux yields a system where the interference between the signals is minimized and power budget can be set for each signal independently. When the receiver sensitivities are similar, it is possible to build a power efficient system/network, since the induced penalty can be small when the BB signal does not overlap with the carrier or sideband of the RoF signal. However, in order to avoid PolMux/Demux in a system where the receiver sensitivities are much different, it would be required to keep the RoF-to-BB ratio in levels that do not destruct the reception of one of the two signals. This means, though, that in the receiver having the lower sensitivity a large amount of power will be wasted, resulting in a power inefficient network.

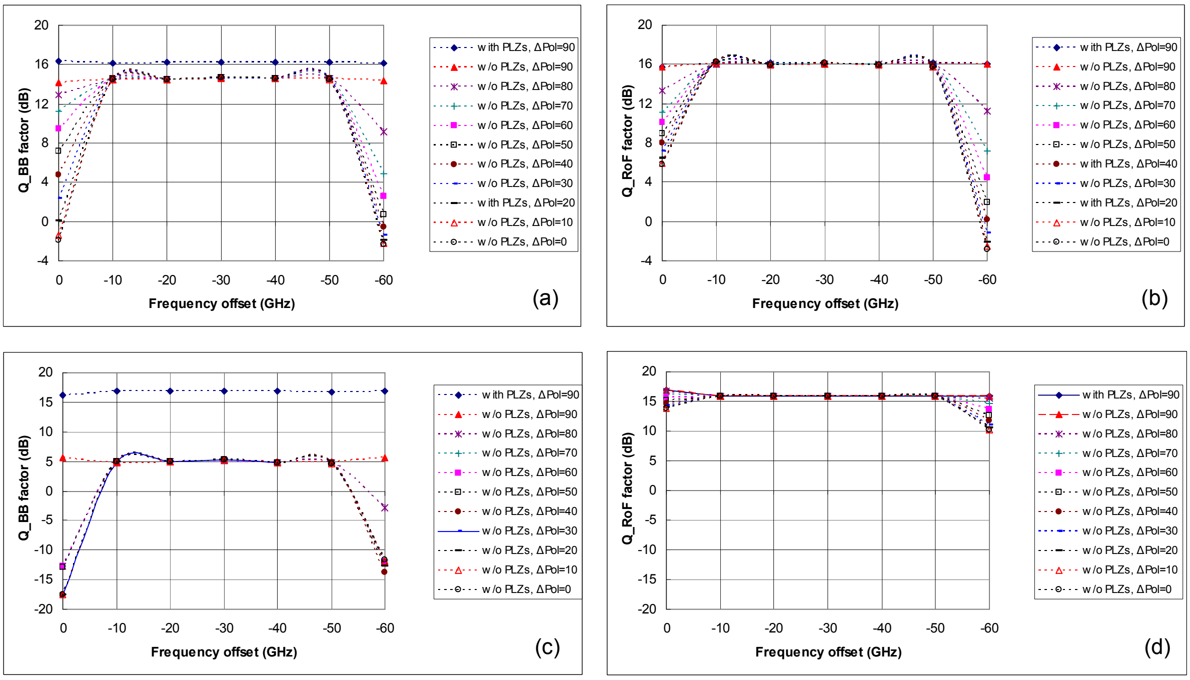


Figure 41: Q-factor evaluation for different frequency offsets between the carrier of the mm-wave signal and the wavelength-interleaved BB signal and for varying the difference in the SOP (ΔPol). The BB receiver sensitivity is (a,b) 3-dB (c,d) 15-dB lower than the RoF one

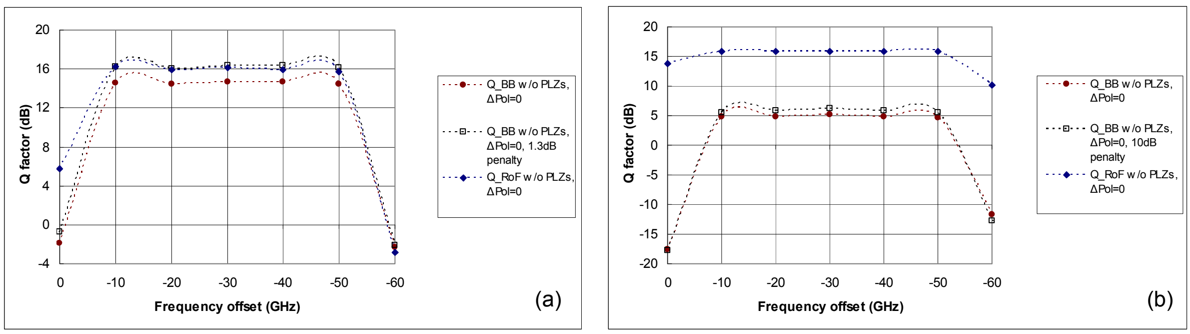


Figure 42: (a) 1.3-dB penalty in the received optical power at the BB receiver achieves a 16-dB Q-factor when the difference in the sensitivities is 3 dB. (b) The degradation in the Q-factor cannot be overcome even by a 10-dB penalty when the difference in the sensitivities is 15 dB, rendering PolMux/Demux necessary.

Summary

The convergence of diverse services over a common optical fiber infrastructure yields physical layer challenges. These are due to the different characteristics and requirements in simultaneously transmitting signals of different modulation format and bit rate. These different signal characteristics impact the design of the corresponding receivers, which, in principle, feature different sensitivities. The example of a ring/bus access network that integrates BB and mm-wave signals was used to show the impact that a large difference in the receiver sensitivities has on the transmission performance. In particular, a large difference renders necessary for the BB and mm-wave signals to have orthogonal polarizations. Similar receiver sensitivities can simplify the system hardware, while maintaining at the same time a power efficient system and network.

RF transfer function of RoMMF link

RF transfer function of a MMF link based on the electric field propagation method is described and analyzed, based on the model previously reported in (Gasulla and Capmany 2007), in order to evaluate the conditions upon which broadband transmission is possible in RF regions far from baseband. From such a model, it can be concluded that MMFs offer the potential for broadband RoF transmission in the microwave and millimeter wave regions in short (2-5 km) and middle (~10 km) reach distances. Much of this potential is related to the fact that the MMF link behaves like an imperfect microwave photonic transversal filter, featuring a non-constant delay between adjacent samples (i.e. mode groups). However, the potential for transmission over longer distances requires further researchIn this subsection the influence of the optical source characteristics over the MMF frequency response is evaluated. Parameters defining its characteristics such as the linewidth, the chirp and the wavelength emission are analyzed.

At first, the effect caused by the source linewidth is reported in the following figures for a fibre length of 3km and 6km and a source chirp set to zero. It has been assumed a parabolic graded index exponent, i.e. $\alpha = 2$. The rest of parameters take the same value as those indicated in above sections. The frequency response is displayed for a typical distributed feedback laser (DFB laser) with a rms linewidth of W=10MHz, a multimode Fabry-Perot laser (FP laser) with W=5.5nm and a LED with W=30nm. As it can be observed from Fig. 43(a), for the case of L=3Km, a first resonance featuring a 3-dB bandwidth of around 2GHz in the case of the DFB laser and around 1.9GHz in the case of the FP laser is obtained at around a central frequency of 8.5GHz due to the transversal filtering effect, while no resonance is present when a broadband LED source is applied. Furthermore, for a DFB laser source the attenuation in the higher-than-first resonances remains under similar values whereas for a FP laser source the second and following resonances are rapidly decreased in electrical power. Therefore, exploiting the possibility of transmitting broadband signals at high frequencies using a MMF link is contingent on the use of low linewidth sources, as presented in (White 1999).

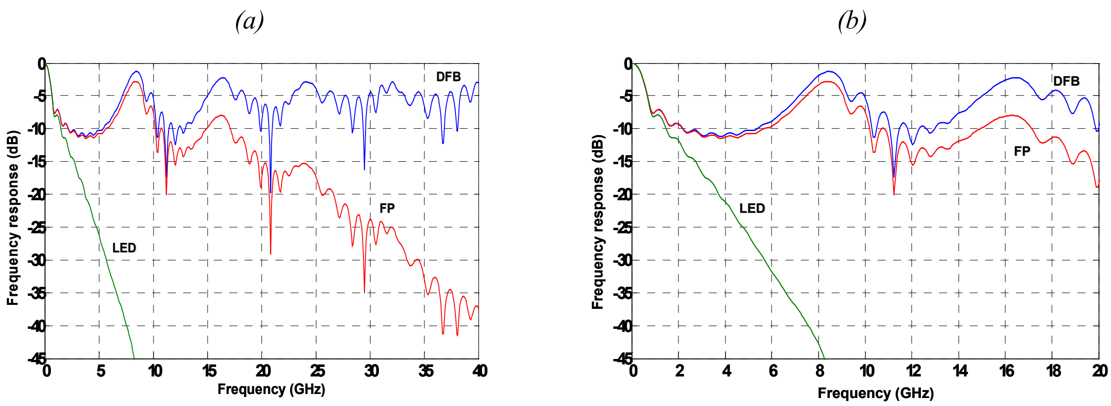


Figure 43: (a) Influence of the temporal coherence of the source on frequency response for a fibre link of L=3Km. (b) Influence of the temporal coherence of the source on frequency response for a fibre link of L=6Km.

Secondly, the influence of the source chirp over the MMF frequency response has been studied. For the simulations a source with a linewidth of W=10MHz has been considered with a parabolic index profile optical fibre in L=6km link length. Three values of the source chirp are illustrated in the following figure. The rms deviation of the coupling autocorrelation function was adjusted to $\sigma = 0.0021$. The rest of the simulation parameters take the same value as aforementioned.

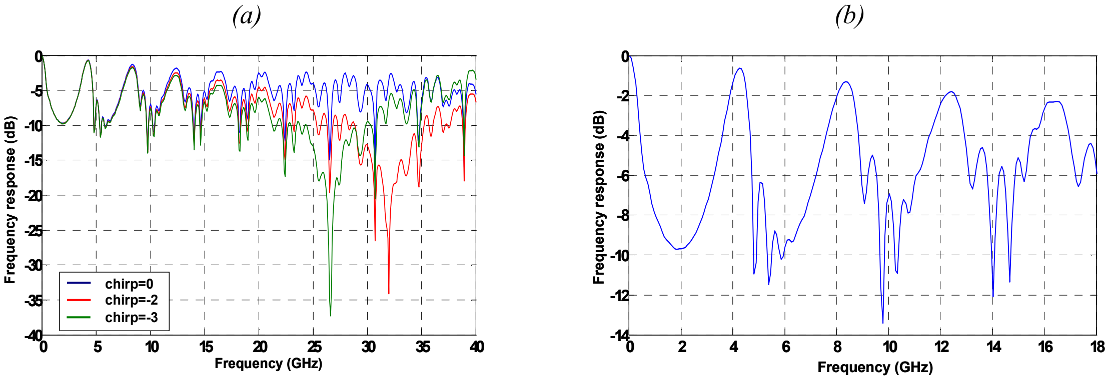


Figure 44:- (a) Frequency responses and Carrier Suppression Effect for different values of the source chirp for a fibre link of L=6Km. (b) Zoom of the frequency response considering the condition chirp=0.

Considering the case of a chirp free source it can be observed that the contrast ratio (roll-off of the passband) between the transversal filter resonances and the secondary side-lobes is dramatically reduced as the RF frequency increases. This is due to the fact that the difference on the propagation delays between adjacent mode groups is not a constant value, i.e. the MMF link behaves as an imperfect transversal filter and, consequently, it is possible to provide broadband transmissions at higher frequencies than baseband through a multimode optical fibre. This fact can be seen, particularly, in Fig.44 (a); chirp=0 featuring a region with small losses identified at frequencies above 20 GHz. Below this region, RF transmission can also be performed but at determined bands corresponding to the filter resonances (bands centred at 4.3 GHz, 8.4 GHz, 12.4 GHz and 16.4 GHz each one providing a minimum 3-dB bandwidth of around 1 GHz can be selected in this region, see Fig. 44(b)). Cases selecting chirp=-2 and chirp=-3 illustrate the influence of the carrier suppression effect which cannot be neglected. The first notch of the frequency response relative to a chirp=-2 is situated at approximately 32 GHz while it appears at 26 GHz for the condition of source chirp=-3.

Finally, the MMF frequency response is also evaluated regarding the wavelength emission provided by the optical source. This parameter also links with the optical fibre properties, as parameters such as the core and cladding refractive indices, the material dispersion, the propagation constant, the intrinsic attenuation or the number of propagated modes strongly depends on the optical wavelength launched into the fibre. Fig. 45 depicts the 2-km-long MMF frequency response for two different sources, namely a Distributed Feedback (DFB) laser and a Fabry-Perot (FP) laser, for 650, 1300 and 1550 nm operating wavelengths. The intrinsic attenuation was considered to be 3dB @ 650nm, 0.7dB @ 1300nm and 0.5dB @ 1550nm, respectively. Source linewidths were simulated with W=10 MHz and W=5 nm for the DFB and F-P optical sources, respectively. From both figures, it is worth pointing out that the high-order resonance central frequencies are located at different points and, what is more important, at 1300 nm wavelength it provides the highest 3-dB high-order resonance bandwidth comparing with the case of 650 nm and 1550 nm. Moreover, in Fig. 18(b) it is clear the influence of the material dispersion at 650 nm for sources with low temporal coherence (i.e. high linewidth values). These facts are related with the dispersion values in silica MMFs, typically around -3 ps/nm/km and +17 ps/nm/km at 1310 nm and 1550 nm respectively. Experimental results shown in Fig. 46 are in accordance with the expected behaviour.

(a) *(b)*

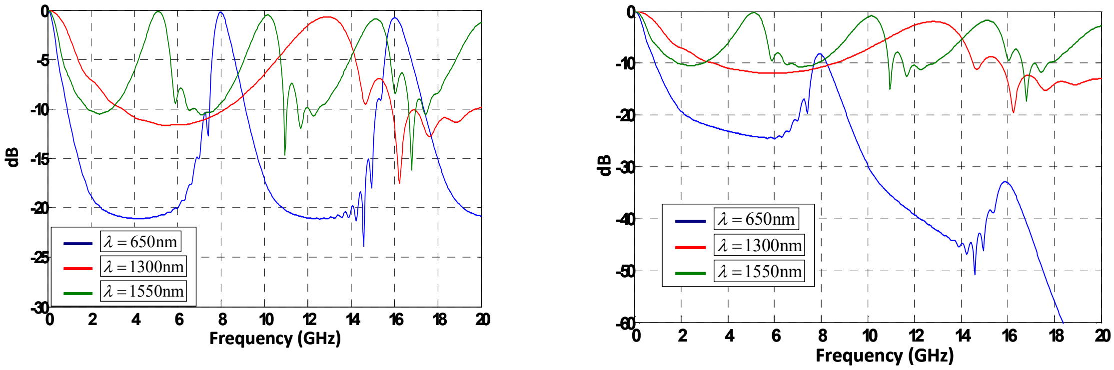


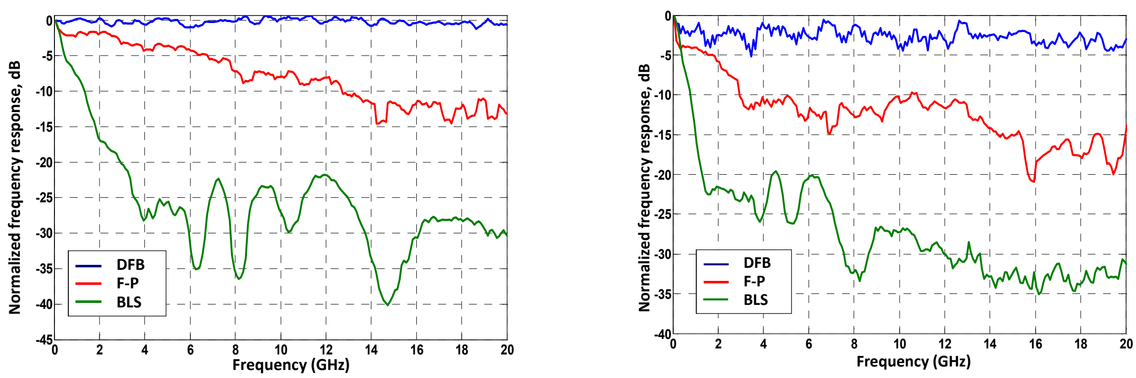
Figure 45: (a) 2km-long MMF frequency response at different DFB (W=10 MHz) source wavelengths. (b) 2km-long MMF frequency response at different FP (W=5 nm) source wavelengths.

<u>References</u>

[1] Gasulla, I. and J. Capmany (2007). "Analysis of the harmonic and intermodulation distortion in a multimode fiber optic link." Opt. Express 15(15): 9366-9371.

[2] W. R. White, M. D., W. A. Reed and T. Onishi (1999). "Intermodal Dispersion and Mode Coupling in Perfluorinated Graded-Index Plastic Optical Fiber." IEEE Photon. Tech. Lett. 11(8): 997-999.

(a) *(b)*



(c)

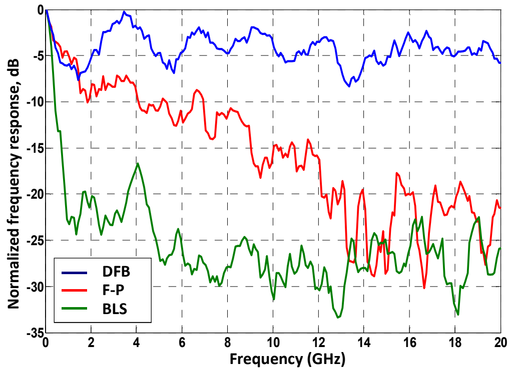


Fig. 46: Measured influence of the optical source linewidth on the frequency response of a (a) 3050 m, (b) 6100 m and (c) 9150 m MMF link.

Millimeter-Wave Photonic Components for Broadband Wireless Systems

We report on advanced millimeter-wave (mm-wave) photonic components for broadband radio transmission. We have developed self-pulsating 60-GHz range quantum-dash Fabry–Pérot mode-locked laser diodes (MLLD) for passive, i.e., unlocked, photonic mm-wave generation with comparably low-phase noise level of -76 dBc/Hz @ 100-kHz offset from a 58.8 GHz carrier. We further report on high-frequency 1.55 µm waveguide photodiodes (PD) with partially p-doped absorber for broadband operation (f_{3dB} ~70–110 GHz) and peak output power levels up to +4.5 dBm @ 110 GHz as well as wideband antenna integrated photomixers for operation within 30–300 GHz and peak output power levels of -11 dBm @ 100 GHz and 6 mA photocurrent. We further present compact 60 GHz wireless transmitter and receiver modules for wireless transmission of uncompressed 1080p (2.97 Gb/s) HDTV signals utilizing the developed MLLD and mm-wave PD. Error-free (BER = 10^{-9}, 2^{31} - 1 PRBS, NRZ) outdoor wireless transmission of 3 Gb/s over 25 m is demonstrated, as well as wireless transmission of uncompressed HDTV signals in the 60 GHz band. Finally, an advanced 60 GHz photonic wireless system offering record data throughputs and spectral efficiencies is presented. For the first time, we demonstrate photonic wireless transmission of data throughputs up to 27.04 Gb/s (EVM 17.6%) using a 16-QAM OFDM modulation format resulting in a spectral efficiency as high as 3.86 b/s/Hz. Wireless experiments were carried out within the regulated 57-64-GHz band in a lab environment with a maximum transmit power of -1 dBm and 23 dBi gain antennas for a wireless span of 2.5 m. This span can be extended to some 100 m when using high-gain antennas and higher transmit power levels.

Ultra-wideband radio-over-fiber techniques and networks

Motivations and results obtained regarding the optical distribution of a 60 GHz radio signal throughout buildings to provide users with Ultra-Broad-Band Wireless Home Area Network with data rates >1Gbps and continuous coverage.

Photonic Millimeter-Wave Generation and its Applications in High Data Rate Wireless Access

Microwave Photonics is widely considered as a disruptive technology for high data rate wireless communications. Discussion of technological trends in enabling photonic solutions for high data rate wireless access systems operating in the millimeter-wave regime. Besides technical achievements, a focus is also put on worldwide regulations for wireless communications in the E-band (60-90 GHz).

Quantum dash mode-locked lasers for millimetre wave signal generation and transmission

We present the remarkable characteristics of quantum dash mode-locked lasers and how they could be used for low phase noise signal generation, for high data rate wireless transmission and radar in the millimeter-wave frequency range.

4.6. Joint Activity – Techniques for Colourless ONUs

Members

UNIROMA3, UCL, UPC, ISCOM, UCAM, TUE, IBBT

Objectives

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

Research Topics

Use of reflective devices in PONs

Dynamically Reconfigurable PONs

OFDM PONs

Athermal lasers for PONs

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.

- **Bas Huiszoon, PhD Researcher at TUE, hosted by UAM from 01/03/2008 to 10/07/2008**

Performance evaluation of an optical transparent access tier Code sensing capabilities are implemented in the network which enables to resolve the contention and an architecture is proposed. A first requirement is extensively analyzed in the work namely the coherence between the (past) state which is sensed at the node and the actual state at the aggregation node. Four different packet distributions are considered in the study.

Based on the results, a transmission scheduling is considered as a protocol to avoid contention in optically transparent networks employing optical codes as optical address. The submitted paper to the IEEE Journal on Selected Areas of Communications has been accepted for publication in the February 2009 edition.

The concept of interference-aware transmission in transparent OCDMA networks is further analyzed in a follow-up study, and a second journal article is expected as output.

- **Mireia Omella, Phd student at UPC, hosted by AIT from 01/04/2008 to 10/04/2008**

Upstream Transmission in WDM PONs at 10Gbps Using Low Bandwidth RSOAs Assisted with Optical Filtering and Electronic Equalization This work has experimentally demonstrated that, despite their limited electrical bandwidth, RSOAs can be used as low cost wavelength independent sources at ONUs and allow error free 10Gb/s upstream data transfer over more than 85Km when combined with optimum filter offset and electronic DFE at the receiver end. Symmetrical transmission at high bit rates (10Gbps) using RSOAs in Central

Light Source access networks is a key goal for next generation PONs, and related activities. We have published the results of this mobility action to ECOC08: "Upstream Transmission in WDM PONs at 10Gbps Using Low Bandwidth RSOAs Assisted with Optical Filtering and Electronic Equalization ". Also it is planned to submit later results to a journal.

- **Kivilcim Yuksel, Research Assistant at FPMs, hosted by FT from 15/11/2010 to 19/11/2010**

OFDM for future access networks - OFDM (Orthogonal Frequency Division Multiplexing) appears as a promising multicarrier modulation technique, which finds an interesting application area for the optical access networks thanks to the spectral efficiency and the possibilities offered by OFDM in terms of multiple access (OFDMA). Up-to-date information was provided to the student on the next-generation Passive Optical Networks (NG-PON), NG-PON standards, utilisation of Optical OFDM in PONs, and ongoing projects of Orange Labs on these technologies by the way of briefings, technical meeting and brief demonstrations. Fruitful discussions were taken place on PON monitoring. An active participation to the ongoing measurements to investigate the effect of the laser source parameters on the IQ-AMOOFDM permitted a better understanding of lab activities.

Parties agreed on considering the potential new collaboration topics between FT and FPMs in terms of graduation projects and/or common PhD thesis.

- **Mireia Omella, Phd student at UPC, hosted by FT from 08/03/2010 to 05/06/2010**

Investigation of novel wavelength shifting techniques for next generation networks - The performed mobility has allowed performing two different studies with experimental validation based in the reflective semiconductor optical amplifier (RSOA) for access networks. The first demonstrated the capacity of a RSOA to act as a novel wavelength shifter. A 2.5GHz translation has been obtained. It allows upstream transmission signal in the same channel as the assigned by the downstream but shifted enough to reduce the effects of Rayleigh Backscattering, in a system based in bidirectional optical fibre with upstream data at 2.5Gb/s. The second is related with the upstream transmission at 10Gb/s by using as a modulator a RSOA of 1.5GHz of bandwidth (BW) and high chirp. In conventional conditions it is not possible to detect at a BER lower than 10^{-2}. After applying phase adjustment at the ONU and simple RC equalization at the input of the RSOA, levels higher than 23dB of power budget between the OLT and the ONU at FEC limit have been achieved. The RC equalization is based on a simple electronic circuit consisting of a capacitor and a resistor to increase the bandwidth up to 3GHz. The phase adjustment is done by the use of a programmable (in amplitude and phase) optical filter. It has been demonstrated that the RSOA's chirp and the chromatic dispersion of the optical fibre can be compensated by programming the proper phase in the optical filter, with a flat response in terms of amplitude.

These investigations have allowed the acceptance of two papers in congress: ECOC 2010 in Torino (Italy) Mo.1.B.5 RSOA as a Sawtooth Generator for Rayleigh Backscattering Effect Mitigation and ANIC 2010 (postdeadline) en Karlsruhe (Germany) AThD2 10G-PON Using High Gain RSOA as ONU Transmitter and Optical Phase Adjustment at the OLT

Publications

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Research Contributions

RSOA-ONU

A **first scenario** consists in using only one fibre per ONU with the same wavelength for upstream and downstream. Bidirectional transmission over optical fibre networks may yield a large cost improvement due to a simplification of the network infrastructure and can also provide a cost-effective way to upgrade distribution networks by adding bidirectional channels, thereby increasing the bandwidth efficiency in the network system. This solution has been adopted in PONs where the spectral efficiency has to be kept high, so that each tree can only acquire the use of a single wavelength, on which down- and also upstream data is imprinted for full-duplex transmission. In addition, a single fibre access is intended for each ONU, also reducing user connection and deployment cost.

However, signals propagating in opposite directions at the same wavelength suffer significant impairment. As a light wave propagates along an optical fibre, it continually loses energy due to **Rayleigh Backscattering (RB)** created by microscopic fluctuations of refractive index.

In this joint activity, a novel method has been studied and tested. It consists in shifting the incoming wavelength at the ONU in order to avoid the overlap of the spectrum while maintaining the new wavelength inside the same array waveguide grating (AWG) channel. Although this work has been mainly focused on Rayleigh Backscattering, the same technique could also be used to avoid reflections close to the ONU. The device used for this shifting is a simple RSOA.

The **second topic** deals directly with the **chirp** present in the transmitter, in our case a RSOA, to increase the transmission capacity by adjusting the phase of a programmable optical bandpass filter at reception.

Phase modulation with a sawtooth waveform produces so-called serrodyne frequency shifting of optical signals[1]. It can be used for optical gyroscopes, spectroscopy, coherent optical communication systems or other applications. Creating and amplifying electrical high speed sawtooth is generally difficult due to its broadband spectrum consisting of many harmonic components.

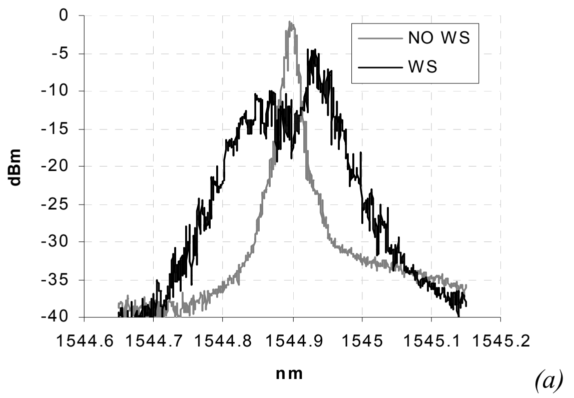
In previous work, the optical carrier frequency translation has been obtained by introducing the sawtooth signal in an e/o phase modulator1 or by adding a link of highly non linear

[1] I. Y. Poberezhkskiy et al., J. Quantum Electronics. 41, 12 (2005).

electrical transmission line[2]. In this experiment, the own phase modulation created by the RSOA's transient chirp produces the translation.

The idea is to shift the wavelength by a few GHz, in order to avoid or reduce the overlap between the signals, while maintaining the optical carrier inside the same WDM channel[3]. An RSOA is used to perform wavelength shifting by introducing an electrical square signal with low duty cycle. It constitutes also a new method to obtain a sawtooth signal at GHz, although in the optical domain.

The input signal for the RSOA is generated with a pattern generator with the word "10001000" at a bit rate of 10Gb/s, and after it is amplified by a RF electrical amplifier whose bandwidth (BW) is 10GHz. The optical input power into the RSOA has to be high enough to enter in a partial saturation. The best results have been obtained with an optical power bigger than -10dBm. The RSOA's e/o BW is 1GHz. Figure 46 shows the optical output signal in time domain and Figure presents a spectrum comparison with and without applying the modulation to the RSOA, measured with an Optical Spectrum Analyzer (OSA) with 0.01nm resolution. The wavelength shifting can be observed, with around 8 dB of carrier suppression, but also an increment in its linewidth.



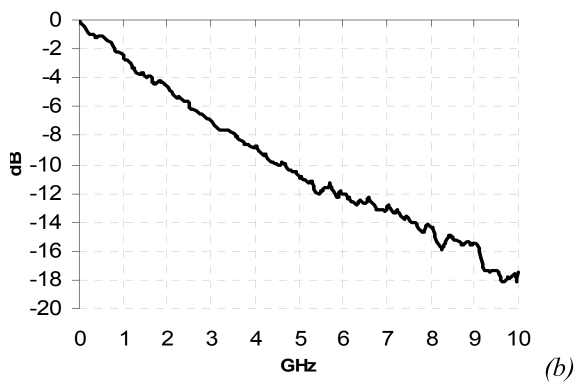


Figure 46. a) Spectrum at the RSOA output with and w/o the electrical modulation b) RSOA e/o BW

<u>RB mitigation. Experimental set up</u>

In order to demonstrate the concept, and separate the different effects contribution, the ONU consists of several elements that are not optimized for cost efficiency, thus using for example, a RSOA plus an EAM instead of an integrated REAM-SOA chip. The set up is presented in figure 47. A CW signal at 1535nm is introduced from the OLT. Between the OLT and the ONU there is a bidirectional uncompensated link consisted of standard SMF-28 fibre. The laser optical power is fixed to 3dBm to avoid non linear effects in the fibre. At the ONU, the CW signal arrives first to the RSOA. The electrical low duty cycle square signal described in last section, together with a DC bias of 130 mA is applied through a bias-T to the RSOA. The optical sawtooth signal generated by the RSOA enters the EAM, which is used to modulate the upstream data.

[2] D. M. S. Johnson et al., Optics Letters, vol. 35, no. 5, pp. 745-747, March 2010

[3] M.Omella et al., J. Lightwave Technol. 27, 17 (2009).

The utilized EAM presents around 15 dB of insertion loss. Its return loss is around -27dB, for this reason, in order to separate the effects of reflections and RB, it has been isolated from RSOA by using circulators and angled connectors.

A 2.5Gbps NRZ data stream with PRBS of 2^7-1 is introduced into the EAM modulator. This data will be mixed with the optical signal coming from the RSOA.

In order to create the WS, the input current of the RSOA has to allow a signal with high extinction ratio. This can be a problem for the EAM data modulation because the sawtooth signal can appear as noise in the ones, remaining very little eye opening for the data. To overcome this trade-off between WS quality and ER available for the data, the solution is to synchronize both PRBS, as it is presented in Figure right. An EDFA has been introduced in the ONU in order to take complete BER curves for all the cases.

When the modulation in the RSOA is not used, the current of EAM and RSOA have been optimized again. At the OLT, the receiver consist of an optical band pass filter TB9 with a BW of 0.22nm and an APD whose BW is 10GHz.

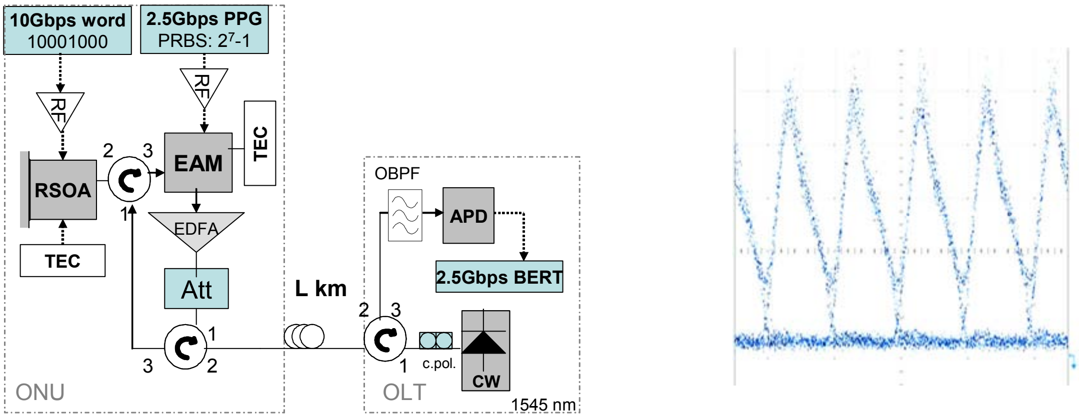


Figure 47. Set up (left) and EAM's output (right) after PRBS of EAM and RSOA synchronization

RB Mitigation. Experimental Results

The system performance has been evaluated for back to back (BTB), 10.3km and 26.3 km in terms of bit error rate (BER) versus optical power in port 3 of the OLT circulator. As the power is changed in the ONU, the received optical power will be directly related with the optical signal to RB crosstalk ratio (OSRBR). The measured optical power in that point (port 3 OLT circulator) when the fibre is not connected to the ONU is directly the RB power (plus the circulator losses).

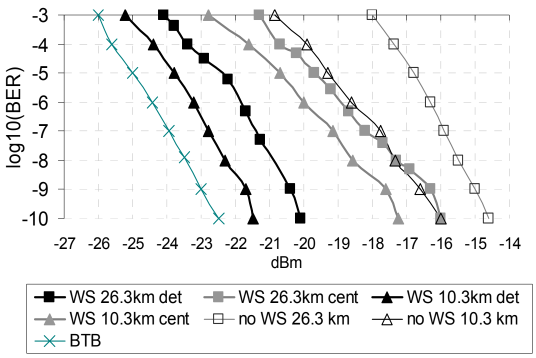
The BER curves, shown in figure 48, compare the performance of the system for each distance, taking into account 3 cases: no WS, WS with the filter of the OLT centred in the point of maximum transmission, and WS with such optical filter detuned around + 0.2nm. Detuning the filter without applying the WS, does not produce any improvement because the upstream signal is at the same wavelength than the RB. As expected, the curves for the 10.3 km spool require less optical power than the ones of 26.3km to achieve low BER due to its smaller RB contribution. The 1.12dB of difference is translated into around 1.5dB of penalty for the fibre of 26.3 km for BER equal to 10^{-9} if no WS is applied, while it is around 1.2dB for the WS cases.

Without doing WS, the penalty due to RB effects is 8 dB for 26.3 km for a BER of 10^{-9} and around 6.5dB for 10.3 km, which is translated into a requirement of OSRBR of 14.1dB and 13.7dB respectively.

The created WS allows reducing the penalty due to RB by itself, although the big improvement comes when the OLT optical filter filters out part of the RB component. In real networks this could be performed using the periodicity of an array wave grating (AWG) where all the upstream wavelengths come slightly detuned from the channel maximum transmission point.

With the filter in its central position, the system improves around 1.3dB for 26.3km and 1 dB for 10.3 km, thus requiring an OSRR of 12.8dB and 12.7dB respectively. With the filter detuned around 0.2nm, the WS is able to require 5.3dB and 5.1dB less power for 26.3km and 10.3 km to achieve a BER of 10^{-9} compared with the case of no WS. It means an OSRBR of only 8.8dB and 8.6dB for 26.3km and 10.3 km respectively.

The electrical eye diagrams after APD receiver, for a length of 26.3 km and an optical power of -20dB, are presented in Figure .b2. The eyes on the left side have been taken with the filter in the central position and the ones on the right for the filter detuned 0.2nm. In the upper ones the WS was activated and the bottom ones are for the no WS case. In the detuned case with WS, it can be observed that although the crossing point is not centred due to the sawtooth signal shape of the transmitter, the eye is open and clear, while if the filter is centred some spots appear in the eye. When the WS is not used, the crosstalk due to RB is too big and the eye is filled with spots.



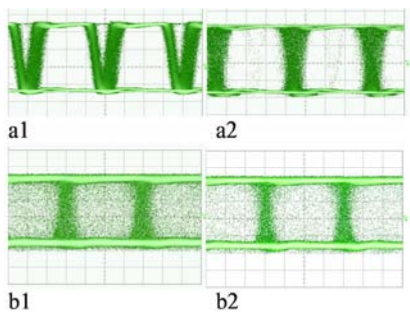


***Figure** 48. BER results (left) and Eye diagrams for 26.3km after APD with a) and without b) WS, with the filter detuned (1) and centered (2) for the same optical power (-20dBm) (right).*

10G-PON using High Gain RSOA as ONU Transmitter and Optical Phase Adjustment at the OLT

For the deployment of next generation 10G-PON, coexistence with current deployment and cost-effectiveness are key factors. The RSOA can be used as a colourless low cost ONU transmitter. However, the low electro-optical bandwidth and chirp limit in most of the cases the applicability of RSOAs with data rates up to 2.5 Gb/s. New generation of RSOAs are starting to be reported with higher bandwidth and gain. Direct modulation at 10Gb/s only using a simple RC circuit to increase its e/o bandwidth has been reported[4]. The chirp is taken as a tool[5] to increase the bandwidth by using the slope of an optical filter, and together with a DFE/FFE electronic equalizer after the optical receiver, allows upstream transmission at 10Gb/s over more than 80 km. Here, an optical filter capable to be configured in attenuation and in optical phase is used at the OLT. Signal degraded by the dispersion and RSOA chirp can be partially restored only changing the phase of this filter. The RSOA allows transmission over 10km and 26 km with high Power Budget (PB) at FEC limit at 5Gb/s and 10Gb/s while it was impossible originally to transmit at 10Gb/s due to its high chirp.

Capacity enhancement. Experimental set-up

The used set up is presented in figure 49. A CW signal laser at λ=1561nm with 5dBm optical power is sent from the OLT to the ONU. This wavelength is used to modulate the upstream with a NRZ PRBS 2^9-1 signal at a bit rate of 10.3125 Gb/s with a bias current of 100mA. An RC filter enhances the e/o BW from 1.2GHz to 3GHz. An attenuator is placed between the OLT and the ONU to fix the PB. At the OLT the receiver part is composed by an erbium doped fibre amplifier (EDFA), the optical filter and an APD with limiting amplifier. Figure 48 also shows the RSOA ASE curve. 10G-EPON standard proposes the 1574-1580nm bandwidth assignment for the 10 Gb/s downstream[6]. This RSOA is precisely centred in those wavelengths, with a 3dB optical bandwidth of 44 nm.

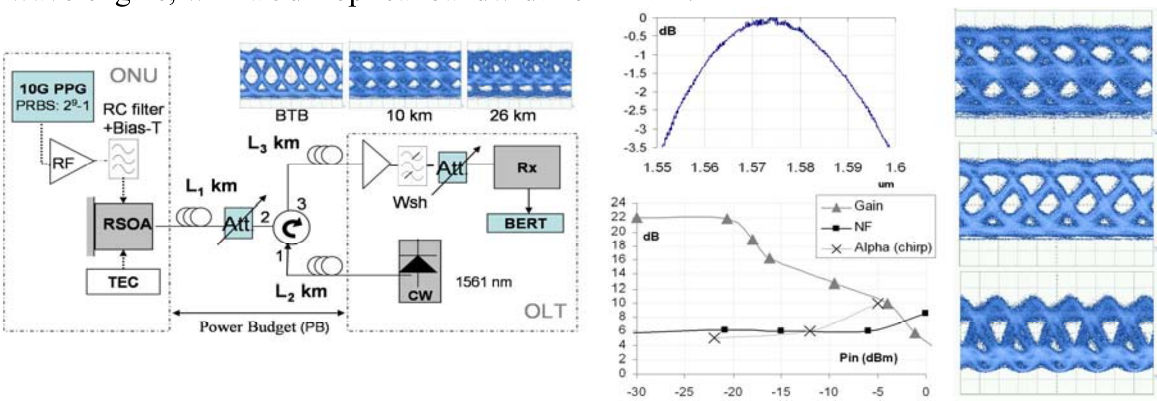


*Figure 48. **Left:** Set up and eye diagrams in BTB, and after 10km and 26 km. Middle up: RSOA ASE curve. Middle bottom: RSOA's gain, noise factor and chirp respect optical power. **Right:** eye diagram comparative after 10km with a simple flat filter centred (top), a filter detuned (middle), the flat filter centred with a specific phase (bottom)*

The device presents a maximum of 22dB of gain at 100mA and the noise factor is between 6 and 8 depending on the optical power. Chirp has also been measured obtaining an alpha parameter of 5 to 10 depending also on the optical power. Finally the optical fibre has been

[4] B. Schrenk et al., Photon. Technol. Lett., vol. 22, no. 6, pp. 392–394, March 2010.

[5] I. Papagiannakis et al., J. of Lightwave Tech., vol. 28, no. 7, pp. 1094-1101, April 2010

[6] K. Tanaka et al., Journal of Lightwave. Tech. vol. 28, no. 4 pp. 651-657, Feb. 2010

placed either taking into account RB, only L1 in bidirectional transmission and also by two separated spools L2 and L3 unidirectional.

Experimental results

The chirp of the RSOA closes the eye after 10km at 10Gb/s being not possible to detect the signal. The eye diagrams of the right column in figure 49 shown a comparative with the signal after 10km with a simple flat filter centred (top), a filter detuned (middle), and the flat filter centred with a specific phase (bottom). Figure 49c presents the effect of the optical filter Waveshaper (Wsh). The differences between offset filtering and phase were small so only one trace has been plotted for vision simplicity. The chirp, together with the chromatic dispersion, creates null transmission points at around 5.5 GHz for 10km and 3.4 GHz after 26km. The optical filter restores the signal, thus allowing the detection at the OLT. In Figure f it can be seen the flat filter used for 10km.

Figure 49a and figure 49b show the BER for 10.3125 Gb/s for 10km and 26km using the Wsh. Figure. 49d and 49e present the BER for 5.15625 Gb/s (without Wsh) also for 10 km and 26km. According to the gain presented in Fig. 58 and the power of 5dBm from the OLT laser, using only one fibre, the optical signal to RB ratio (OSRBR) is around 24.5dB for a PB of 10, OSRBR=11dB for a PB of 20, OSRBR=9dB for a PB of 23 and OSRBR=-3dB for a PB of 30. The FEC limit of 10^{-3} is considered as in the new standards. At 10.3125 the maximum PB is 20 dB using a bidirectional fibre and 23 dB if two unidirectional fibres are used, while at 5.15625 Gb/s PB of 23 can be afforded with 1 fibre as a maximum, while PB of 30 is possible by using two fibres. As a final remark, using a PB of 10dB, the BER curves present the same behaviour for 1 and 2 fibres approach.

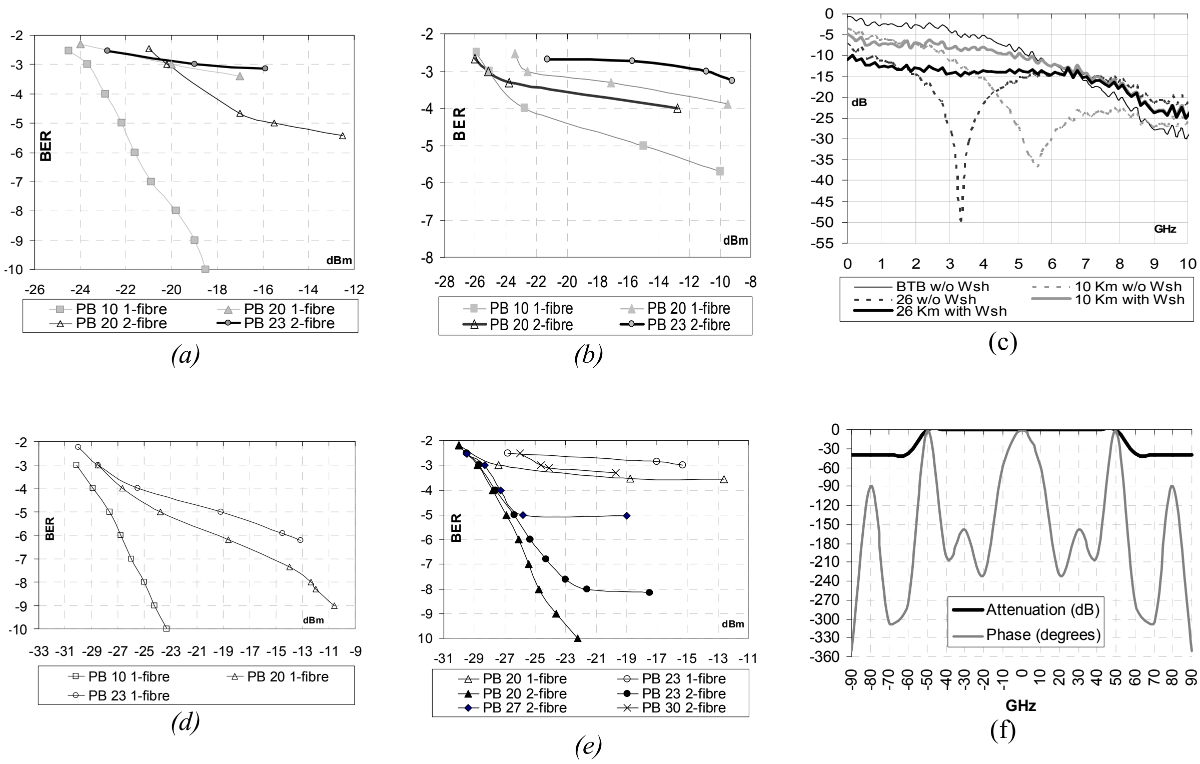


Figure 49. BER with respect optical power for 10.3Gb/s and 10km a) 10.3Gb/s and 26 km b) 5Gb/s and 10km d) 5Gb/s and 26km e). In c) e/o response for BTB, 10km and 26km with and w/o Wsh. In f) attenuation and

phase of the optical filter for 10km phase adjustment

Conclusions

Two different works related with the use of a RSOA at the ONU premises have been developed.

The first work presents a procedure to achieve an optical sawtooth signal at a bit rate of 2.5Gbps by using only digital signal consisting of a low duty cycle rectangular signal as an input for a RSOA with a BW of 1GHz. This produces a 2.5GHz shifting of a CW carrier because of phase modulation produced in the same RSOA due to its transient chirp. This effect can be used to partially mitigate the penalty of RB in PONs with ONUs presenting small amplification like SOA-REAM configurations. An experiment has been performed taking an RSOA and an EAM for the proof-of-concept. More than 5 dB of improvement have been obtained with 26.3 Km, requiring less than 9 dB of OSRBR to get a BER of 10^{-9}.

In the second work, with phase adjustment at OLT, an RSOA of 1.2 GHz of BW and high chirp has been used to transmit at FEC limit at a bit rate of 10.3Gb/s with a power budget of 23dB and at 5Gb/s with a power budget of 30dB. RB limits this power budget to 20dB (OSRBR=11dB) and 23dB (OSRBR=9dB) for 10.3Gb/s and 5Gb/s respectively. Phase adjustment avoids the attenuation of the filter compared with detuned optical filtering and provides similar results.

Wavelength Converting Optical Access Network for 10Gbit/s PON

This work demonstrates a proof of concept wavelength conversion system that consolidates multiple existing Passive Optical Networks (PON) architectures into a long-reach wavelength division multiplexing backhaul. We have previously proposed a network making use of a wavelength converter unit based on the Cross Gain Modulation (XGM) properties of Semiconductor Optical Amplifiers (SOA) [1] for consolidation of 2.5GBit/s PON systems. A demonstration of the XGM wavelength converter was built in the laboratory, as shown in Fig. 2. An input pump or data signal modulates the XGM converter SOA gain, which in turn modulates the CW probe wavelength, the filtered signal at the CW Probe wavelength is the converted signal at the probe wavelength which is the inverse data. However, there exists some drawback of the XGM wavelength converter that may become an issue as the access network data rate is increased to 10Gbit/s.

A solution to these problems is to use XPM based on a dual SOA Mach-Zehnder Interferometer (SOA-MZI) wavelength converter [2], an integrated XPM wavelength converter was used in our experiment. This scheme operates by using the input signal to modulate the carrier density in the active region of the SOA, which in turn modulates the refractive index. The result is phase modulation of the CW probe signal. The interferometer configuration of the SOA of figure 50 transfers the phase modulation into amplitude modulation due to the constructive and destructive interference depending on the phase change. The advantage of using XPM is that the phase modulation is not wavelength dependent [3], therefore it will be possible to conserve the extinction ratio when converting from any wavelengths within the CWDM band. This greatly benefits the ONU design, because it enables wavelengths from low cost, colourless ONUs to be converted to a tightly controlled pump wavelength, allowing the use of DWDM in the backhaul section of the PON while maintaining simplicity for ONUs in the customer's premises.

The XPM scheme also allows smaller gain variation for performing the conversion. Hence, the effect of chirp is reduced and therefore it allows transmission at more than 10Gbit/s and over longer distances. The ability to bias the phase shifter in the XPM converter allows the interferometric SOA converter to operate either on the positive or negative slope of the interferometer. The positive mode of operation will mean negative chirped converted signals which may enable transmission of 10Gb/s signal over long distances of standard SMF.

As next generation of access network will have a larger distribution area, the performance of long distance backhaul transmission through Standard Single Mode Fibre (SSMF) needs to be studied. Fig. 51 is the proof of concept system used for testing the transmission distance of

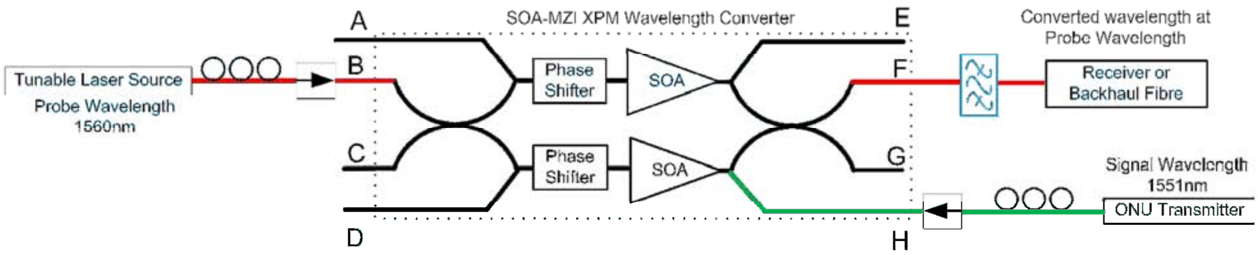


Figure 50 SOA-MZI wavelength converter utilising cross phase modulation, the dash line section contains the integrated SOA-MZI XPM Wavelength converter

the XPM wavelength converter. The signal from the ONU at 1551nm is first transmitted over a 20km PON distribution section with the splitter/combiner represented by a -12dB attenuator to simulate the loss of a 1:16 splitter. The probe wavelength is 1560nm onto which the data is converted. For the SOA-MZI device used, it was observed that the input signal power to the SOA-MZI needs to be above -8.5dBm for the wavelength converter to produce sufficient phase modulation due to an extra 3dB loss in the input coupler and up to 1.75dB loss in the fibre to device coupling. The optical signal power reaching the wavelength converter after 20km of fibre and 1:16 splitter is lower than the minimum required operating power of the SOA-MZI device, and therefore a pre-amplifier will be required before the wavelength converter.

At 20km backhaul, it was possible to test the Inverting and Non-inverting operation modes. The results are shown in Fig. 52. The inverted converted signal was too corrupted to be measured after 40km due to the positive chirp generated by the inverting mode of operation, as was seen previously with the XGM wavelength converted signal that was transmitted through a SSMF, but since the chirp in the XPM case is less, the signal managed to travel 20km and still remained error free.

It can be seen that there is a 3dB penalty between the two signals due to the non-inverting signal having a higher extinction ratio at the output. The introduction of negative chirp as a result of interference on the positive slope of the SOA-MZI means the converted signal pulse can travel longer distanced in a SSMF because this type of pre-chirped signal is dispersion compensating. After 40km of backhaul section the non-inverted converted signal is still error free. However, after 60km the signal power is reduced to -13.6dBm which is too low to maintain error free performance. A booster SOA was required to amplify this signal resulting in the new schematic shown in Fig. 11.

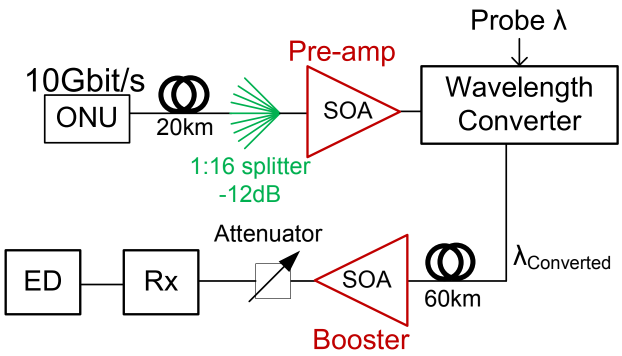


Figure 51. Schematic of a wavelength converted PON with 60km backhaul section, with an amplifier before the receiver to boost the signal power level

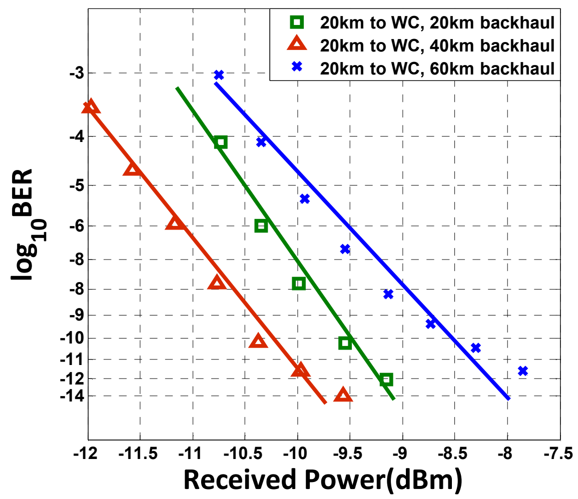


Figure 52. Transmission distance measurements for 20, 40, 60km backhaul

The result between the 20km, 40km un-amplified backhaul and the 60km amplified backhaul BER performance result is shown in Fig. 52.

Athermal lasers for PONs

Work has been conducted to develop a new control algorithm with reduced mode-hopping is demonstrated for uncooled WDM Cband channel generation from a DS-DBR laser with 100GHz spacing and low thermal drift up to 70°C. 10Gb/s external modulation with transmission over a 25km link is achieved.

An uncooled and colourless optical transmitter using a tunable digital super-mode (DS) distributed Bragg reflector (DBR) laser has been demonstrated. Wavelength tuning or constant wavelength operation independent of temperature is achieved by simple control of the currents to the different laser sections. By using an optimised algorithm, a substantial reduction in mode hopping occurs.

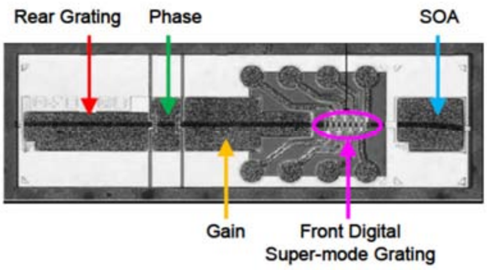
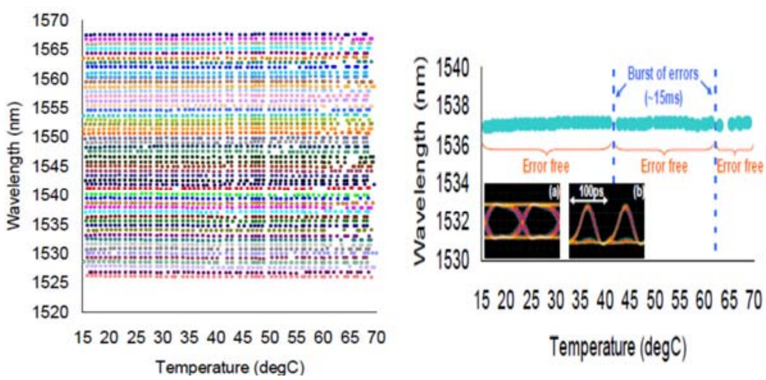


Fig. 53 Top view of a DS-DBR laser chip

Fig 53 shows the configuration of the DS-DBR laser used in this work. The laser consists of gain, phase, rear grating and multiple front grating sections. A semiconductor optical amplifier is integrated at the front end to enable output power equalisation. Sub-band selection is made by adjusting the injection current in a pair of adjacent front grating contacts. The output wavelength is tunable within a sub-band by controlling the rear grating and phase currents. Here the output wavelength of the laser is controlled autonomously by using an open loop algorithm which changes the current to the front and rear grating sections as a function of laser temperature. Additional fine control can be accomplished by varying the current to the gain and phase sections.

An open-loop control algorithm is applied to each of the WDM channels in the C band (1550nm). It is possible to maintain the wavelength of each of 53 channels (100GHz spacing and around 41nm coverage) with less than ±0.15nm wavelength deviation over a temperature range from 15 to 70°C (fig. 54(a)). Only controlled mode hops occur in most channels as it shown in fig. 54(b). The system operates error free even when the ambient temperature is varied continuously from 15°C to 70°C. There is a ~15ms burst of errors at the longitudinal mode hop of 41°C and at 61°C whilst the laser is automatically reconfigured to use another supermode. The recovery time can be reduced by optimising the modulation speed of the electrical drive to the laser. In a real system, the mode hops that occur at few temperatures up to 70°C can be predicted owing to the known performance of the laser. The positions of mode hops can be relocated to minimize their occurrence in a known environment.



(a) *(b)*

Fig 54. (a) Coverage of C-band uncooled WDM channels (53 channels with 100GHz spacing). (b) Wavelength stability and transmission performance of a representative channel over a temperature range from 15 to 70°C. Including signal eye diagram in NRZ operation, and RZ eye diagram for BER measurements (insets).

Dynamic Reconfigurable Optical Access Network Architectures

Optical access networks are widely deploying to replace copper-based access networks. The fast-growing demand from the end-users is the driving force behind this wide scale replacement. The availability of high-speed connections to the end-users in turn inspires folks to come up with interesting, useful, and bandwidth-consuming applications, e.g., 3D YouTube, BitTorrent, and Immersive TV. This cycle forces optical access networks to further upgrade their capacity by increasing the transmission bit rate per wavelength and the number of wavelengths per fiber. However, the huge aggregated capacity of the system now raises an issue of network resource under utilization since user demands are highly fluctuating. Thus, intelligent features such as optical reconfigurability are introduced to efficiently utilize network resources. By the optical reconfigurability, it means that an optical network unit (ONU) can be reallocated to another wavelength channel in the system if required.

Introducing reconfigurability increases system complexity in both physical and logical layers, thus increases the system cost. Therefore, a quantitative evaluation of its benefit is essentially needed to tradeoff with increased system cost. The collaboration between TUE and IBBT is essential since the evaluation requires strong competences in both TUE expertise in the physical layer and IBBT expertise in the logical layer.

Optical access networks are required to provide large bandwidths to home/business users, and

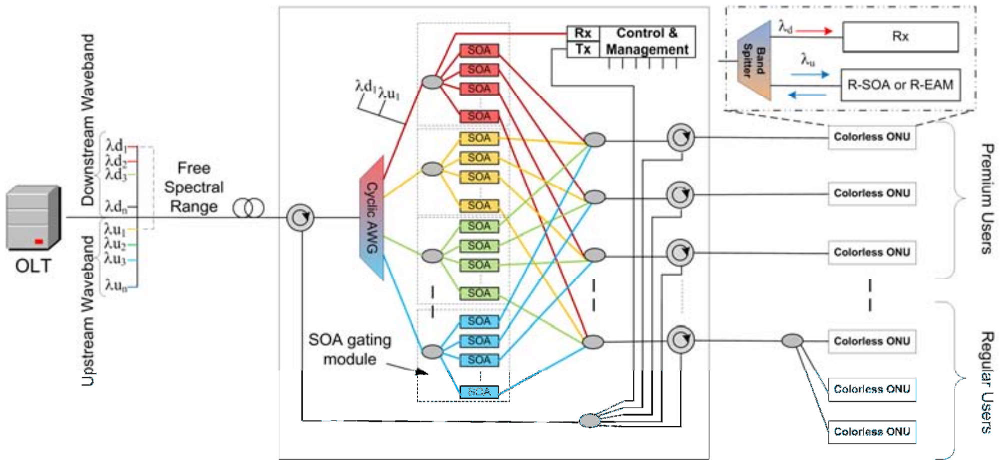


Figure 55. Active routing optical access network architecture

mobile backhaul. These users generate highly fluctuating traffic over time. For example, a home user demands bandwidth mainly in the evening for applications such as high-definition videos. During the day, the bandwidth can be diverted to a business user who has high demand for a virtual video conference and high-volume file transfers for short durations. The ability to divert bandwidth on demand means that network resources can be more efficiently utilized. A static Wavelength & Time Division Multiplexing Passive Optical Network (WDM-TDM PON) has huge capacity but lacks the reconfigurability required to adapt wavelength configuration to instantaneous traffic. The traffic statistical multiplexing in a static WDM-TDM PON can only be performed in the time domain within a wavelength channel, not across all channels.

Network architecture

Figure 55 shows the proposed network architecture, where a remote node (RN) based on a semiconductor optical amplifier array (SOA-array) is able to route desired wavelengths to one or more output ports. Each RN output port can connect to one optical network unit (ONU) or several ONUs by employing a passive power splitter according to service level agreements (SLAs) between the network operator and the subscribers.

The OLT transmits two wavelength bands: data-modulated downstream wavelengths and un-modulated continuous-wave (CW) wavelengths to be remodulated at the ONUs for upstream. A downstream wavelength has a corresponding upstream wavelength where the spectral distance is one Free Spectral Range (FSR) of the cyclic arrayed waveguide grating (AWG) in the RN. As a result, each pair of wavelengths is output from the same AWG port towards a SOA gating module. The ON/OFF states of SOAs in the gating module determsine which RN output port the wavelength pair will be routed to. Note that the wavelength pair can be routed to more than one output port. This wavelength pair reaches the destined ONU and is split by a downstream-upstream waveband splitter. The downstream signal is detected at the receiver (Rx) and the CW upstream signal is modulated by a colorless reflective-type modulator in the ONU such as a reflective semiconductor optical amplifier (R-SOA) or a reflective electro-absorption modulator (R-EAM). As the downstream-upstream waveband splitters directs the whole downstream waveband to one port and upstream waveband to the other, the colorless property of the ONU is achieved without the use of a tunable laser and a tunable receiver. The upstream wavelength with data is reflected back and propagates towards the OLT due to the bidirectional property of the waveband splitter.

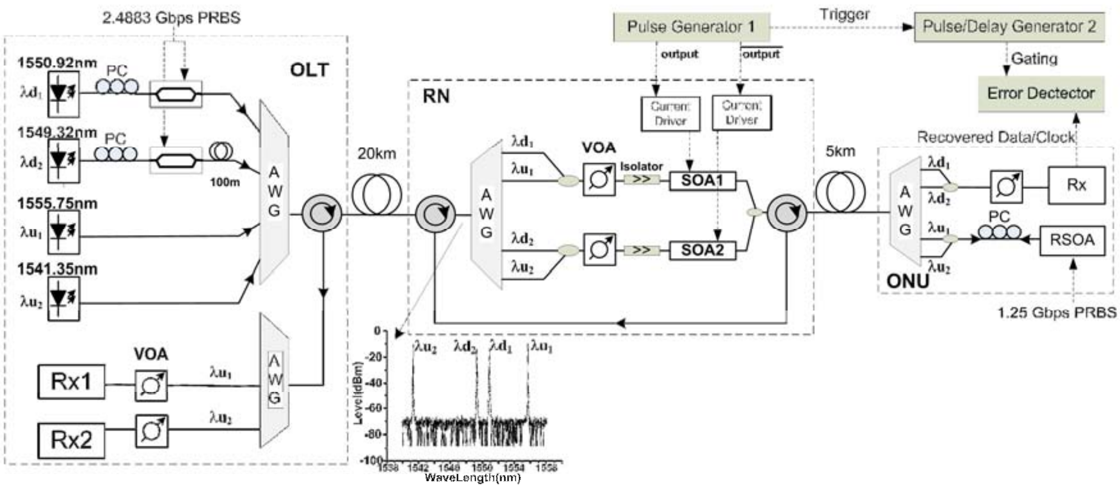


Figure 56. Experiment Setup

The control and management subsystem of this architecture not only requires signalling channels between the OLT and ONUs but also between the OLT and the RN. This is realized by allowing the RN to send and receive control information on a dedicated timeslot of the first wavelength pair. The remaining bandwidth can still be used by other ONU(s). By means of the signalling channel, a dynamic bandwidth allocation (DBA) algorithm process in the OLT is able to instruct the RN to route wavelengths based on current traffic status. On a high level, ARON can be seen as a set of PONs, each operating in TDM mode on a different wavelength pair. Therefore, DBA is able to work at two levels. In the first level, DBA distributes ONUs across the set of PON and in the second level, DBA distributes bandwidth to ONUs within a PON.

Figure 56 shows the experimental setup of ARON, where the OLT transmits four wavelengths, two for 2.5Gbps 223-1 pseudo random bit sequence (PRBS) downstream data and two CWs for upstream, which will be modulated by 1.25Gbps 223-1 PRBS data at ONU side. These wavelengths based on the ITU-T grid are selected because of the limited availability of DFB laser sources in our lab. To emulate a cyclic an AWG in RN, wavelengths in the same pair are combined again after the AWG. In the ONU, a similar configuration with AWG is used to emulate a waveband splitter. By using 100m fiber after the λd2 external modulator the data in two downstream channels are uncorrelated. The splitting ratio of 1:64 is emulated by the variable optical attenuator (VOA) placed in front of each SOA (from CIP Technologies).

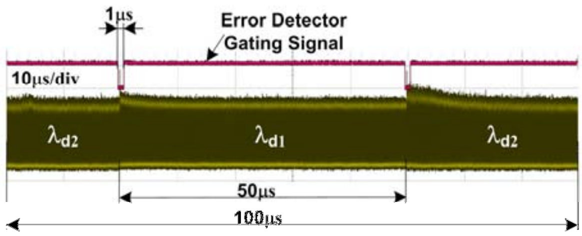


Figure 57. Time traces of optical power at ONU Rx and error detector gating signal.

The ONU is assigned either of the two wavelength pairs (λd1, λu1) and (λd2, λu2). Each pair is allocated for 50µs periods by switching the corresponding SOAs. The ON/OFF control signal is generated by pulse generator 1. Figure 57 shows optical power at ONU Rx input. Optical power overshoot at the beginning of each 50µs period is caused by imperfect impedance matching between current driver and SOA bias pins.

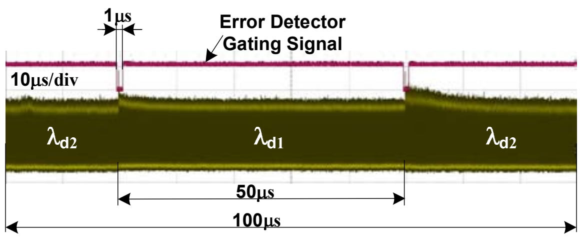


Figure also shows the gating signal for error detector generated by pulse/delay generator 2. The errors are counted at high level of gating signal and ignored at low level of gating signal. During the switching moment between two wavelengths, error detector ignores errors for 1µs in order to show error free transmission. Hence, ONU can be successfully relocated to new wavelength channel with 1µs guard time, which can guarantee seamless performance of on-going services.

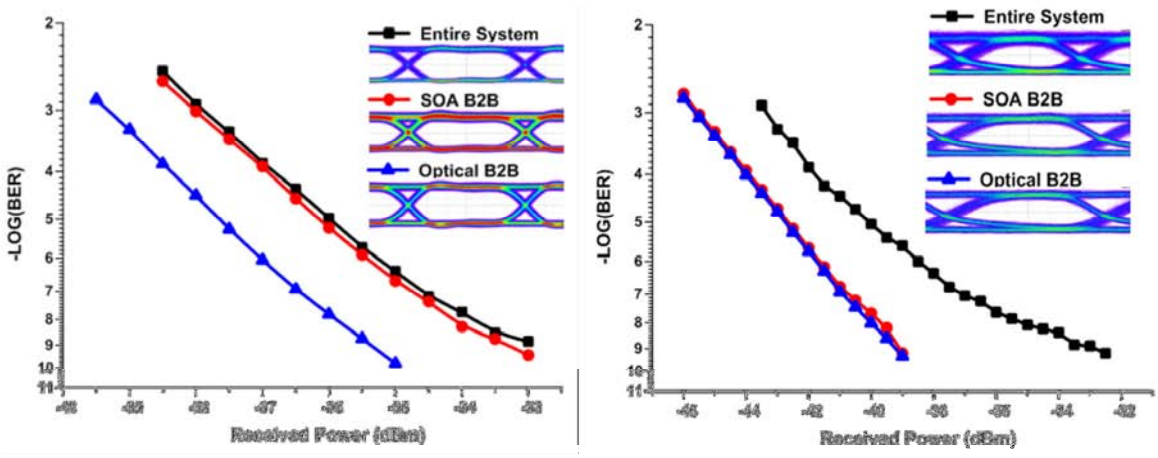


Figure 58. 2.5 Gbps downstream BER tests (left), 1.25 Gbps upstream BER tests (right)

BER tests are shown in figure 58for downstream in which three cases are measured including the entire system, SOA back-to-back (B2B), where 20km and 5km fibers before and after RN are removed, and optical B2B. It is shown that the performance of the entire system suffers a power penalty of 2dB when compared to optical B2B. The entire system plot and SOA B2B plot is almost similar revealing that the SOA is the dominant source for downstream signal impairment. In the upstream case, the entire system suffers a 6 dB penalty compared to optical B2B. However, it takes only 2.5 dB penalty to obtain 10^{-4} error rate as the entire system plot get closer to optical B2B plot when received power reduces. The eye diagram produced by RSOA has long rising and falling edges and low extinction ratio as shown in Figure causing such high penalty. In contrast to downstream, upstream SOA B2B plot almost coincided to optical B2B reveals that transmission distance is the dominant source for upstream signal impairment, e.g., backscattering. SOA is no longer the dominant source because only upstream CW seeding signal traverses through SOA.

We propose and demonstrate a fully flexible reconfigurable WDM-TDM PON architecture for dynamic capacity allocation. The RN architecture based on SOA gating modules gives 1μs switching time to reconfigure the optical connections. Moreover, RN integration is possible as SOA gating modules can be monolithically integrated in a single chip6. Despite of received and transmitted wavelengths changing over time, ONU architecture allows it to be colorless without tunable receiver and tunable laser. Hence, low-cost ONU is achieved.

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Annex 1: Inventory of Expertise – Summary

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