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Abstract:

This document is the second deliverable of the WP23 “Topical Project on Optical communication networks in support of user mobility and Networks in Motion”. This report gives an overview of the WP23 activities during the first year of this topical project and the plans for the second year. During the first year of this topical project, six joint activities have been discussed. Details on the progress and plans for these activities are presented. Two (2) conference/workshop papers and one book under preparation are the dissemination outcome of these joint activities.

Keyword list:
Hybrid optical/wireless networks, optical networks for user mobility, Networks in Motion

Disclaimer

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2. Executive Summary

This document is the second deliverable of the topical project (TP) “Topical Project on Optical communication networks in support of user mobility and Networks in Motion”. This deliverable aims to provide the results and outcomes of the running joint activities (JAs) as well as to present the activities that are planned for the coming year. In total, 5 JAs are active in the framework of WP23. JA 6 “Hardware implications issues for networks in motion” is discontinued due to internal changes in Ericsson. Thus, the involved partners cannot support this activity anymore. Finally, the current state and future plans of the remaining JAs are presented.

3. Introduction

Playing the role of a Network of Excellence, the BONE project has brought together over several years of research activities in Europe in the field of Optical Networks and it intends to repeat and validate this effort by stimulating a more intensified collaboration, exchange of researchers and building on its centralized activities, Topical Projects (TP), and Virtual Centres of Excellence (VCE) that can serve to European industry with education and training, research tools and test-beds and eventually pave the way toward new technologies and architectures.

This work package, identified as a TP on ***Optical Communication Networks in Support of user mobility and Networks in Motions***, combines a large number of partners currently working on various research fields interoperable to each other.

3.1.1 TP Objectives

Within the next few years, networks in motion will play a central role in the people's lives, worldwide. An upcoming networking concept is emerging based mainly on the requirements of mobile working groups of people of various societal sectors that demand ubiquitous connectivity. The individual subscribers themselves will increasingly carry around their own short-range personal network which is constituted when networked personal devices interconnect and create a Personal Area Network (PAN).

Many groups of users exist who follow a slowly or a fast mobility pattern and therefore access on mobile vehicles (car, train, airplane) or just to people moving on foot becomes a necessity. The moving networks often need to communicate with each other or the outside world, resulting in a unique new form of network namely the "*network in motion*". Thus the surrounding infrastructure needs to be able to support a large amount of personal network connections. For such new application scenarios, it is critical that the next generation of networks employs intelligent components and devices that in a way sense the user needs and are able to provide guaranteed content delivery in an efficient and secure manner (while providing the privacy of the communication).

For such a system to run successfully, intensive research must be done. Particularly, the use of optical network solutions in the aggregation and core part of the network is essential and requires extensive research in the both the networking and technology areas.

The planned effort in this work package will be divided in three main activities according to the identified objectives, which will run in parallel for the duration of the project. The first activity is ***technology oriented*** and will focus on the investigation and development of novel approaches able to support networks of wireless users that require rapid handover characteristics and high bandwidth connectivity. The second activity focuses on the ***aggregation network*** that supports the wireless users and specifically on switching solutions with rapid reconfiguration characteristics. The third activity is ***network and control layer*** oriented and will study new MAC, routing and signalling protocols to support the characteristics of networks in motion.

The three activities cover research areas that can be initially developed independently but under the same general focus as this will be defined by the properties of networks in motion. Therefore, first, it is important to define a common knowledge platform about the possible solutions and the properties of these novel network approaches that support seamless connectivity of various wireless users in a rapidly reconfigurable environment. The purpose of this knowledge platform will be:

- *To provide the basic requirements and characteristics that novel technology and networking solutions should target in.*
- *To identify the limitations and challenges that require a possible solution and consequently push technology and networking towards these directions.*

Finally it is of interest in this work package to join together efforts that could possibly evaluate or even demonstrate complete solutions in support of the objectives.

More specifically this topical project is focusing on providing collaborative research towards three main directions identified in the following objectives:

- *To perform studies on intelligent technologies and design challenges for wireless access in networks in motion (e.g. based on radio over fibre (RoF), free-space optics (FSO), or conventional wireless solutions with optical fibre feed)*

- *To perform studies on networking properties and switching characteristics for the aggregation and core networks in support of networks in motion (e.g. Switched Ethernet based solutions or advance schemes like OBS/OPS),*
- *Development of control plane and signalling algorithms and protocols for networks in motion (e.g. MAC layer design or network layer approaches with QoS quarantines, resource reservation approaches etc.*

3.1.2 Deliverable goals

The main goal of this deliverable is to report the results and outcome of the performed activities within the framework of this TP and also to report the activities that are planned for the remaining time of this TP.

4. Participants

This section covers the interested partners and participants in this TP (WP23). According to the Annex I (Description of Work), there are (16) partners in total, which are collaborating in this WP. Besides, there are also some additional interested partners, who will collaborate in joint research activates. Table 1 (in alphabetic order of partners' short name) provides a list of participant and the code of joint activity(ies), in which they are involved. A detailed description of these joint activities is provided in the next section.

Table 1: Participating partners in joint activities of WP23

Partner Number	Short Name	PM Allocation	Joint Activity Code
P19	AIT	3.5	2, 3, 4, 5, 6
P08	COM	0.5	-
P49	Ericsson	0.5	1
P04	FRAUNHOFER	1.5	-
P01	IBBT	0.5	-
P20	ICCS/NTUA	1.0	-
P28	ISCOM	0.5	2
P37	IT	0.5	2
P30	POLITO	0.5	-
P35	TELENOR	1.0	-
P05	TUB	0.5	-
P36	TUE	0.5	5,6
P11	*UAM*	-	5,6
P45	UCAM	1.5	-
P46	*UCL*	-	3
P06	UDE	1.00	1
P47	UEssex	0.75	-
Affiliate Partner	*UH*	-	3
P15	UPVLC	0.5	4

5. Joint Activities

Based on common interests of partners the following joint activities were planned within this TP. Given the inventory of expertise, which is also circulated among the partners, it is possible to have more joint activities during the next year of this TP. The table of research topics is periodically circulated among the interested partners to make new collaborations/integrations possible. Table 2 contains the key information regarding the Joint Activities that are planned so far. In addition to the current planned activities, and given the inventory of partner expertise, it is possible for all participants in this TP (WP23) to plan other new activities during the term of this topical project. As it is shown in the following table, 5 joint activities with 2 mobility actions have been planned for this work package. These joint activities span till the end of the second year of this TP.

Table 2: Summary list of the planned joint activities

No.	JA Title	Contact Person	Participants	Mobility Action	Deadline
1	State of the art definition for components supporting FSO networks in motion	Antonio Teixeira (Teixeria@ua.pt) Giorgio Maria Tosi Beleffi (giorgio.tosibeleffi@sviluppoeconomico.gov.it) Silvia Di Bartolo Gabriele Incerti	IT, ISCOM, AIT		M36
2	Converged MAC algorithms for unified optical wireless functionality	Pandelis Kourtessis (p.kourtessis@herts.ac.uk), Milos Milosavljevic (m.milosavljevic@herts.ac.uk)	UH, UCL, AIT		M36
3	UWB Radio-over-fibre transmission in indoor environments using different media	Roberto Llorente (rllorent@dcom.upv.es) Ioannis Tomkos (itom@ait.edu.gr),	UPVLC, AIT	Yes	M24
4	Optimizing service delivery in a converged hybrid optical-wireless network	Bas Huiszoon (bas.huiszoon@uam.es), Ioannis Tomkos (itom@ait.edu.gr), Ton Koonen (a.m.j.koonen@tue.nl)	UAM, TUE, AIT	Yes	M36
5	All-optical Routing Architecture of Radio Signals using Label Processing Technique for In-building Optical Networks	Ton Koonen (a.m.j.koonen@tue.nl), Bas Huiszoon (bas.huiszoon@uam.es), Ioannis Tomkos (itom@ait.edu.gr)	TUE, UAM, AIT		M36

5.1 State of the art definition for components supporting FSO networks in motion {IT, ISCOM}

5.1.1 Motivation and objectives

As already mentioned in the previous deliverables, in the last decades, many new technologies have been proposed and discussed to solve the last mile bottleneck of telecommunication networks. Thanks to its high bandwidth, easy of connections, low cost characteristics, free-space optics (FSO) represent a good candidate for short reach, hundreds of meters, connection becoming an alternative solution to fiber based and/or existing RF network-user interfaces. Taking care of the atmospheric conditions and carefully controlling the beam misalignments, FSO could be suitable to temporary high data communications in motion network scenarios [1].

5.1.2 Main outcomes and results

ISCOM and IT carried out a joint activity, with the collaboration of AIT, regarding the set up of a wireless test bed on the area surrounding the ISCOM premises. An FSONA 1.25 GEthernet wireless system has been purchased by ISCOM and mounted on its roof as reported in Fig. 1.

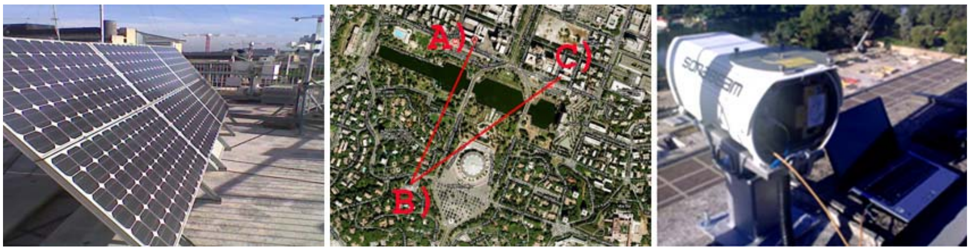
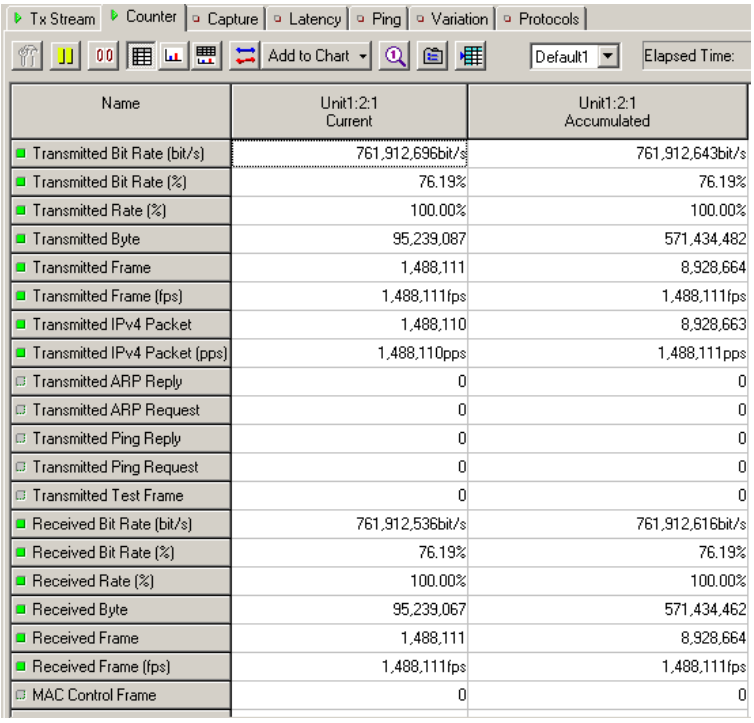


Figure 1. Wireless Set Up: Photovoltaic Station to supply the FSO Heads [Left], Test Bed Area [Center] (A and C are ISCOM premises while B is a Tower 60m tall also called “the mushroom”, The FSONA FSO system [Right]

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 little wood. Thus fog, humidity and extreme scintillation effects can be studied. In Fig. 2 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 2. Preliminary Results with statistics on the traffic sent between the FSO heads.

5.1.3 *Next steps*

Within this year and on these topics a formal agreement has been signed within BONE and the COST ICO802 with the help of the team. A chapter about Optical Wireless has been submitted and published on Intech, a Web Publisher, and a paper entitled "*Towards an Hybrid Gigabit Ethernet Wired Wireless Low Power Consumption Passive Optical Access Network*" has been submitted to OFC 2011. All this work has been carried out in the framework of WP23 also in collaboration with WP13 on Access and the people involved consider it fundamental also for possible new project submissions (FP7/FP8).

5.2 *Converged MAC algorithms for unified optical wireless functionality {UH}*

5.2.1 *Motivation and objectives*

The motivation behind the research and development of integrated wireless-optical networks becomes evident when considering the multifaceted advantages of such a solution for broadband access. The interoperability of wireless terminations and optical network termination units offers the flexibility and robustness, inherent in wireless access technologies. Such flexibility pertains to user mobility, users' peer communication, and multi-hopping capability, while the robustness can be introduced by implementing wireless mesh topologies, in which the users can be served through a multitude of paths. Further converged architectures offer the high capacity and dynamic bandwidth allocation schemes offered by next generation optical networking schemes. This offers significant advantages in the load-balancing issue, since dynamic ONU selection schemes can monitor the network status and offer solutions in congestion problems on-the-fly.

The combination of these traits renders the overall architecture more self-sustained, since the effective integration of flexible resource allocation, multi-path wireless access and sophisticated broadband media delivery protocols in the network layer creates a more sophisticated platform that minimizes the necessity for monitoring and corrective interventions. The cost effectiveness of such schemes creates new opportunities for service and network providers, since futuristic services can be provided over a more reconfigurable, easily deployable and profitable networking framework.

Towards the technical evolution of wireless-optical access networks, this joined activity presents important solutions to problems relating to this direction. QoS by means of service differentiation, service level agreement and buffer queuing status for individual subscribers is in the focus by seeking the development of dynamic bandwidth and wavelength allocation algorithms in a new MAC suite that would allow centralised management of ONU requirements on demand in addition to extended time frames associated with resource assignment and packet propagation.

The following objectives have been identified to measure this joint activity's scientific achievements:

1. *Network Planning and Processing Management for Integrated Wireless-Optical Networks*

   This first objective will investigate primarily the MAC layer requirements (e.g. efficient distribution of bandwidth resources and end-to-end service delivery). In addition, network dimensioning studies will be performed resulting in detailed specifications regarding the network capacity and reach, number of served users, maximum guaranteed bandwidth per user etc. The basic outcomes are expected to provide network requirements with respect to the convergence of existing PON technologies like GPONs or EPONs, their possible updates (e.g. 10G GPON) and the originally proposed wired/wireless advanced PONs.

2. *Novel Dynamic Bandwidth Allocation Schemes*

   This objective aims at developing and demonstrating a dynamic MAC protocol suite for legacy and radio-enabled PON link spans that would enable extended wavelength band overlay integration of mobile end-users. The protocol development would initially include bandwidth to wavelength scalability in view of novel algorithms, extensively accounting for wireless functionality to increase the MAC efficiency for legacy and radio ONUs.

3. *Innovative Routing protocols adapted to Hybrid Networking*

   Issues pertaining to routing protocols that will be designed and deployed over the proposed hybrid network are of major importance to the success of the overall venture. The expected research outcome in regard to the specific topic relates to the design of novel strategies able to cope with the idiosyncrasies of such topologies, e.g. the asymmetric nature of both the optical backhaul and the wireless mesh topology, the dynamic and unpredictable nature of the wireless medium. Furthermore application awareness should be looked at to enhance QoS support through a cross-layer approach, in which routing decisions will take into consideration the type of traffic that needs to be routed. Our approaches will be compared with state-of-the-art routing mechanisms for optical networks, wireless mesh topologies and hybrid architectures.

Topology

Broadband wireless technologies, e.g. WiMAX [10] and Long Term Evolution (LTE) [11], would be employed to supply wireless terminations at selected ONUs. This could be implemented as a fibre termination to basestation (BS) ONUs. The architecture could consist of a legacy PON with novel wireless-enabled OLT and ONUs where the OLT controls the bandwidth allocation for all ONUs centrally. In particular to allow multiple wireless channel propagation in a typical sectorised approach over a legacy PON infrastructure, the wireless channels could be transmitted through the optical fibre after they have been downconverted to baseband NRZ and mapped to typical PON standard services (T-CONT in case of GPON).

In addition, the application of WDM to assign each ONU base station a unique P2P logical connection with the OLT provides the undisputable solution for increased capacity and improved network efficiency. In view of the proposed topology, extended wavelength band overlay [12] could support dynamic reconfiguration of wireless and wireline radio networking with low cost components employed in the OLT and ONU/BSs. This could be achieved by coarse wavelength propagation over the currently deployed splitter-based PONs. Consequently any wavelength in the operating spectrum could be partly or exclusively assigned to different ONU/BSs, providing in the later service level similar to WDM-PONs.

The topology would benefit from a flat control plane and seamless convergence by which signaling and control messages are directly exchanged between the OLT and end users. On-demand bandwidth provisioning to further enhance the wireless users capacity for example can be provided by dynamically distributing traffic over the mesh network. Significantly, the presented topology provides an advanced networking solution in the form of resilience since the application of wireless mesh allows channels from neighboring ONU/BSs to access users in the coverage area of a failing base station.

To that effect the control layer should adhere to service level agreement (SLA) and TCONT differentiation in the case of a GPON for instance. However, the classical DBA schemes employed in GPONs are not suitable for converged GPON and LTE networks for example due to the distinct transmission, bandwidth management methodologies and packet formats. To enable more efficient integration, an effective mapping mechanism is required between GPON priority queues and LTE service connections. Also since multiwavelength operation is in the focus, extra fields should be incorporated to the GPON frame format for each radio ONU during registration. Information such as the "wavelength sharing priority" needs to be included in the report message by adjusting the gate and the report packets used to establish communication between the OLT and ONUs.

5.2.2 Main outcomes and results

Towards the development of algorithms satisfying the objectives of a converged optical/wireless end-to-end network, preliminary work should be contacted aiming at providing all the requirements and optimal solutions for the optical backhaul network to efficiently being able to support wireless routing. This is expected to be achieved by defining at a first stage and subsequently enhancing the preferred options at the PON MAC layer. Also with regards to the network implementation, a choice should be made on the wireless topology to be utilized. To that extent, the application of a Radio-over-Fibre (RoF) network topology will be in the focus in this work. Any wavelength in the selected operating spectrum could be partially or exclusively assigned upstream to different ONU/BSs, providing in the latter service levels similar to wavelength division multiplexing PONs (WDM-PONs) without requiring any modifications in the remote node (RN).

On each wavelength, multiple microwave WiMAX channels are arranged in a FDM window to address individual ONU/BSs. The same FDM window could be carried on multiple wavelengths reducing maximum radio frequencies on an optical carrier. Consequently, high bandwidth optical and electrical components are not required. In downstream, the WiMAX licensed RF channels are shifted in frequency to address individual ONU/BSs using a predetermined LO and BPFs prior to being combined and modulated onto an optical carrier. At an ONU/BS a single LO, compared to multiple in a base-band approach is only required operating on the same frequency, as in the OLT, for the specific ONU/BS to downshift the channels. Multiple BPFs are then needed to select each channel prior to transmission over the air.

The requirements for the successful integration of Optical/Wireless networking would include

- Providing high capacity backhauling for emerging wireless networks
- Allowing the coexistence with legacy networks (E/GPONs, WiMAX, LTE)
- Supporting Multi-wavelength overlay over splitter PON and AWG-based PON architectures

Dynamic Multi-Wavelength operation (DMW) over PON (GPON, EPON) infrastructures can be applied either by upgrading the existing single-wavelength PON, or by introducing a completely new Dynamic multi-wavelength PON topology and MAC protocol. To that effect a GPON upstream map frame format enhancement has been developed to support DMW operation over splitter-based GPONs, together with an algorithm to manage the bandwidth allocation among the supported wavelengths. OPNET modelling of the performance characteristics of a DMW-GPON Fibre-to-the-Home (FTTH) topology has demonstrated a minimum 100 Mb/s bandwidth provision for each of 32 ONUs with a maximum 0.09 s packet delay for the lower service level agreement (SLA) ONUs.

The application of extended band overlay has been previously demonstrated over a standard GPON topology and has been shown to provide an ideal interim solution for smooth, dynamic and on-demand capacity upgrade [13]. This was achieved by reviewing the upstream and downstream frame format maps and consequently developing a new protocol based on the dynamic bandwidth allocation (DBA) algorithms previously developed for single-wavelength GPONs as explained in [13]. To adapt and extend these algorithms for coarse WDM operation, extra fields were incorporated into the GPON frame format [14]. Both the grant and the report packets used to establish communication between the OLT and ONUs were reconfigured to support dynamic multi-wavelength operation. Out of the twelve bits, in the Flags-field of the GPON upstream map frame format, the six unused reserved bits were utilized by assigning four bits to express the ONU's operating wavelength for proceeding cycles and two bits to specify the packet type, e.g. whether it is a control packet or data packet as shown in Figure 3. The same bits will be used to provide wireless connectivity over the specified wavelengths in proceeding protocols.

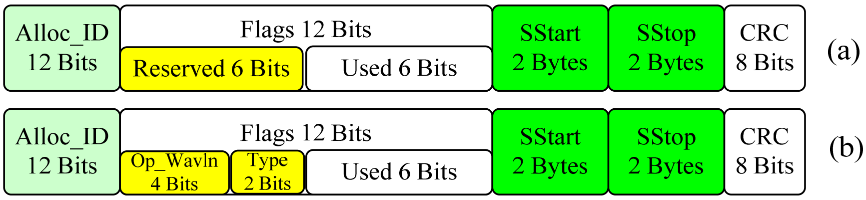


Figure 3. GPON upstream map frame format, (a) Single-wavelength, (b) DMW.

The wavelengths utilised by each ONU for data transfer can be defined during the ONU's registration stage by means of each ONU reporting its supported wavelengths to the OLT [13]. To demonstrate the maximum transmission time-slot utilisation for each operating wavelength and consequently provide reduced packet delay, a scheduling algorithm was developed that prioritises user transmission according to traffic status.

The Dynamic Multi-Wavelength Protocol

The aim of the DMW protocol is to increase the upstream bit-rate by introducing dynamic allocation of bandwidth concurrently in the wavelength and time domains. This has been initially achieved by developing the DMB algorithm [15] and modifying the GPON frame format to support multi-wavelength operation. The DMB algorithm facilitates three SLAs to assign each ONU with a guaranteed minimum bandwidth, to satisfy their basic service requirements, plus an additional allocation of extra bandwidth on demand, based on the assigned SLA. In the DMW algorithm presented here, a fourth service level is introduced to comply with modern service level provisioning [16] and to provide greater user experience and network flexibility. In addition, an extra upstream wavelength, bringing the total to five, is introduced with respect to previous DMW developments [13] to scale-up wavelength assignment in view of the ITU-T G.984.5 standard [12].

During ONU registration the OLT puts a request for each ONU to confirm the supported wavelengths. This is crucial to distinguish between different network sectors and bandwidth provision status among ONUs. Consequently, the OLT assigns the upstream bandwidth available in every polling-cycle in three stages. In the first stage, and after having received the requested bandwidth from each ONU, the OLT calculates a safety margin to refine the maximum cycle time for bandwidth allocation independently for each wavelength, allowing for more accurate population of the polling cycles with considerable decrease in idle time slots. The safety margin is determined by considering the overall ONU minimum bandwidth requirement and the ONU SLA contracts. In that manner the OLT allocates ONU bandwidth by means of the individual total network capacity depending on the time and wavelength measures ($BW_{\text{total available}}$), minus the safety margin as seen in equation (1).

$$BW_{\text{total available}}(\text{multi - wavelength}) = BW_{\text{total network}}(\text{multi - wavelength}) - \text{safety margin} \quad (1)$$

The maximum allocated bandwidth for ONU$_i$ ($ONU_{\text{Allocated\_BW}}$) is then assigned according to the DMB algorithm [14] as seen in equation (2).

$$ONU_{\text{Allocated\_BW}} = \begin{Bmatrix} BW_{\text{ONU\_Reqested}} & if \ BW_{\text{total reqested}} \langle \ BW_{\text{total available}} \\ BW_{\text{ONU\_Max.allowed}} & if \ BW_{\text{total reqested}} \rangle \ BW_{\text{total available}} \end{Bmatrix} \quad (2)$$

After the first stage is completed, the second stage is introduced to manage the network bandwidth allocation process in a more efficient manner by excluding random distribution of ONU traffic among the different wavelengths that in cases could result in exceeding the maximum available cycle-time, as shown in Figure 4. To that extent the OLT specifies the highest ONU allocated bandwidth, positions it at the end of the cycle, expecting to increase the network throughput, and distributes the remaining ONU allocated bandwidths i order from high to low. In the third and last stage, the OLT commences assignment of the ONU time-slots to different wavelengths in sequence, starting by λ_{up0} to reach λ_{up2}. This process allows the OLT to guarantee that the last ONU time-slot in λ_{up2} can fit within the safety margin as shown in Figure4. Only three wavelengths and

16 ONUs are shown in Figure4 for algorithm demonstration purposes. This approach potentially produces a shorter polling cycle length, a reduction in the ONU upstream packet waiting-time in proceeding cycles, and hence increased network utilization.

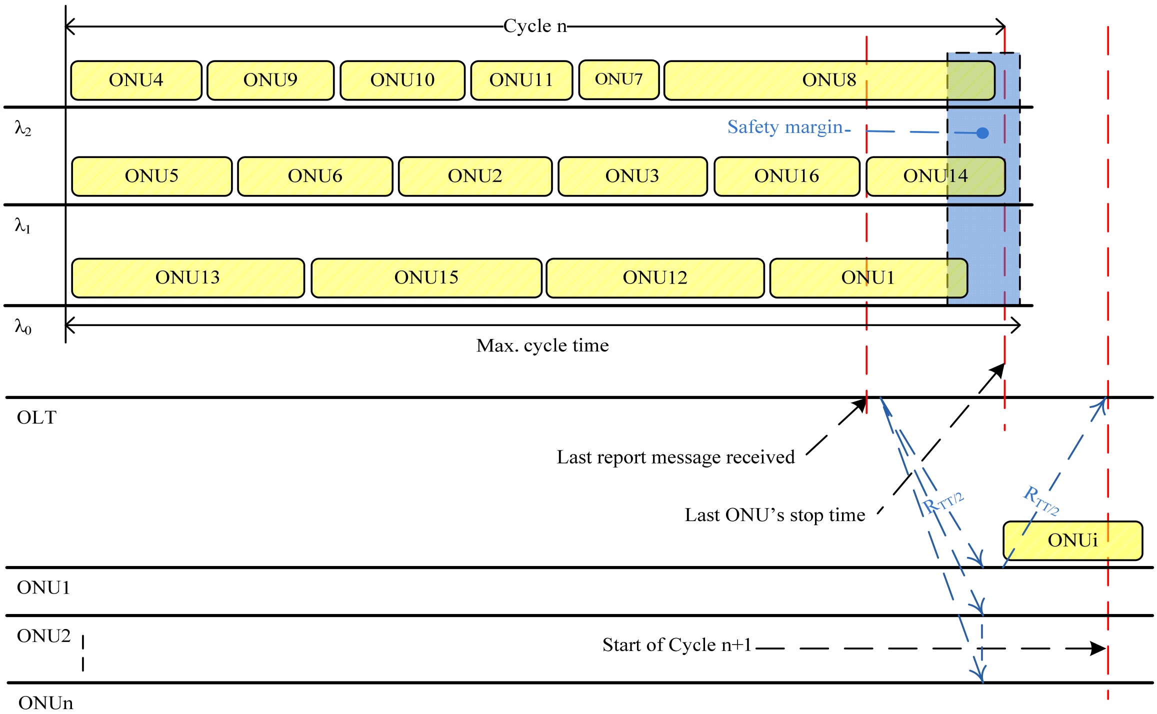


Figure 4. Principles of the DMW-GPON bandwidth assignment.

OPNET performance analysis

To investigate the performance of the DMW protocol a FTTH-based GPON network was modelled using the OPNET v.14.5 platform with pareto self-similar traffic with typical Hurst parameter of 0.8, 1.24416 Gbit/s upstream data-rate, 2.488 Gbit/s downstream data-rate, and 32 ONUs, assigned in manner of 4 ONUs SLA_0, 4 ONUs SLA_1, 8 ONUs SLA_2, and 16 ONUs SLA_3 to comply with a typical current network and the near future end-users. Each ONU was connected with an end-user under a 100 Mbit/s line speed fibre cable, moreover, a 196 bits GPON guard-time between the ONU traffic, a 1.5 ms maximum cycle time, and is stated before 3% safety margin was used.

The single-wavelength GPON can achieve higher basic bandwidth per ONU by reducing the number of the ONUs in the network, it shows in Figure 4. It can provide each of the 32 network ONUs with a basic bandwidth of 30 Mbit/s, while DMW provides a minimum bandwidth of 100 Mbit/s for each ONU by using only three wavelength signals. Furthermore, it clearly indicated that, the channel throughput performance for each wavelength signal has the same throughput even by using a safety margin of 3% of the total network capacity.

It can be observed, while the maximum throughput of each wavelength of DMW-GPON is equal to the single-wavelength DMB-GPON, the total network throughput of DMW-GPON is three time the DMB-GPON.

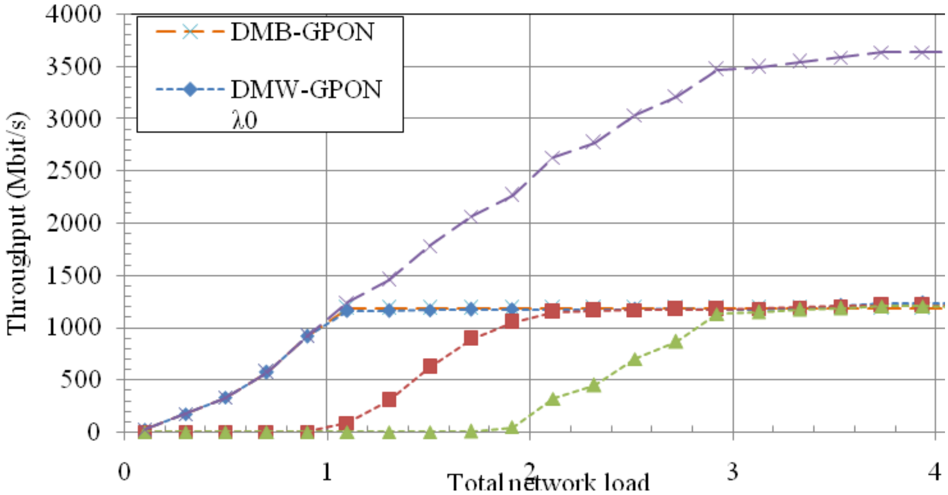


Figure 5. Throughput against total network load for single-wavelength and DMW-GPON.

While the mean packet delay for deferent SLAs of single-wavelength DMB-GPON overcomes 0.1 s when the total network load achieves one wavelength capacity, the DMW provide much reduced mean packet delay performance stays low at 0.03 s (which is satisfy the recommended one-way delay requirement of the interactive applications defined by the ITU-T recommendation G.1010 [17]) until the total network load reaches three wavelengths capacity as seen in Figure5 which makes it a good candidate to support the real-time service (such as conversational voice and videophone). This gain or reduction in the delay came as a result of increasing the basic bandwidth of each ONU to 100 Mbit/s compared to 30 Mbit/s in case of single-wavelength protocols.

Even at higher network load for DMW-GPON, the lower service level ONUs (highest delay) delay stays below 0.1 s (which is below the boundary-limit of 0.4 s of the one-way delay of the interactive applications defined by the ITU-T recommendation G.1010 [17]) as shown in Figure 6.

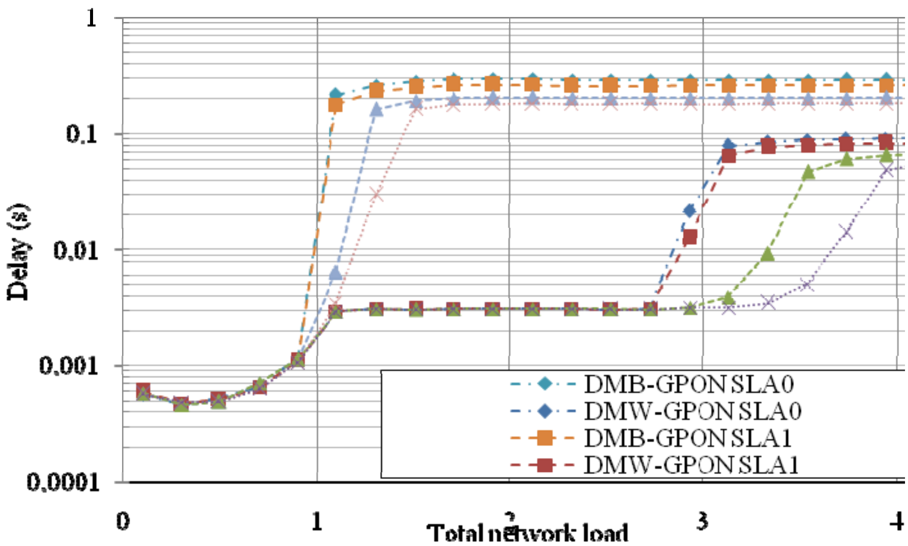


Figure 6. Mean packet delay against total network load for single-wavelength and DMW –PON.

5.2.3 Next steps

The DMW protocol methodology and the corresponding enhancements in the GPON upstream format map have been presented to accommodate multi-wavelength operation by means of smoothly upgrading the existing single-wavelength GPON infrastructure. This upgrade has been achieved by utilising additional bits in the frame fields to define the operating wavelength and packet type transfer for each ONU. The performance benefits of the multi-wavelength operation providing an aggregate transmission bit-rate of 3.7 Gb/s if only three wavelengths are utilised with 32 network ONUs served with a minimum bandwidth per ONU of 100 Mbit/s are demonstrated using OPNET. A reduction gain in the mean packet delay in comparison with the single-wavelength GPON was achieved. In summary, the DMW approach could enable an upgraded-GPON to be a good candidate to support the next generation access (NGA) network providing both sufficient bandwidth and appropriate QoS to deliver future FTTH.

Following steps should include further developing and evaluating algorithms that will be able to allocate optical network resources in a dynamic manner, exhibiting not only QoS but also the QoE requirements of different types of services, alongside congestion levels in the ONU. This could involve solutions, whereby each wavelength could be shared by many different ONUs in time but also where the number of wavelengths assigned to each ONU as a whole could change based on the temporal bandwidth demands.

In addition, the realisation of convergence in view of wireless data propagation over the optical infrastructure would be crucially associated with the deployed network architecture and mode of signal transmission. For RoF, BSs are able to simultaneously transmit their packets bidirectionally as dictated by the centralised wireless MAC in the OLT that is independent of the PON MAC. Therefore, no additional DBA algorithm is required to arrange data transmission for RoF. Having said that, for the convergence of xPON and wireless technologies (WiMAX/LTE), undergoing currently major development to provide the future broadband access, the associated protocols and frame formats will require modifications in order to convey wireless data transparently.

Since a RoF infrastructure is based on the use of FDM, exclusive sub-carriers should be assigned to each BS downstream. Multiple sub-carriers form a FDM window that is transmitted on the same, wavelength. Multiple wavelengths could also be available in downstream for resilience between the overlapping mobile users at individual ONU/Bs. In upstream however, in order to avoid OBI at the OLT receiver, it is assumed that each BS is transmitting on a dedicated non-overlapping wavelength. The BSs can thus simultaneously transmit their signals bidirectionally as dictated by the centralised LTE/WiMAX MAC in the OLT. However, an extra propagation delay, either among the BS and mobile devices or the BS and OLT, could limit the network performance and should be carefully considered and evaluated. Tot tackle this, in long reach application in particular, a remote MAC in a middle office (MO), between the OLT and ONU/BSs, could be responsible for processing only time sensitive packets, reducing considerably the delay associated with long distance transmission.

As a first step towards this development new frame control fields should be incorporated at the PON frame format presented above to account for dynamic subcarrier allocation in the network DS.

An enhancement of the DMW protocol

Even though the DMW protocol exhibits superior traffic allocation management over the TDM-PONs, the multi-wavelength domain operation raises additional challenges that would need to be addresses for optimum protocol performance. The first challenge is synchronisation between wavelengths, as the OLT will need to wait after the last network ONU report message has arrived before it starts calculating and allocating bandwidth. The issue raised here as a result is the time difference between the last arriving report message and the last transmission ONU. In case of single-wavelength operation, the last transmission interval, belongs to the last transmitting ONU In multi-wavelength operation though, the last transmission interval in a wavelength is not necessary related to the last transmitting ONU in the network, since the OLT manages bandwidth in the network as a whole and not on a wavelength basis.

Secondly and equally important, the intra-cycle bandwidth management process followed in the already developed DMW algorithm, even when using the safety margin, is limiting the cycle duration to the maximum cycle limit. To that extent, it could easily be the case that one of the wavelengths for example is fully utilised while the remaining underused. This section attempts to address and provide solutions to these issues.

While in the DMW algorithm the ONU with the highest allocated bandwidth is positioned first and at the end of the transmission cycle, in the Advanced-DMW (ADMW) algorithm, the OLT will select and assign the n (where n is the number of supported wavelengths) ONUs with the highest allocated bandwidth at the transmission tail of each wavelength as shown in Figure 7.

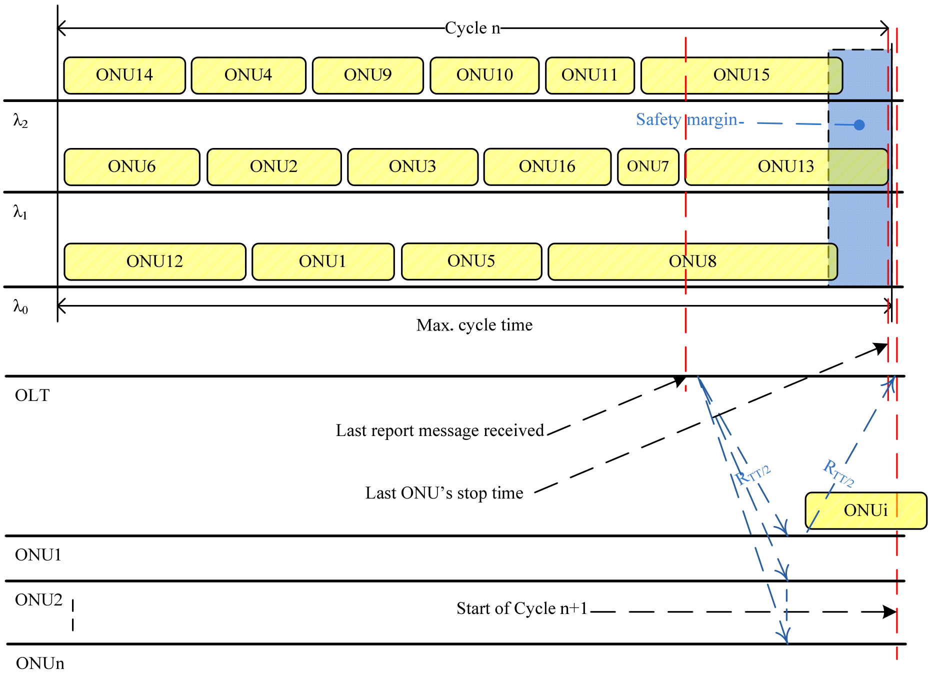


Figure 7: ONU traffic allocation in view of the ADMW algorithm

In contrast to the DMW algorithm, the OLT in ADMW first sorts the bandwidth allocated bandwidth to ONUs in order, from high to low, and then it selects the first n (where n=1,2,... the supported wavelengths) highest ONUs and assigns each one of them randomly to the end of each wavelength cycle. The application of the ADMW algorithm is expected to reduce the idle times between cycles for each of the supported wavelengths and as a result in a uniform wavelength throughput utilisation as will be confirmed by the forthcoming results.

Implementation of the ADMW protocol required modifications to the OPNET network models presented in the previous sections although at the very slightest to allow for direct comparison between the two protocols. In particular, the OLT process model would need to reflect the ADMW requirement in assigning the selected highest ONUs at the end of each wavelength in every cycle. This was achieved by only changing the code in the OLT process model.

As a first measure of the new protocol performance, the adjacent cycles' idle time (or bandwidth) profile is shown in Figure 8. Contrasted to the DMW algorithm a clear reduction in the overall network idle intervals is portrayed with a much smoother, continuously decreasing characteristic drawn for the ADMW algorithm from very low values of network load corresponding to less than a wavelength occupancy. This becomes obvious if thought that the highest bandwidth ONUs are assigned first and while the load increases, the second highest bandwidth occupancy ONUs are assigned to available time slots for each wavelength not leaving empty slots. Finally the idle-time (wasted-bandwidth) recorded under higher network offered load for the DMW algorithm reaches its minimum value at around 7 Mbit/s. The equivalent value for the ADMW algorithm is less than 1 Mbit/s.

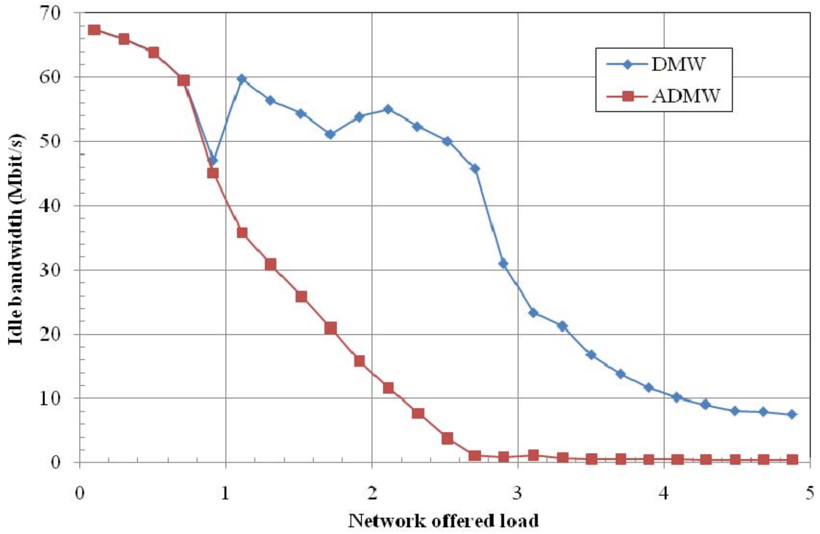


Figure 8: Average idle bandwidth between cycles for the DMW and ADMW algorithms

As seen in Figure 9, the throughput performance of the ADMW-GPON resembles that of the DMW concerning the fact that when the operating wavelengths reach their maximum capacity in succession, a serial wavelength loading approach is still utilised. It is worth noticing though that each wavelength has recorded 10 to 20 Mbit/s increase in throughput when compared to the individual wavelengths with the DMW algorithm.

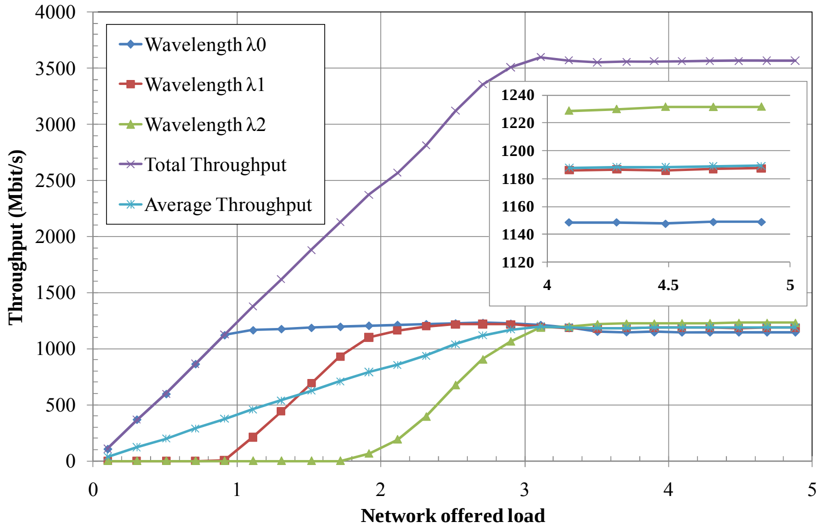


Figure 9: Throughput performance for ADMW-GPON

Regarding the mean packet delay characteristic, the decreased adjacent-cycles' idle time is, expected to reduce the buffering time in the ONUs and as a result the time packets are stored waiting for the next cycle to start. This is reflected in Figure 10, where the ADMW packet delay performance displays, a reduction of 1 ms in the at high network load compared to DMW protocol, that will provide a relaxed accommodation for delay sensitive application at the higher network load.

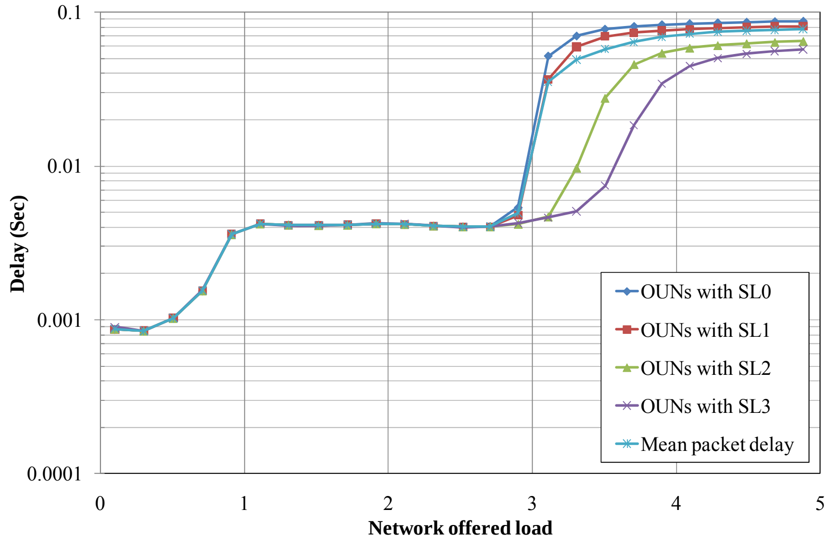


Figure 10: Packet delay performance of the ADMW-GPON for different service levels

An additional performance characteristic is introduced at this point to compare between the two algorithms, known as the intra-cycle's idle time (or bandwidth). The intra-idle time's maximum value is reported at the beginning of each wavelength's utilisation, decreasing progressively till the OLT introduces another wavelength and soon. Although there is not significant performance variation between the DMW and the ADMW algorithms since they both populate wavelengths in succession, this performance criterion will be proven extremely important in evaluating the current protocols with the one to be described later. Also it was not necessary to compare previously between the DMW and TDM algorithms given that the idle-time (wasted bandwidth) figure within the cycle is not applicable for single-wavelength DBAs.

As still shown in Figure 11 though, the ADMW shows less intra-cycle idle bandwidth compared to the DMW algorithm especially during the second and third wavelength population processes, that became as a result of the decreased cycle time because of the ONU's allocation mechanism in ADMW, and the limited idle time within the cycle, compared to longer cycle time in DMW which results more idle time within the cycle specially below the full network load. This reduction adds to the adjacent-cycle idle time figure to increase the total network throughput.

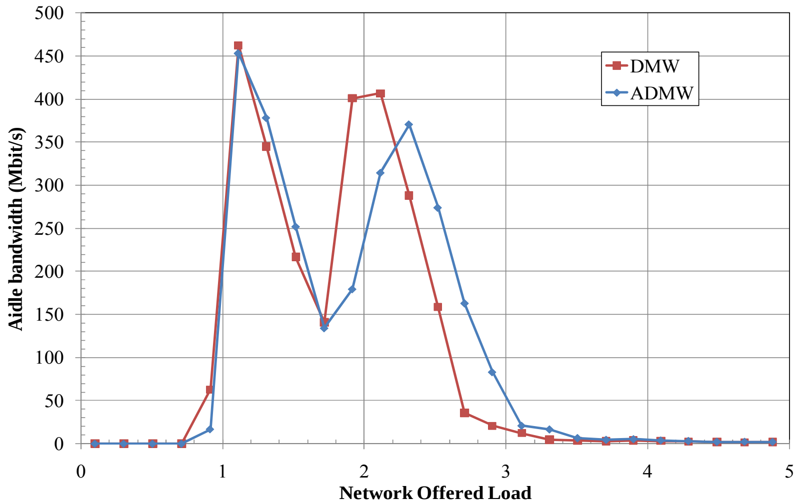


Figure 11: total idle bandwidth per cycle for ADMW and DMW algorithms

MAC Protocol design for the support of RoF over a multi-λ PON

To allow FDM operation in the network DS, the frame control fields presented in the previous sections are redefined accounting for legacy G/EPON protocols and their modification to host the essential functionalities. Among the necessary control fields to be incorporated in the DS frame, an ONU identifier, ONU_ID, field defines the total number of supported ONUs. As already stated a Class of Service, CoS, differentiation field is not required since RoF is transparent to PON transmission, simplifying the frame complexity and functionality. New to the DS frame header is also a SubCarrier Allocation identifier, SCA, field used by the OLT to specify the transmission mode for each ONU. The bits allocated to this field define the number of supported transmission modes, currently distinguishing between a Fixed Subcarrier Allocation (FScA) and a Dynamic Subcarrier Allocation (DScA) mode of operation. In FScA and DScA the Low_SC and High_SC fields are used to define the assigned subcarrier group range. The distinction lies on the fact that in FScA subcarrier groups are allocated to ONUs continuously while in DScA subcarrier groups are allocated to ONUs only for the next transmission window.

The US frame incorporates fields addressing ONU Registration only since for RoF multiwavelength transmission is employed upstream.

5.3 UWB Radio-over-fibre transmission in indoor environments using different media {UPVLC,AIT}

5.3.1 Motivation and objectives

Ultra-Wide Band (UWB) technology for wireless multiple access communications are receiving great interest for the last years due to its unique features such as spectrum coexistence with other wireless services, RF front-end simplicity (enabling potential low cost terminals), good radio wave propagation (robustness against multi-path fading, material penetration) and high bitrate. Several applications can be found ofr UWB radio-over –fibre in user mobility networks or networks in motion. One example is the optical fibre in-car distribution that can be used for providing multimedia connectivity and even car-safety functionalities.

Two main UWB implementations are being further developed nowadays. From one side, WiMedia-defined signals which are based on multi-band orthogonal frequency division multiplexing (MB OFDM) modulation that has been adopted in the standard ECMA-368 specification. From the other side, impulse radio (IR) technology signals increases the accuracy as employs short radio pulses, typically in the picoseconds range. IR-UWB is able to provide high-speed communications, localization and ranging simultaneously.

The proposed work comprises the radio-over-fibre transmission of both OFDM and IR UWB signals for in-building applications, e.g. offices or home environments, over different media as standard single mode fibre (SSMF) or multimode fibre (MMF).

The objective of this joint activity is to study (experimentally and by simulation) the performance of UWB signals in radio-over-fibre transmission for in-building applications in terms of quality of signal, bitrate, spectral efficiency, fibre maximum reach and others, considering, if possible, the effects of the fibre transmission on the UWB radio path.

5.3.2 Main outcomes and results

A comparison of the in-building transmission performance of the two main ultra-wideband (UWB) implementations, OFDM-based (OFDM-UWB) and impulse-radio UWB has been done experimentally and by simulation in this joint activity. Two main outcomes are highlighted:

- First, both UWB implementations providing similar spectral efficiency were analysed experimentally in UPVLC when transmitted over 300 m of standard single mode fibre (SSMF) or multimode fibre (MMF) link.
- Second, a VPI and Matlab simulation model has been implemented by AIT considering the UWB channel response of an indoor environment.

Figure shows the setups implemented to evaluate the performance of the distribution of OFDM UWB and impulse-radio UWB over SSMF and MMF.

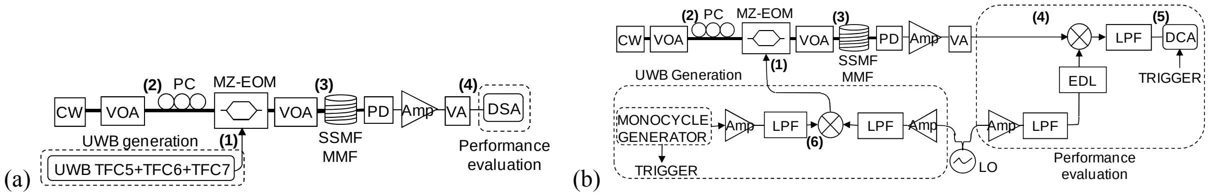


Figure 12. Experimental setup for performance evaluation of (a) OFDM UWB and (b) impulse-radio UWB distribution over fibre for indoor range. CW: Continuous-wave laser, VOA: Variable optical attenuator, PC: Polarization controller, PD: Photodetector, Amp: Electrical amplifier, VA: Variable electrical attenuator.

The UWB signal under study is externally modulated with a continuous-wave optical carrier at 1555.75 nm by a Mach-Zehnder electro-optical modulator (MZ-EOM) ($V\pi$=1.46 V_{DC}) working as a conventional double-sideband modulator. A variable optical attenuator is employed before the MZ-EOM to adjust the power launched to the fibre by adjusting the power at point (2) in Figure (from now referred as P2) emulating the central office. The modulated signal is transmitted over fibre (SSMF or MMF) and the optical power launched to the fibre at point (3) in Figure (from now referred as P3) is adjusted with a second attenuator in order to analyze the link budget. After fibre transmission, the signal is photo detected properly depending on the optical media: A 40 GHz PIN photodiode is employed for SSMF and a 7 GHz photo receiver consisting in a PIN photodiode with 50 µm MMF pigtail and an integrated transimpedance amplifier is employed for MMF transmission. Subsequently, the power spectral density (PSD) of the photo detected signal is adjusted with an electrical amplifier (26 dB gain and 5 dB noise figure) followed by a variable electrical attenuator to accomplish, at point (4) in Figure 12, the UWB spectral mask defined in current regulation with a maximum PSD of -41.3 dBm/MHz [20], [21].

In order to evaluate the performance of OFDM UWB in optical fibre in-building distribution, the measurement setup shown in Figure 12(a) has been implemented. A multi-channel MB-OFDM UWB signal is generated combining the UWB signals from three transmitters (Wisair DV9110). Each UWB transmitter is located at frequency band #1, #2 and #3 respectively from UWB band group #1, performing a non hopping time frequency code (TFC5, TFC6 and TFC7), which enables a multi-channel MB-OFDM UWB transmission. The OFDM signal comprises 3 channels of 528 MHz bearing 200 Mbit/s each with QPSK modulation (as specified by ECMA-368 standard). This provides an aggregated bitrate of 600 Mbit/s and 0.378 bit/s/Hz spectral efficiency (10 dB frequency range of 3.168-4.752 GHz). The maximum PSD of the generated OFDM-UWB signal is -42 dBm/MHz. In Figure 13, EVM results for OFDM-UWB over 300 m SSMF (a) and MMF 50 µm (b) transmission are presented and compared with B2B configuration for the MMF photoreceiver at a P2 of 13.9 dBm. The received spectrum after both kinds of media are shown in Figure 13(c) and (d).

The experimental results indicate that OFDM-UWB transmission is feasible for optical launch power levels of 2 dBm for both SSMF and MMF distribution. The impulse-radio UWB implementation achieves error-free SSMF transmission from -4 dBm launched power. Successful MMF transmission can be only achieved for impulse-radio UWB at 3 dBm launched power level.

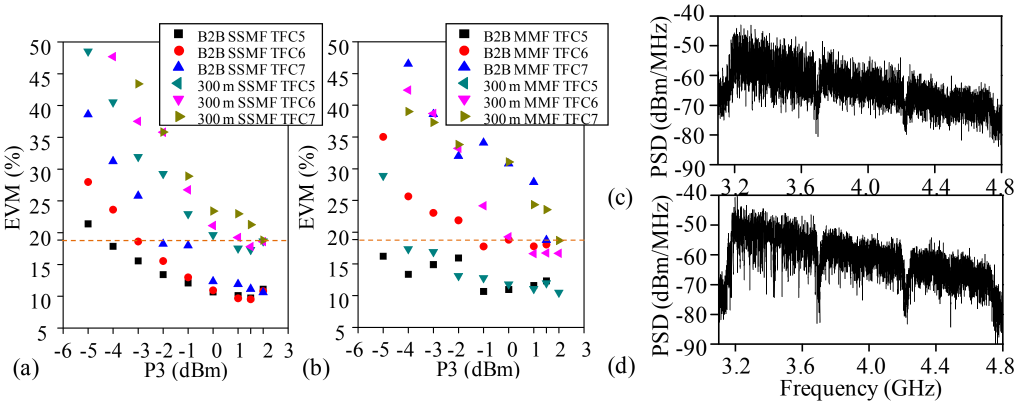


Figure 13. Measured EVM for OFDM UWB performance after 300 m (a) SSMF and (b) MMF distribution with P2=13.9 dBm. ECMA threshold in dashed line. Measured received spectrum at P3=2 dBm after 300 m (c) SSMF and (d) MMF distribution

These results have been checked by simulation using Photonics VPI software. The device specifications of the modules correspond to the ones available at the laboratory and the setup is the same as shown in Figure 12(a). The power levels along the system are adjusted with the ones measured experimentally for a fair comparison. Simulated and experimental results are in very good agreement as shown in Figure 14.

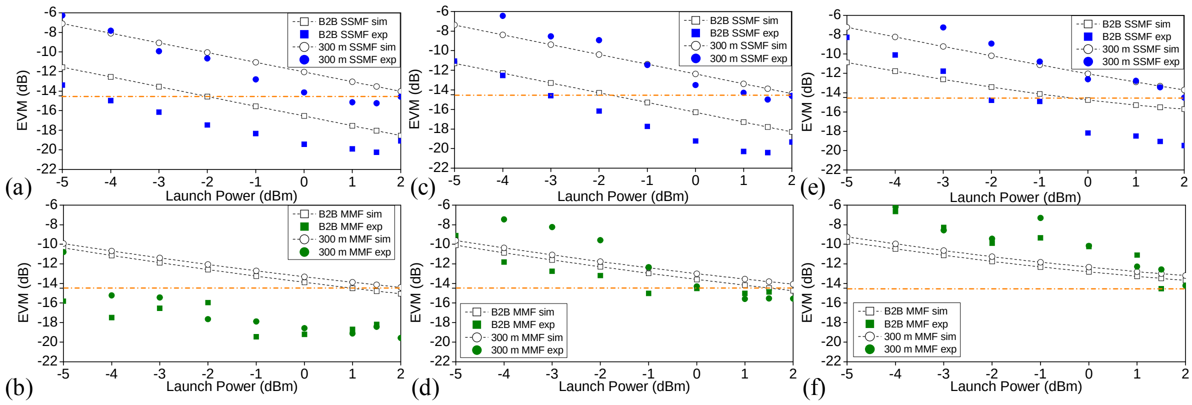


Figure 14. Simulated EVM for OFDM UWB performance for (a)(b) TFC5, (c)(d) TFC6, (e)(f) TFC7 after 300 m SSMF and MMF distribution respectively

For the MMF case, TFC6 (channel at 3.96 GHz) is the one that fits most the simulation results. For MMF propagation, simulation results (in dashed line in Figure 14) are worse than experimental, due to the phase lock used in simulation that does not correct the whole constellation rotation. The experimental data measured with DSA solve better this phase shift. From the simulations we observed that symbol mapped constellations present less dispersion in MMF than in SSMF. For this reason, in most of the cases the experimental EVM results are better in MMF than in SSMF. This is due higher power losses in the connectors of SSMF compared with the low-losses imposed by the transmission in 300 m SSMF. This effect can be seen in the difference in SSMF between B2B measurements and 300 m propagation results. This difference is much lower in the MMF case. If longer optical fibre distances were used (in the range of km), SSMF could lead to better results than MMF, but for short range communications MMF exhibits better performance.

Simulation and experimental results agree on that a typical range for in building distribution of 300 m can be reached using both SSMF and MMF media with launch power ranging from 1 to 2 dBm.

The second part of this activity evaluates the performance of impulse-radio UWB over fibre in-building distribution. The experimental setup implemented was shown in Figure 12(b). The generated monocycles after amplification and low-pass filtering (3.3 GHz bandwidth) to remove noise are shown in Figure 15(a) and (b). This signal corresponds to that measured at point (6) in Figure 12(b). Figure15(c) and (d) show the detected impulse-radio UWB pulses at point (4) in Figure 12(b) after 300 m SSMF distribution with P2= 13.7 dBm and P3= -3 dBm.

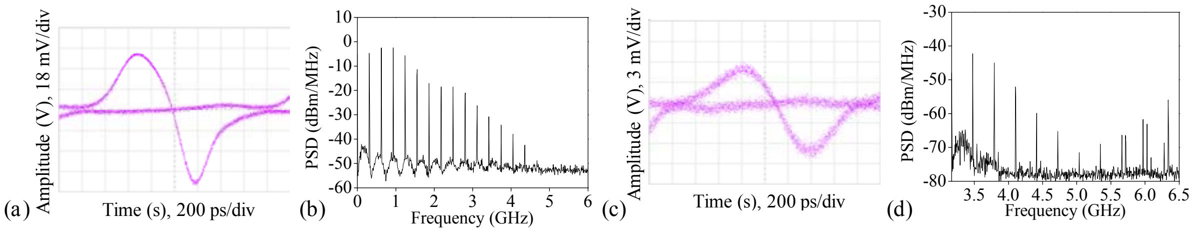


Figure 15. Generated baseband monocycle at point (6) in Figure7(b): (a) eye diagram and (b) spectrum. Received impulse-radio UWB signal at point (4) in Figure(b) with P2= 13.7 dBm and P3= -3 dBm: (c) eye diagram, (b) spectrum

Figure 16 shows BER results for impulse-radio UWB over 300 m SSMF and MMF transmission compared with the corresponding optical B2B configuration as a function of P2. For SSMF distribution (Figure 16(a)), error-free transmission is achieved in the range of P3 from -4 to 4.7 dBm. It can be observed that BER values maintain at P3 in the range from -3 to 2 dBm while the higher P3 the better BER at P3 higher than 2 dBm and the lower P3 the worse BER at P3 lower than -3 dBm. In this case, BER is independent on P2. The results for MMF distribution shown in Figure 16(b) indicate that the best BER is achieved at P3 about 3 dBm for all P2 from 12 dBm to 13.7 dBm, but error-free transmission is only achieved at a P2 of 12 dBm. Comparing with B2B case, the performance with MMF transmission is always worse.

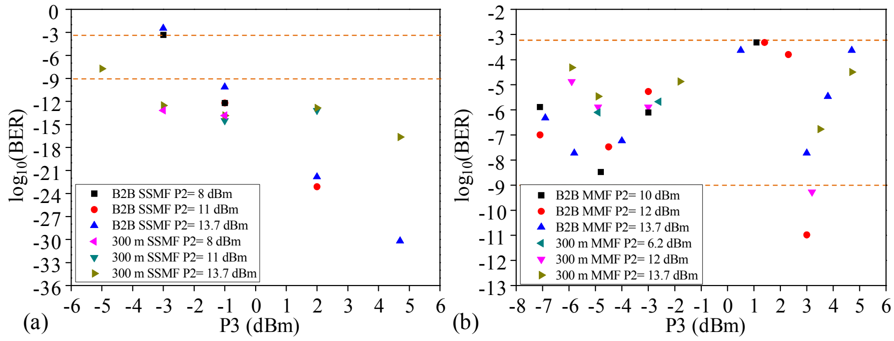


Figure 16. Impulse-radio UWB performance compared with optical back to back configuration for (a) SSMF and (b) MMF distribution. BER limits in dashed lines.

From the experimental results, impulse-radio UWB requires less optical launched power than its OFDM-UWB counterpart for successful SSMF transmission over a distance of 300 m. In the case of MMF, the experimental results exhibit a large variance and successful transmission over 300 m can only be achieved at a launched power of 2 dBm for complete OFDM-UWB or 3 dBm for impulse-radio UWB.

This activity has produced the following publications:

- Marta Beltran, Maria Morant, Joaquin Perez, and Roberto Llorente, "Performance Evaluation of OFDM and Impulse-Radio Ultra-Wideband over Fibre Distribution for In-Building Networks", IEEE International Conference on Ultra-Wideband, Vancouver, Canada, 9-11 September 2009.
- Maria Morant, Joaquin Pérez, Marta Beltrán and Roberto Llorente, "Performance Evaluation of In-Building Radio-over-Fibre Distribution of Multi-Band OFDM UWB Signals", 2009 IEEE International Topical Meeting on Microwave photonics, Valencia, Spain, 14-16 October 2009.

In the second part of the activity, AIT developed a simulation model with VPI and Matlab of UWB radio propagation. Due to frequency-selective fading behavior of the indoor UWB channels the transmitted signals typically propagate via several different paths (multipaths) from the transmitter to the receiver. Although UWB channels can mitigate the multipath effect, in dense multipath environments like indoor environments the channel will suffer from destructive interference (deep fading).

When there is deep fading on the subcarrier, the system has to rely solely on strength of error correction code to recover lost information. As the code strength decreases, the performance gap from AWGN starts to increase (also known as loss in diversity).

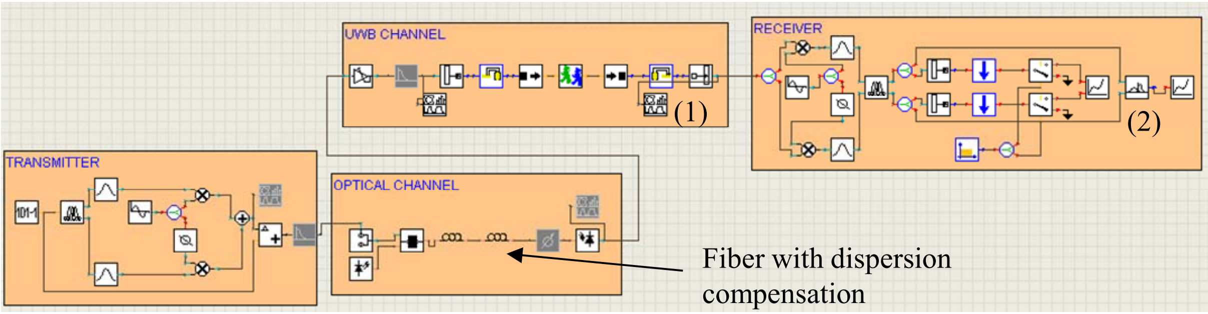


Figure 17. Matlab/VPI UWB simulation model.

It can be observed in Figure 18 and Figure 19 that even without fiber and UWB channel the QPSK received constellation is not perfect.

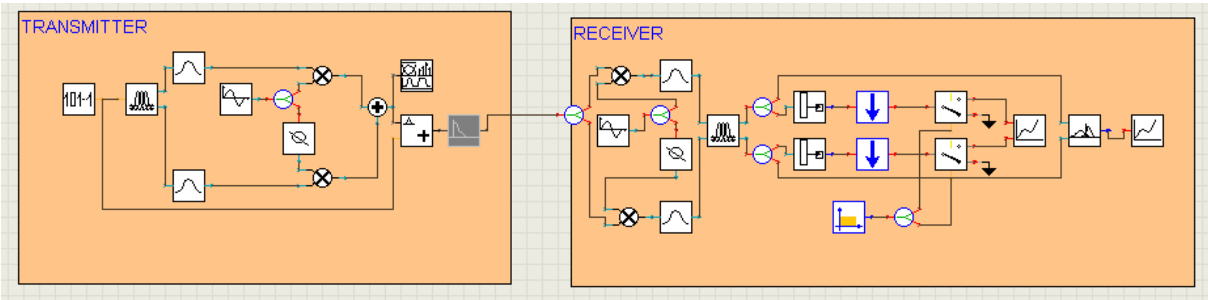


Figure 18. Initial simulation schematic

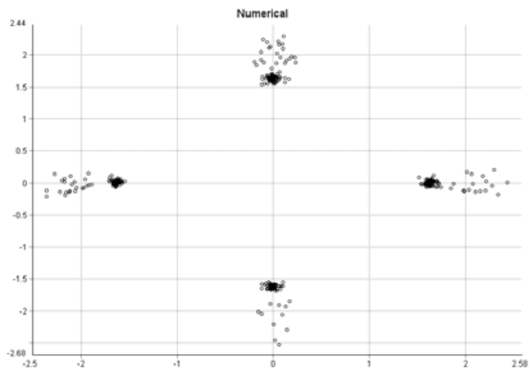


Figure 19. Initial QPSK constellation

The simulation generates a QPSK modulated signal using 16 Subcarriers with 20% cyclic prefix. This signal is distributed by a spool of fiber of 10 km. The optical signal is generated with a DFB laser with 1 MHz of linewidth and 5 dBm launch optical power.

The UWB channel considers a statistical model for Indoor Multipath propagation based on IEEE 802.15.3a channel model which impulse response is shown in Figure 20. The antenna separation is taken in a statistical representation for distances of 0 – 4 m line of sight (LOS).

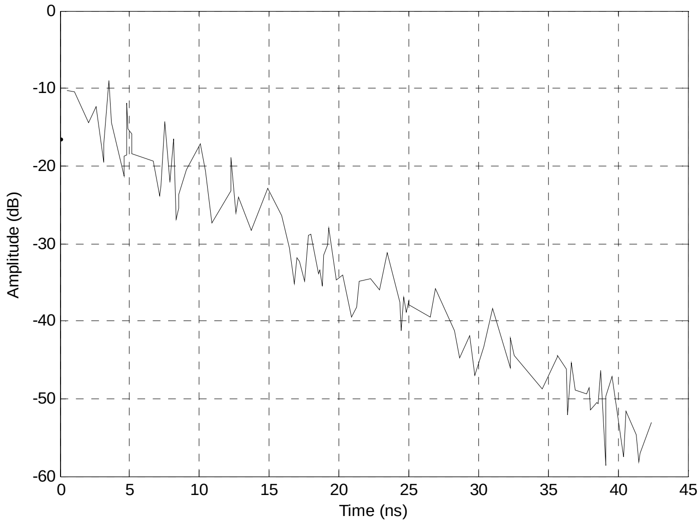


Figure 20. UWB Channel Impulse Response Indoor Environment

The simulation parameters for the optical fibers of the schematic shown in Figure 17 are summarized in Figure 21. Finally the received spectrum and example constellation is shown in Figure 22 and 23.

(a)

Physical		
ReferenceFrequency	193.1e12	Hz
Length	span	m
GroupRefractiveIndex	1.47	
Attenuation	0.2e-3	dB/m
AttFileName		
Dispersion	17e-6	s/m^2
DispersionSlope	0.08e3	s/m^3
NonLinearIndex	2.6e-20	m^2/W
CoreArea	80.0e-12	m^2
Tau1	12.2e-15	s
Tau2	32.0e-15	s
RamanCoefficient	0.0	

(b)

Physical		
ReferenceFrequency	193.1e12	Hz
Length	span*16/90	m
GroupRefractiveIndex	1.47	
Attenuation	0.5e-3	dB/m
AttFileName		
Dispersion	-90e-6	s/m^2
DispersionSlope	0.21e3	s/m^3
NonLinearIndex	2.6e-20	m^2/W
CoreArea	80.0e-12	m^2
Tau1	12.2e-15	s
Tau2	32.0e-15	s
RamanCoefficient	0.0	

Figure 21. VPI Simulation parameter for (a) propagation fiber and (b) fiber with dispersion compensation

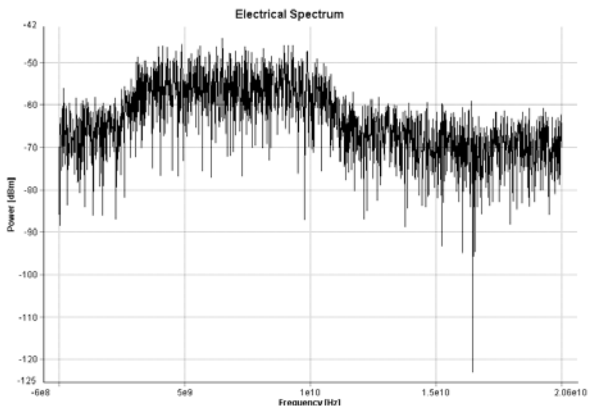


Figure 22. Received spectrum measured at point (1) of fig. 12.

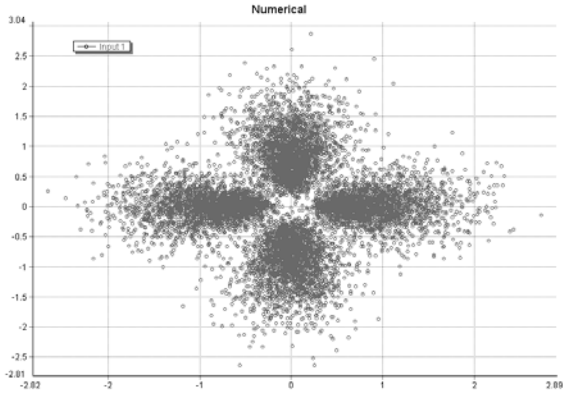


Figure 23. QPSK constellation measured at point (2) of fig. 12.

5.3.3 Next steps

Further investigations of the UWB performance over other optical media will be conducted.

5.4 Optimizing service delivery in a converged hybrid optical-wireless network {UAM}

5.4.1 Motivation and objectives

The main motivation behind the JA5 is to support next-generation wireless networking with an optical access network, to apply novel concepts that increase its reconfigurability and that improve its resource usage, and to evaluate the performance considering different metrics. The topology is also taken as subject of study.

The main objective of JA5 is to propose a flexible and fast-reconfigurable network architecture that is optimized for high-bandwidth mobile networking. Non-mobile users are also considered and the network should be easily overlaid in existing access solutions, e.g. current fibre-to-the-home solutions.

As expected outcome, the JA5 considers to demonstrate the feasibility of its architecture for horizontal and vertical handovers between different kinds of next-generation wireless networks by means of physical-layer simulations and small-scale lab experiments. Several joint publications are planned.

5.4.2 Main outcomes and results

Network architecture

The members of the JA5 published a paper at the OSA ANIC 2010 conference in Karlsruhe (Germany) which described the network architecture, its principle of operation, the philosophy behind it, and the technology used. Figure 24 shows a multi-layer reconfigurable optical-wireless network architecture as proposed by JA5.

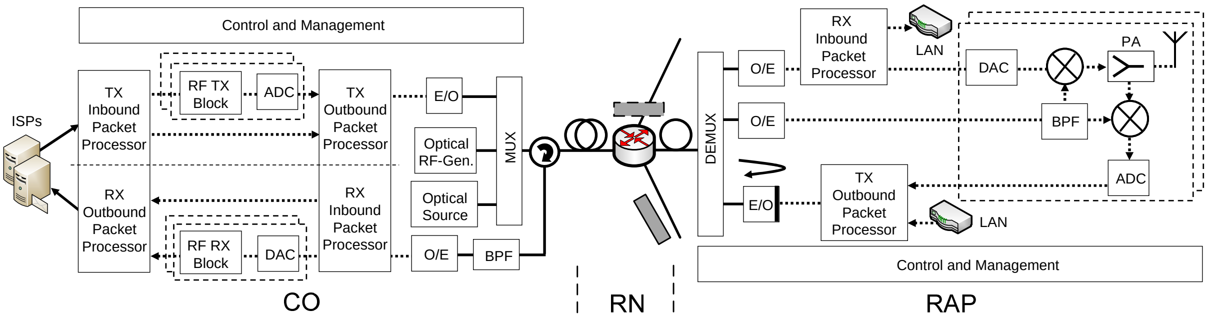


Figure 24: An optical-wireless network architecture with multi-layer reconfigurability showing two optical bursts on the same wavelength [22]

The optical-wireless network architecture showed in Figure 24 features multi-layer reconfigurability, digital signal processing, integration potential, and intelligence centralization. The mobile networking dynamics are handled centrally across different networks and transport technologies. Additionally, the radio access points (RAPs) are remotely-seeded for a colorless operation and deployment.

In particular, bandpass sampling is employed to digitize radio frequency (RF) signals at the central office (CO) and at the RAP. It allows for a digital link between the CO and RAP instead of an analogue which is common for radio-over-fiber techniques. As a result, an increase in dynamic range and a decrease in component requirements is expected. Additionally, the digital signal processing allows the optical link and the RAP to become RF network agnostic when the design is made correctly. Note that such bandpass sampling techniques are well-known in the area of software defined radio considering the radio link between base stations and mobile handhelds.

A common limitation is the bandwidth of the analog-to-digital converter (ADC) and digital-to-analog converter (DAC) and the RF central carrier of most next-generation networks is too high to be digitized by commercially available ADC/DAC technology. Up and down-conversion to intermediate-frequencies is proposed by using a local oscillator (LO) that is remotely generated. On the one hand, complexity is increased by the additional photo diode at the RAP, but on the other hand the multi-layer reconfigurability is enhanced because the LO-frequencies are fully controlled at the CO.

In order to study the network architecture in more detail, the JA5 decided on a work plan for 2010 with the following sub-tasks:

- T2 Design, requirements and scenarios of optical-wireless architecture
- T3 Implement architecture in simulation environment for proof-of-principle
- T4 Capacity planning in optical PHY and reconfigurability study for wireless networks and user activity patterns
- T5 Experimental demonstration optically supported handovers using a reflective solution for the uplink

Finally, time limitations did not allow starting working on T4. In the remaining of this section, the main outcomes and work done in each of the tasks T2, T3 and T5 is described.

T2 Design, requirements and scenarios of optical-wireless architecture

Considerations on user mobility

It was decided that user mobility scenarios will be approached in terms of applications, users and locations, rather than time span. The following parameters should be taken into consideration:

- Types of mobile devices
- User density
- Residential/business/urban/rural area
- Applications and corresponding bandwidth requirements

It is important to understand how the aforementioned parameters impact the design of a wireless/wired converged network. Furthermore, there is a major difference between nomadic and mobile users. Nomadic users are those users who although connect to the network from difference places, they are not connected while in motion. On the other hand, mobile users remain connected even while moving. Handover issues relate to mobile users, while bandwidth requirements will be more stringent for nomadic users. It is worth mentioning that in this context, an always-on mobile user does not necessarily receive data continuously. For example, a mobile phone needs to be always available but the voice service is only occasionally used. In this work the voice-over-IP service is considered.

Regarding the location and speed of the reconfigurability, the mobile user requires a speedy reconfigurability close to its vicinity while a nomadic user may be supported with a slower reconfigurability which has to be done at a coarser scale, i.e. throughout more parts of (a) networking tier(s).

Here are some considerations on user mobility and the impact of the networking environment:

- Device/user differentiation: laptop users will mostly tend to be nomadic, while PDA users will have a high degree of mobility. Laptop users could show mobility when traveling (mostly by train, less by bus, car) for a duration large enough (over 20 minutes?), although this kind of mobility can be accommodated as network mobility, i.e. an in-train mobile network (network in motion). On the other hand, PDA users can dynamically behave as nomadic or mobile users at any time/place.
- Urban areas: while in intercity journeys, network mobility may be the preferable approach, in urban metro/bus/tram lines, this may not be the case. In cities with reliable and extended public transport system, many PDA users will have a mobile behaviour while moving from one part of the city to another. In cities were people (who can afford high-tech devices) tend to use their own means of transport, PDA users will have a largely nomadic behaviour. Furthermore, an urban area will house a higher density of users with strong network demands such as early adopters, (international) business people, and an industrial or academic environment that relies on high-tech services.
- Rural areas: low mobility is expected due to low number of users (a few cells can cover an area that would require many more cells in an urban scenario) and limited areas of action.

It can be concluded that an optical-wireless network only makes sense in a highly populated urban area because that is where users show a high degree of mobility while being connected to the network. Contributing factors are the large daily movements to/from work, extended public transport systems, small cell sizes, and full coverage by several types of wireless networks.

Mobile traffic market forecast

Cisco regularly publishes data regarding their Visual Networking Index (VNI) which is an ongoing initiative to track and forecast the impact of visual networking applications on global networks. A recent white paper reports a 108% compound annual growth rate (CAGR) of mobile traffic in the period 2009 until 2014 [23]. The total amount of traffic reaches 3.4 exabytes per month in 2014 and it is estimated that about 66 percent is generated by video-related services. This is shown in Figure 25.

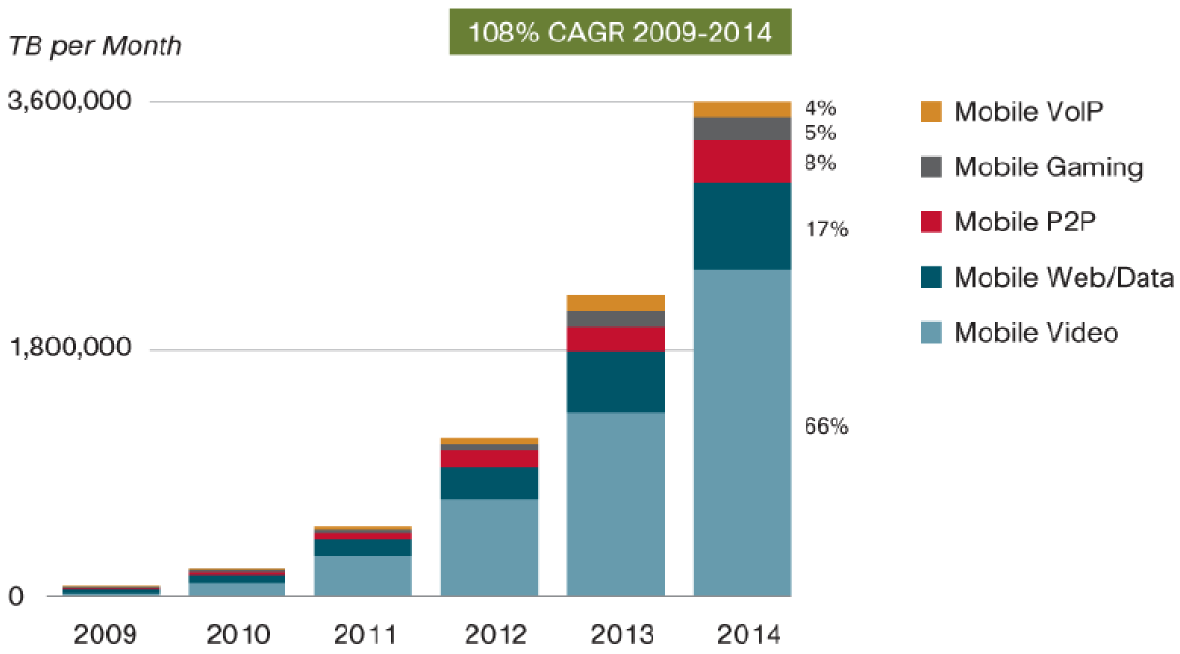


Figure 25: Video as main contributor to mobile traffic, 2009-2014 [23]

It is clear that next to entertainment, the availability of information when being mobile, i.e. the mobile web/data service, remains to be an important asset of the networking experience. Regarding the handset supporting the mobile services, the laptop or notebook computer has the largest share amongst four considered types of devices. This is shown in Figure 26.

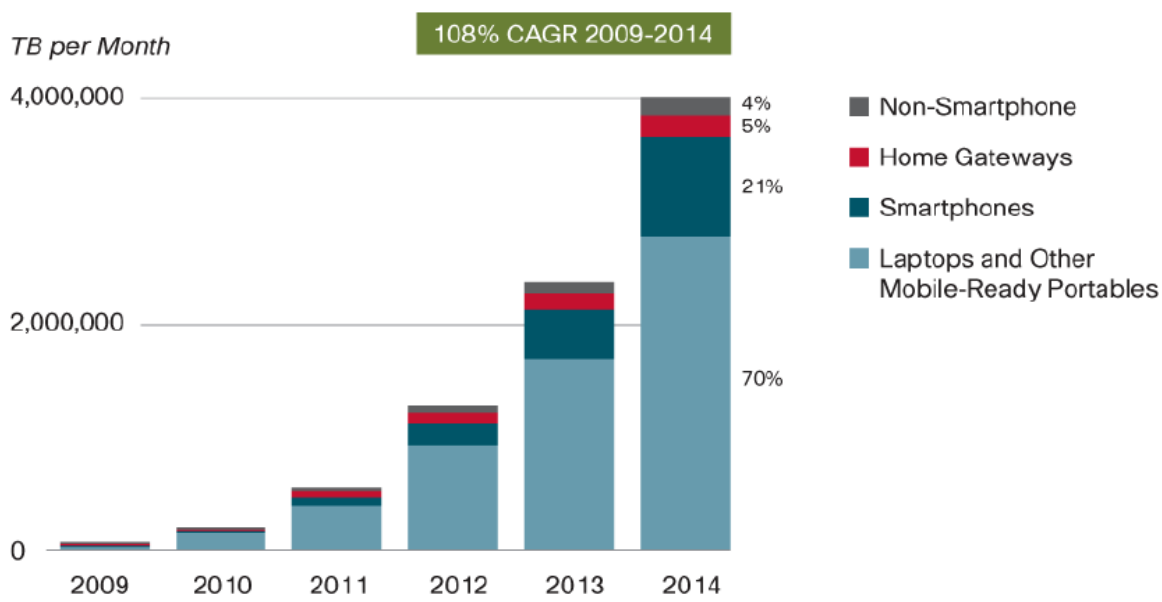


Figure 26: Laptops and smartphones drive traffic growth [23]

Intuitively, this is related with the screen size that enhances the quality of experience of a video service. The increase in computer power in laptops and smartphones, such as iPhones, enables the support of a wide-range of applications previously not supported, and therefore this leads to a significant increase of generated traffic per device compared with basic-feature mobile phones [23].

The backhaul of the base stations supporting mobile networks should be able to handle the large amounts of traffic forecasted. Therefore, a clear demand exists wireless networking provisioning using fiber-optic infrastructures.

Service requirements

A broad overview of application requirements is given in [24] in terms of bandwidth and quality of service (QoS) for fixed and mobile networks. Part of the data is shown in Table 3 for fixed networks.

Table 3: Bandwidth and QoS requirements for different applications on fixed networks with the bandwidths shown in Mbps [24]

Service	Peak down/up	Mean down/up	Max. delay	Max. jitter	Packet loss
Broadband	100/10	5/0.56	*	*	*
Stand. def. (SD) video broadcast	3/0	3/0	< 2 s	< 40 ms	< 3 E-3
High def. (HD) video broadcast	10/0	10/0	< 2 s	< 40 ms	< 3 E-3
VoIP	0.008/0.008	0.008/0.008	< 70 ms	< 20 ms	< 3 E-3
Gaming	0.25/0.25	0.20/0.20	< 50 ms	< 10 ms	< 5 E-2
SD video conference	3/3	2.2/2.2	< 100 ms	< 10 ms	< 3 E-3
HD video conference	10/10	8.67/8.67	< 40 ms	< 10 ms	< 1 E-4

It was concluded in [24] that fixed and mobile networks present similar QoS requirements while mobile applications have lower bandwidth requirements due to the limitations in wireless network bandwidth as well as in the screen size and resolution of the networked device. Thus the values shown in Table 3 for the delay, jitter and packet loss also hold for mobile applications.

Regarding the bandwidth requirements of mobile networks, estimation can be made based on Figure 26 because it is shown that two types of mobile terminals dominate amongst the devices that drive mobile data traffic. In fact, the laptop and smartphone constitute 91% of the total in 2014, and therefore the most recent models of those devices may serve as general case for the near-future bandwidth requirements in mobile networks. A rough comparison can be made through typical screen sizes (or: resolutions) of recent mobile devices. For example, the latest models of the Apple iPhone and Apple iPad have the following features, as shown in Table 4.

Table 4: Features of several mobile devices [25,26,27]

Model	Resolution	Wireless network	Battery life using 3G	Weight
Apple iPhone 4	960x640p, incl. HD camera (720p)	WLAN 802.11n, UMTS/HSDPA	Max. 9 h	173 g
Apple iPad	1024x768p, no camera	WLAN 802.11n, UMTS/HSDPA	Max. 6 h	730 g
Samsung i8910	640x360p, incl. HD camera (720p)	WLAN 802.11b/g, HSDPA	Max. 6.5 h	148 g
Nokia X6	640x360p, incl. camera (640x360p)	WLAN 802.11b/g, HSDPA	Max. 6 h	122 g

The resolution of several devices is close to the lowest high-definition video resolution of 1280x720 pixels (720p). Several devices do have a 720p camera on board and a lot of internal memory (up to 16 GB). The maximum data rate per device can be achieved in the WLAN-modus that allows 200-300 Mbps to be received when the 802.11n standard is supported. It is clear that battery life and weight accommodate the user to be mobile. Actually, the lowest data rate gives less mobility in terms of battery life which can be understood considering the distance between a UMTS radio access point and the mobile device. That distance is much lower in case of a WLAN access point. If a digital video broadcast-handheld (DVB-H) receiver is used, e.g. via a USB-port at the devices, data rates up to 30 Mbps per user can be expected to receive digitally broadcasted television signals.

Video services

Below are several application examples of real-time, streaming and best-effort video services, similar to [28].

- <u>Real-time video delivery</u>**:** This is a demanding application and it is foreseen to set the strongest requirements in terms of bandwidth. It should be noted, though, that mobile devices tend to have small-size monitors which effectively reduces the bandwidth demands when compared to high-definition video streaming. On the other hand, in the case of laptop nomadic users, video streaming bandwidth requirements will be higher. Video streaming for mobile users may be required in the following cases:
    - *Video telephony:* this is an emerging application, already provided in 3G mobile systems, that uses bidirectional video and audio transmission. To increase the definition of video streaming, higher bandwidth than currently provided is required which is surely related to the screen size at the user side. The requirements of currently video telephony services could be used as benchmark.
    - *Virtual PC:* A virtual PC application consists of an operating system which is executed on a remote host and it is accessed through the Remote Desktop interface which uses the standard capabilities of terminals running the Windows, MAC or Linux operating system. Consequently, there are two devices involved in this service, the end-user equipment and the remote server. The latter is assumed to be located in the metro network and it is connected to the end-user via the metro/access network. It is clear that the end-user equipment is intended to be a thin client, only in charge of displaying the screen and sending commands (key strokes, mouse clicks) to the server. In this case, the thin client may be a laptop or a smartphone such as iPhone or Android-based devices. It is therefore that regarding the access network, similar requirements hold as with a mobile video telephony service. However, it should be noted that any additional application may be run at the Virtual PC, for example a YouTube video stream. It is assumed that the metro network has the capabilities to host the Virtual PC on a server as close to the user as possible.
- <u>Streaming video delivery</u>
    - *In-vehicle live-TV/internet:* in-car (vehicle in general) entertainment (DVD, CD, radio) may also include TV signal reception as well as internet access. This application sets strong requirements in terms of handover due to the speed of the vehicles. Cell planning may be efficiently done by taking the city street plan into account. Laptop in-car users could be a case of mobile users with very strict requirements in both bandwidth and handover, while in-car entertainment systems may be regarded as mobile game consoles providing high-quality video and internet access. As a case study, similar requirements could be offered by the optical-wireless network in terms of bandwidth, jitter and latency.
- <u>Best-effort video scenarios</u>
    - *Medical applications (telemedicine):* medical care can be facilitated and improved when keeping specialized staff, e.g. doctors and nurses, updated with the latest information with respect to a patient’s condition. Video files are often the outcome when monitoring the condition of a patient. Doctors and nurses can be updated irrespective of their location inside or outside the hospital. Furthermore, when transferring a patient to the hospital, the outcome of the first tests that can take place in the ambulance can be shared with the specialized staff in the hospital.

- *Video on demand:* A user watching a pre-recorded episode or a movie on a mobile device may store parts of the content which should be large enough to be without connection to the network without degradation in the quality of experience. As soon as the user is within network range, a burst of data will be pushed to the mobile device depending on the status and settings of the user. The size of the data burst shall mostly depend on the resolution of the screen and the size.

Next-generation wireless networks overview

Since the optical network is to feed a RAP that is serving a next-generation wireless network, an overview is made of the characteristics of several RF networks. This is shown in Table 5 (next page).

Table 5: Overview of characteristics of next-generation wireless networks

Network	Status	Freq. Spectrum Allocation	Channel Bandwidth	Range	Bitrate/ channel
802.11n	Wireless LAN MAC and PHY Specifications. Amendment 5: Enhancements for Higher Throughput Published Oct 2009	2 bands: 5 GHz and/or 2.4 GHz	20/40 MHz	~up to 70m (indoors)-250 m(outdoors)	74 Mbits/sec per user
60 GHz millimete r-wave (MMW)	802.15.3c-2009 MMW-based physical layer for 802.15.3 standard	7 GHz in 57-64 GHz(unlicensed)	2160 MHz	up to 10m.	150 Mb/s-480 Mb/s (500 Mbps)
3GPP-LTE	EUTRAN Version 8 of 3GPP. (December 2009: First commercial LTE-service by Telia)	WCDMA band, 2.5/2.6 GHz, 2.3 GHz, 2.1 GHz,1900 MHz,1800 MHz,1700/2100 MHz, 1500 MHz, 900 MHz, 850 MHz, 700 MHz, 450 MHz	Scalable ranging from 1.25MHz to 20MHz 1.4, 3/3.2, 5, 10, 15, 20 MHz	< 20km, WAN scale	DL : 100Mb/s SISO; 173Mb/s 2x2 MIMO; 326Mb/s 4x4 MIMO for 20 MHz UL: 58Mb/s 16QAM / 86Mb/s 64QAM
Wimax Mobile	IEEE 802.16-2009 Released May 2009 (IEEE 802.16m expected for mid-2010)	3 bands: 5,86 GHz (unlicensed), 2,3, 2,5 and 3,5 GHz (licensed) & 2,4 GHz (unlicensed)	Scalable bandwidths from 1.25 to 20 MHz (1,25/5/8.75/1 0/20 MHz) Reusability	4 km in urban environment and 10 km in rural areas. (up to 16 km LOS but not desirable for loaded networks)	DL 128 Mbps per sector UL 56 Mbps per sector in 20 MHz channel bandwidth 500 Kbps/user
802.20 (MBWA)	802.20 approved June 2008	Bands with license below 3,5 GHz	5MHz-20 MHz	2 – 40 km MAN scale 4km one single BS	70 Mb/s channel, Per cell: DL: 4Mb/s UL: 1,2Mb/s (for 5 MHz) DL: 1Mb/s UL: 300kb/s (for 1.25 MHz)

Network	Mobility Speed	Data rate (Max)	Applications	Environments	Additional information
802.11n	1.2 -10 km/h	600 Mbit/s (PHY) 400 Mb/s (MAC)	Internet, VoIP & local file transfer, streaming video and music, gaming, network attached storage	Home, office & hot spots	Interoperability between 20 & 40 MHz Bw[i] devices (greenfield format) Backwards compatible with 802.11g, 802.11b and 802.11a (2.4 and 5 GHz)
60 GHz millimeter-wave (MMW)	120 km/h	10 Gbps	Next-generation WPANii Short-distance high speed internet access, streaming content download (video on demand, home theater, etc.).	Ideal for dense deployment, redundant architectures (CMOS allows low cost multi-antenna to increase gain)	High propagation attenuation. Small and directive antenna. Interference-free due to high oxygen absorption(15dB/km) and narrow beam width.
3GPP-LTE	250 km/h. optimized for lower speeds (from 0 to 15km/h)	250 Mbps in a channel 20-MHz wide.	MMOG (Multimedia Online Gaming), mobile TV, Web 2.0, streaming contents	Local /Wide area deployments	Interoperability between GSM / UMTS enhancements to the packet switched all-IP Global roaming
802.16 **Wimax Mobile**	Up to 250 km/h	300 Mbps (802.16m update to offer over 1 Gbit/s speeds)	VoIP, video conferencing, streaming media, multiplayer interactive gaming, Web browsing, instant messaging, media content downloading	Multi-service, multi-access environment	Multimedia and Internet services Interoperability & roaming All-Internet protocol (IP) end-to-end network architecture,
802.20 (MBWA)	250 km/h	260 Mbps		Metropolitan Area Networks	Optimized for full mobility; voice and data Optimized for IP data

Network	Handover management	Effectiveness (bits/seconds and by Hertz)	Maximum cell size	Latency
802.11n	Scanning (active and passive), authentication and reassociation	2,7	cell radius of a couple of hundred meters	<100 ms
60 GHz millimeter-wave	3 handoff mechanisms→ hard handoff (HHO), fast base station switching (FBSS)(optional), macro-diversity handover (MDHO)(optional).	only 0.4 for 1Gbps	micro (500 m) or pico (100 m) cells.	Latency-free
3GPP-LTE	3GPP performs PDCP SDU level context transfer during handovers	5 b/Hz/s for downlink 2.5 b/Hz/s for the uplink	very large cells 5 – 100km with slight degradation after 30km	5ms latency for small IP packets End-user latency <10ms
802.16 Wimax Mobile	Seamless inter-cell and inter-sector handoff. Latency for handover <200ms	0.5 to 4.5 bps/Hz. Lowers as mobility increases.	20.7 km for 3.5 or 7 MHz bandwidth 8.4 km for 5 or 10 MHz bandwidth	less than 50 ms
802.20 (MBWA)	Extended Cell (EC).	3,2 Greater than 1.0 bps/Hz is Expected. *> 1 b/s/Hz/cell*	Cells of 2,5 km *Appropriate for ubiquitous metropolitan area networks and capable of reusing existing infrastructure.*	5.5 ms

Digitized RF-over-fiber of next-generation wireless using bandpass sampling

The transport of digitized radio frequency (RF) signals is shown to have several benefits over the traditional radio-over-fiber (RoF) technologies such as lower restrictions on the linearity of the modulator, a non-decaying dynamic range when the transmission distance is increased, and the usage of mature digital hardware [29]. The digitized RF data stream may added as payload in the packets which are transported in existing and future high-speed optical access networks. In that sense, a seamless integration of fixed and wireless networks can be achieved. A typical network setup is shown in Figure 27 whereby a radio access point (RAP) is connected to a central office (CO).

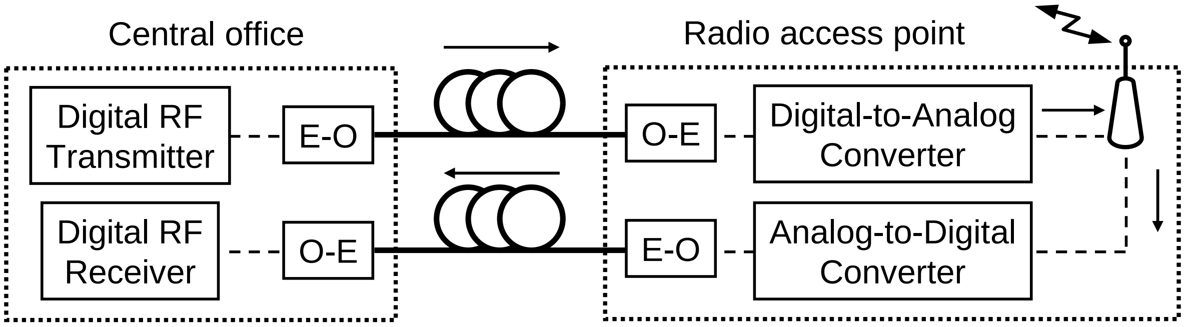


Figure 27: Schematic representation of a digitized RF-over-fiber transmission setup

The wireless networks typically operate at high carrier frequencies while the available bandwidth is limited due to regulation of the spectrum. It is clear that the fractional bandwidth of wireless networks is low, and therefore sampling at the Nyquist frequency, i.e. at twice the highest frequency to be sampled, leads to an inefficient usage of analog-to-digital (ADC) and digital-to-analog (DAC) resources. The bandpass sampling technique relaxes the requirements of the signal processing equipment. It is based on sampling the RF signals at a lower frequency than the Nyquist frequency, and a replica appears at that sampling frequency.

Bandpass sampling is highly effective when information at small bandwidths needs to be sampled which is the case at wireless networks. Two conditions hold for bandpass sampling, namely [30]:

$$\frac{2 f_u}{n} \leq f_s \leq \frac{2 f_L}{n-1} \qquad (1)$$

$$1 \leq n \leq I_g\left[\frac{f_u}{B}\right] \qquad (2)$$

It is clear that the ADC still requires to have a bandwidth equal to the highest frequency of the wireless network, and therefore the scalability is limited with respect to next-generation wireless networks which operate at higher carrier frequencies. Another limiting factor is any out-of-band signal power because it leads to inference during the reconstruction at the DAC.

Table 6 depicts the (highest) carrier frequencies (f_c) and maximum bandwidths of 4 different next-generation wireless networks.

Table 6: Maximum carrier frequency and bandwidth of next-generation wireless networks

Wireless network	f_c (GHz)	B (MHz)
WiMax	11	20
3GPP-LTE	2.6	20
60 GHz (SiGi)	60	2160
WLAN 802.11n	5	40

It is shown in Table 6 that the 3GPP-LTE network already needs ADC/DAC components with a bandwidth of about 3 GHz. The 60 GHz network appears to be not feasible in terms of sampling considering the very high carrier frequency.

Table 7 depicts the bandwidth, resolution, and sampling frequencies of commercially available ADC and DAC components whereby low-end and high-end devices are considered as these are produced by [31].

Table 7: Data from commercially available low- and high-end ADC/DAC devices [31]

	Characteristic	Low-end device	High-end device
ADC	Bandwidth	600 MHz	2.8 GHz
	Resolution	8	8
	Sampling frequency	250 MHz	2.2 GHz
DAC	Resolution	12	12
	Clock frequency	250 MHz	4.3 GHz

The high-end ADC shown in Table 7 has just enough bandwidth to be able to sample the 3GPP-LTE signals but not the other 3 wireless networks. Indeed, ADC and DAC technology is improving and higher performance devices should be widely-available on the short-term; however, a lot of bandwidth is wasted because of the low “fractional” bandwidth of the wireless networks.

Instead, it is proposed to perform a down-conversion before the RF signals are bandpass sampled. Up-conversion is done when the signals are recovered at the DAC. Considering that the CO may serve several different wireless networks, several local oscillator (LO) signals should be available to perform the up/down conversion. At the RAP-side, heterogeneity may also exist meaning that a single RAP may host one or more wireless networks. A photonic and centralized solution is considered here and remote LO generation is employed. In that sense, the reconfigurability is expected to be enhanced.

Remote local oscillator generation using photonic technologies for up/down conversion

A single photonic system is envisioned to serve all RAPs connected to the CO by means of broadcast-and-select. A harmonics generating RoF technology would be suitable because many harmonics are generated at the output of the photo detector (PD) as a function of a single sweep frequency at the CO. The principle of operation of the before mentioned is shown in Figure 28(a)-(c) considering the RAP-side.

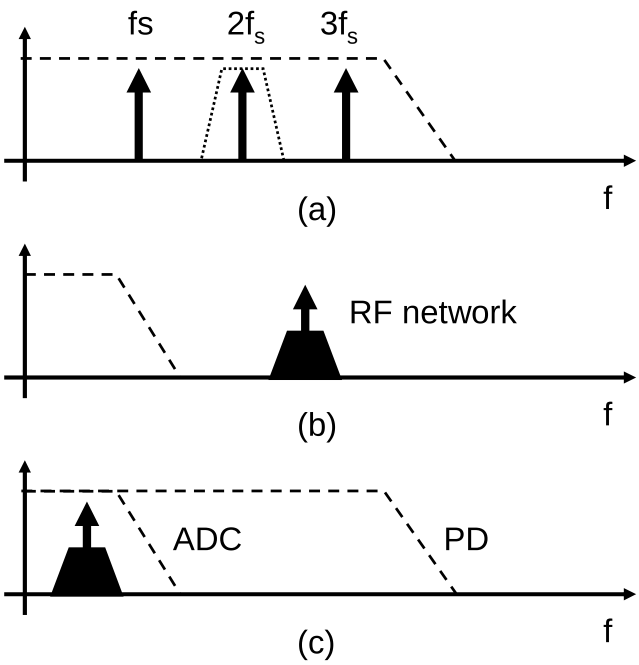


Figure 28: Schematic representation of the radio frequency spectrum in case of down conversion at the RAP using remotely generated local oscillators: (a) Photo diode output with a selected higher harmonic, (b) Wireless network and ADC bandwidth shown, (c) Down converted RF network using selected higher harmonic

The detected higher harmonics at the output of the photo diode are shown in Figure 28(a) with the dashed curve as the photo diode’s bandwidth. Next to the sweep frequency, two higher harmonics are detected. The first higher harmonic ($f=2f_s$) is filtered (dotted) and used in the down conversion because it is closest to the

RF network as shown in Figure 28(b). That figure also depicts the ADC bandwidth which is too low to bandpass sample the RF network. Finally, Figure 28(c) depicts the resulting signal after down conversion as well as the bandwidths of the PD and ADC (dashed). An example of a cost-effective system is the optical frequency multiplication technique [32].

From Figure 28(a)-(c) it is clear that a trade-off exists between optics and the signal processing units. The state-of-the-art in the ADC/DAC modules is shown in Table 7. Regarding the electronics, 10 GHz photo diodes may be assumed widely available because current backbone networks operate at 10 Gb/s speeds or higher, and the global deployment of 10 GbE ports in server farms was predicted to reach its peak in 2015 [33]. A technology deployment at such scale enables photonic components to become cost-effective at 10 GHz.

Moreover, Figure 28(a) and (b) indicate that the first (or: lowest) frequency appearing at the photodiode in Figure 28(a) should be lower than the carrier frequency of the first RF network that falls outside the ADC bandwidth. When considering the data shown in Table 6 and 7, very high PD bandwidths are required to be able to bandpass sample a 60 GHz network even when ADC/DAC bandwidths are increased. To that respect, the 60 GHz network is out of scope in this JA.

Functional requirements of central office and radio access point

Figure 29 shows the architecture of the central office (CO). The CO consists of several electronic processors, an analog-to-digital and a digital-to-analog converter, four electro-optical subsystems, a wavelength division multiplexer and a circulator.

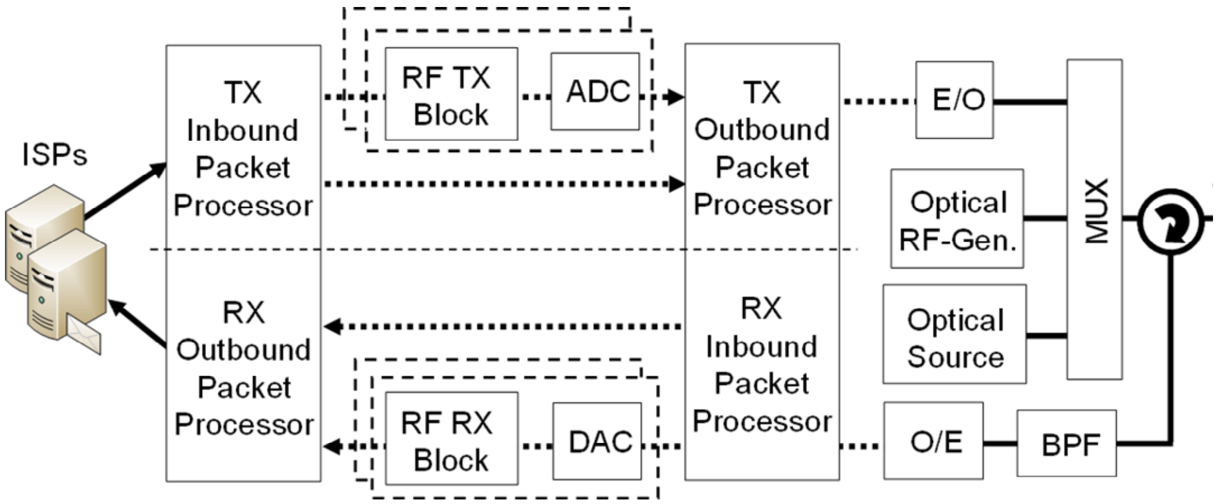


Figure 29: Architecture of the central office [22]

Table 8 provides a description of the components/subsystems that comprise the CO, as shown in Fig 29.

Table 8: Description of components/subsystems of the CO

Subsystem	Function	Bandwidth (BW)	Wavelength	Modulation
E/O	Electro-optic transmitter.	It depends on the ADC and the processors BW. BW to support 1 Gb/s will be considered.	C-band (~1550 nm)	Both external and direct modulation can apply. Since this component is at the CO, the cost of external modulation can be tolerated and will

				be considered. The modulation format is OOK.
Optical RF-Gen.	Provides the RF carriers at the BS. The OFM technique will be used. Other optical techniques, such as optical heterodyning could be considered as well.	The RF carriers of interest are in the microwave range (2-11 GHz). Millimeter-wave carriers (up to 60 GHz or more) could be considered as a next step. Phase modulation (~2.5 GHz) of the optical carrier is required in the OFM technique.	C-band (~1550 nm) Note that OFM generates a broad spectrum. Therefore the carrier of the CW laser included in this module should be suitably far from the wavelength of the E/O module.	No data modulation applies. Phase modulation (~2.5 GHz) of the optical carrier is required in the OFM technique.
Optical source	Provides a CW optical carrier to be remotely modulated at the BS for upstream transmission.	Typical of a DFB laser.	C-band (~1550 nm) Overlap with the optical spectra of the E/O and the Optical RF-Gen. should be avoided.	Does not apply.
BPF	If a reflective element (e.g. an RSOA) is used at the BS, an optical BPF is used to reduce the ASE noise before reception.	In the order of the upstream optical signal.	It matches that of the upstream optical signal, i.e. the wavelength of the optical source.	Does not apply.
O/E	Opto-electronic receiver.	Similar to the E/O BW.	C-band	Does not apply.
MUX	λ-multiplexes the three input optical signals	Channel spacing is determined by the wavelength differences in the input optical signals. The band-pass of each input port is set by the stringent requirements, in this case the optical spectrum of the OFM module (Optical RF-Gen.).	C-band	Does not apply.
Circulator	Enables bidirectional transmission over a single SMF.	Does not apply.	C-band	Does not apply.

Figure 30 shows the architecture of the radio access point (RAP). The RAP consists of several electronic processors, an analog-to-digital and a digital-to-analog converter, two RF mixer for electronic up/down-conversion, an antenna, a diplexer, three electro-optical subsystems and a wavelength division demultiplexer.

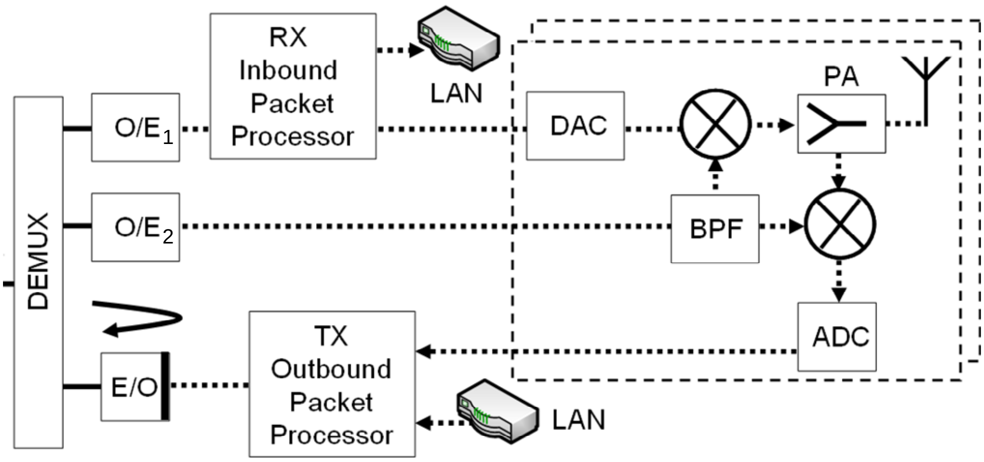


Figure 30: Architecture of the radio access point [22]

Table 9 provides a description of the components/subsystems that comprise the RAP.

Table 9: Description of components/subsystems of the RAP.

Subsystem	Function	Bandwidth (BW)	Wavelength	Modulation
O/E1	Opto-electronic receiver for baseband signals.	Similar to the E/O module at the CO.	C-band	Does not apply.
O/E2	Opto-electronic receiver for RF-carrier detection.	Set by the maximum RF-carrier of interest, e.g. 11 GHz to cover the microwave range.	C-band	Does not apply.
E/O	A reflective element, such as an RSOA for remotely modulating the optical carrier provided from the CO for upstream transmission. Alternatively, an optical modulator could be used, increasing though the cost of the BS.	It depends on the ADC and the processors BW. BW to support 1 Gb/s will be considered.	C-band	The modulation format is OOK.
DEMUX	λ-demultiplexes the three input optical signals.	Similar to the MUX at the CO.	Similar to the MUX at the CO.	Does not apply.
BPF	Electrical tunable BPF to select the RF-carrier of interest.	Narrow pass-band, tunability over the range of interest, e.g. 2-11 GHz to cover the microwave range.	Does not apply.	Does not apply.
Mixers ⊗	Electronic mixers used for up/down-conversion with the RF-carrier selected	Set by the RF-carriers of interest, e.g. 2-11 GHz to cover the microwave	Does not apply.	Does not apply.

	by the electrical BPF.	range.		

T3 Implement architecture in simulation environment for proof-of-principle

To evaluate the performance of this novel architecture, we have built an extensive and complete simulation setup (shown in Figure 31), which is implemented in the VPI TransmissionMaker platform (v8.5) and uses co-simulation with custom-made modules we have implemented in MATLAB (v7.7, R2008b). In particular, the ADC and DAC are implemented in Matlab and were firstly benchmarked with the results shown in Gamage et al [29]. The analogue signal is sampled at the ADC followed by a uniform 8bit-PCM encoder. At the DAC the signal is reconstructed after the corresponding PCM decoder, using a zero-order-hold circuit.

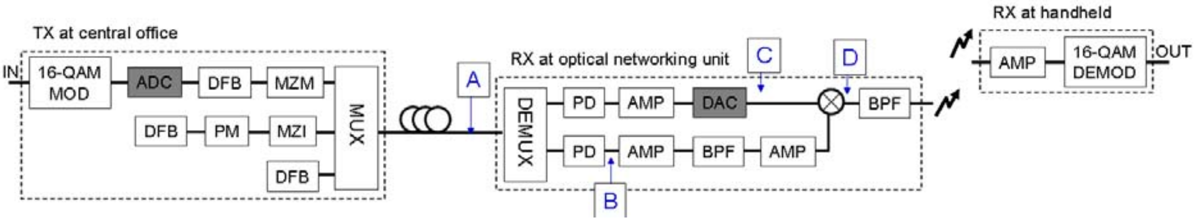


Figure 31: Simulation set-up showing the main building blocks considered in our study. The points of interest in the set-up for which we show results are indicated with a capital letter (A, B, C, D). Grey blocks indicate simulation in MATLAB, all other blocks are simulated in VPI.

In our simulations we considered 2 next-generation wireless signals, namely WiMax and Wi-Fi., which represent high bandwidth available under high mobility and low mobility, respectively. As mentioned before, the upper boundary for the carrier frequency is set by the ADC/DAC bandwidth so we assumed 600 MHz and 2.8 GHz to be representative for low-end and high-end devices. The (original) carrier frequencies of Wimax and WLAN 802.11n are 2.475 GHz (as in [29]) and 5.8 GHz, and the bit rates used are 33 Mbps and 40 Mbps, respectively. The coding employed is 16-QAM and only 128 symbols are simulated due to computing limitations. We point out that 128 symbols correspond with 512 bits at the input of the 16-QAM modulator and 16384 bits at the ADC output. We calculated the optimal sampling frequency and choose an intermediate carrier frequency taking into account the ADC/DAC bandwidths. This leads to 5 different simulation scenarios, namely 2 in case of Wimax (fsample=132 MHz for fcarrier=495 MHz and fcarrier=2.475 GHz) and 3 in case of WLAN (fsample=160 MHz for fcarrier=520 MHz, fcarrier=2.6 GHz, and fcarrier=5.8 GHz).

In the forthcoming we focus on the WLAN case with an intermediate carrier frequency of 520 MHz and a LO at 5.28 GHz being the most demanding case. Figure 32(a) shows the optical spectrum of the transmitted signals (consisting of the digitized RF data, the optical frequency multiplication-OFM signals and the CW carrier) over the optical fiber at point A of the simulation set-up as shown in Figure 31. A fiber length of 10 km is taken in the simulations at 0.18 dB/km. As mentioned in [22], the CW carrier is used in a reflective modulation technique for the upstream channel so for sake of completeness we have included this in our simulations. The resulting signals at the two branches of the receiver after demultiplexing and at points B and C of the simulation set-up of Figure 31 are shown in Figure 32(b) and (c) respectively. In Figure 32(b) we point-out the location of the 5th harmonic at 5.28 GHz which is the LO selected for upconversion. The resulting RF spectrum of the signal after mixing at point D is shown in Figure 32(d). It is clear that the component at 5.8 GHz is filtered by a BPF, radiated and then received by the mobile handheld. We observe error-free transmission after demodulation.

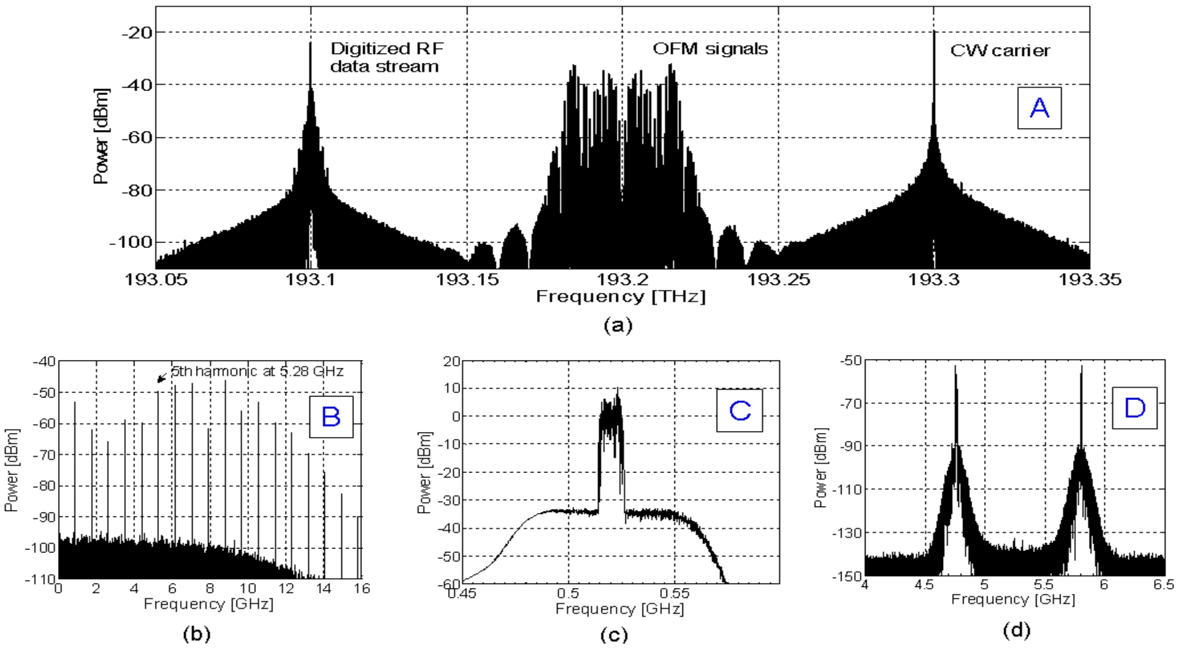


Figure 32: (a) Optical spectrum of the transmitted signals, (b) RF spectrum OFM higher harmonics after the photodiode, (c) RF spectrum recovered WLAN signal at 520 MHz after the DAC, and (d) RF spectrum of the unconverted signals before the BPF

Figure 33 shows a summary of the characteristics of all 5 different cases considered, the received constellation diagrams as well as the associated calculated EVM. Excellent performance is demonstrated in all cases with EVM values ranging between 5% and 6%.

Case	fcarrier (MHz)	fsample (MHz)	bit rate (Mbps)	fsweep (MHz)	OFM harmonic	EVM
(1): WiMAX digitization at intermediate frequency for low-end ADC/DAC bandwidth of 600 MHz	495	132	33	990	1980 MHz (1st)	6.0%
(2): WiMAX digitization at original frequency for high-end ADC/DAC bandwidth of 2.8 GHz	2475	132	33	-	-	5.9%
(3): WLAN 802.11n digitization at intermediate frequency for low-end ADC/DAC bandwidth of 600 MHz	520	160	40	880	5280 MHz (5th)	5.5%
(4): WLAN 802.11n digitization at intermediate frequency for high-end ADC/DAC bandwidth of 2.8 GHz	2600	160	40	800	3200 MHz (3rd)	5.6%
(5): WLAN 802.11n digitization at original frequency for elite ADC/DAC bandwidth of 11 GHz	5800	160	40	-	0	5.4%

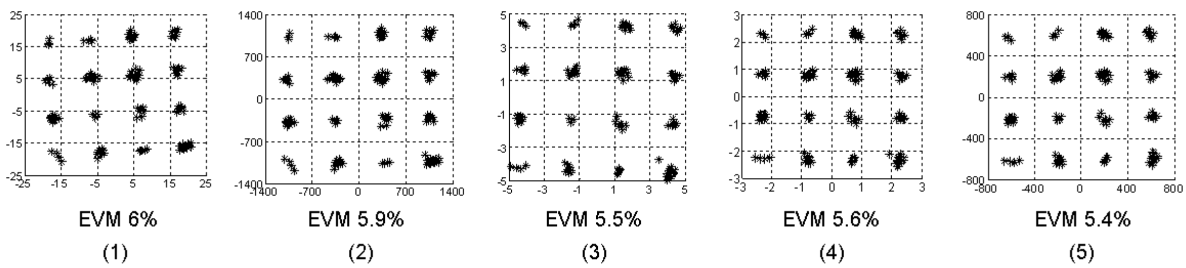


Figure 33: Summary table, constellation diagrams and achieved EVM for all cases of wireless signals

In conclusion, the performance of a novel optical-wireless network architecture was simulated showing excellent performance demonstrating the feasibility of the proposed techniques. An overview paper on the simulation results has been submitted to the Future Network and Mobile Summit 2011, Warsaw, Poland [34].

T5 Experimental demonstration optically supported handovers using a reflective solution for the uplink

At the time of writing of this deliverable, the experimental setup is being prepared using offline digitization of RF signals using the model programmed in MATLAB. The reconfigurable optical setup shown in [35] will be used to transport the digitized RF signals and to perform optical handover experiments using the reconfigurable remote node.

As a first approach, an RF signal generated by a arbitrary waveform generator (AWG) is captured by a digital phosphor oscilloscope (DPO). The resulting sampled RF signal is then fed into the MATLAB model after which ADC and DAC operations are performed in a back-to-back scenario. The recovered RF signal is then fed into a vector signal analyzer (VSA) which then evaluates the quality, in terms of error-vector magnitude (EVM), and the bit error-rate (BER) of the signal. If successful, the optical link is included and handover experiments are performed.

The proof-of-principle is given by the extensive simulations done. A handover scenario is expected to be experimentally demonstrated since this is not trivial in the simulation environments used here. The experiments have been initiated and results could be expected in 2011. A joint paper has been published and a second one is submitted. The overall work done shall be summarized in full-size paper, preferably submitted to a high-impact journal (IEEE, OSA, etc.).

5.4.3 Next Steps

It is expected that the experiments may not be done within the framework of the BONE project (ends 31 December 2010). The JA-members shall strive to achieve concluding results in the first half 2011 pending on availability of (lab-) time and resources.

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5.5 All-optical Routing Architecture of Radio Signals using Label Processing Technique for In-building Optical Networks {TUE}

5.5.1 Motivation and Objectives

The growing demand of broadband services among residential and business customers has fuelled the research and development of numerous wired and wireless technologies to satisfy those demands. Radio-over-fibre (RoF) technology is considered as a key enabler for merging of broadband wired and wireless services in an integrated full service access and in-building networks. In addition, RoF distributed antenna systems are identified as a flexible option for the access architecture of current and emerging wireless access in-building networks as it reduces infrastructure costs and antenna site complexity.

Figure 34 shows an example of in-building access architecture. In this architecture, the main device is the home communication controller (HCC), which arranges communications between rooms and routes signals to the proper rooms according to the label information attached to the data signals. Optical routing based on label information will improve the flexibility and the efficiency of the network resources.

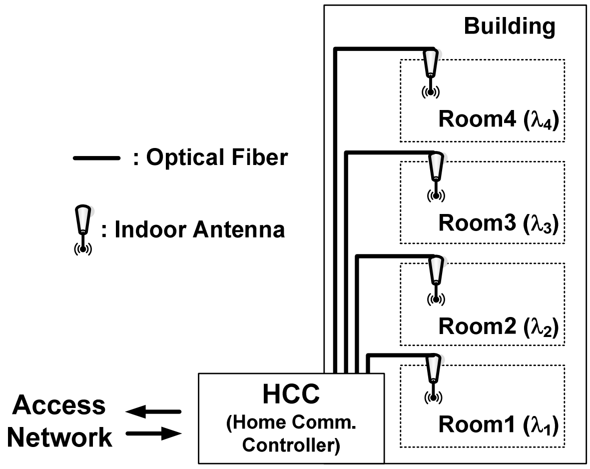

Figure 34. In-building network architecture.

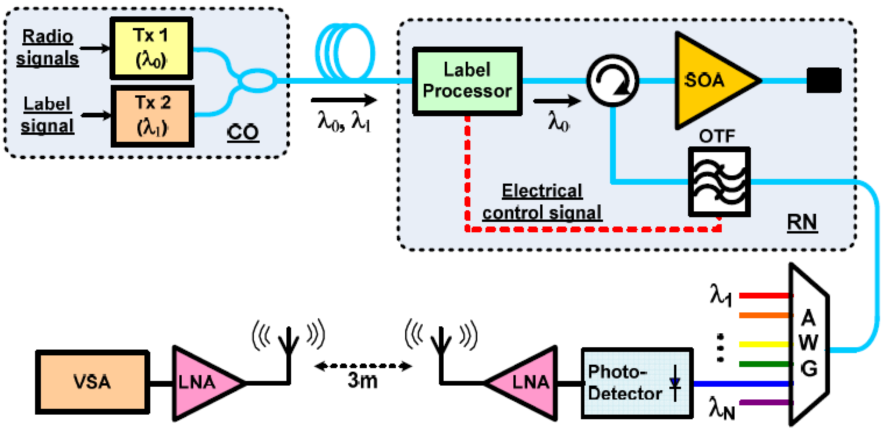

Figure 35: Experimental Setup (CO: central office, RN: remote node, LNA: low-noise amplifier)

The development of wireless communications allows people to be served with broadband seamless connections at any place and anytime. In in-building environments, however, this benefit is still not fully provided yet. In buildings, people can expect several wireless communications such as cellular communication, wireless LAN, wireless connection between devices like Bluetooth. But, each network works separately, which induces management issues and it is difficult to cover a whole building with a single large wireless network.

The Radio-over-Fibre (RoF) techniques, which transmit Radio signals through optical fibre link with unlimited bandwidth, low loss and immunity to electro-magnetic interference (EMI), can offer valuable solutions for this problem. In addition, an RoF system shifts signal processing functionality from the base-stations (BSs) to the central office (CO) and reduces overall system complexity.

A conventional RoF system has a passive ‘broadcast-and-select’ configuration. However, in order to manage dynamic traffic variation with time and place in the networks, RoF systems need to flexibly adjust their configuration according to the traffic situation. A reconfigurable system can improve the traffic handling capability and network operational efficiency.

To implement a reconfigurable RoF system, we propose a new system configuration with a semiconductor optical amplifier (SOA). The combination of the modulated amplified spontaneous emission (ASE) noise and a tunable optical filter allows managing the distribution of Radio signals. We report on the realization of the proposed system and the transmission performance of Wi-Fi (802.11a/g)-compliant signal with 54Mb/s, 52 OFDM subcarriers centered at 2.4GHz. In the demonstration, the Radio signals are successfully delivered through the system including 3m wireless channel with 3% error vector magnitude (EVM) penalty.

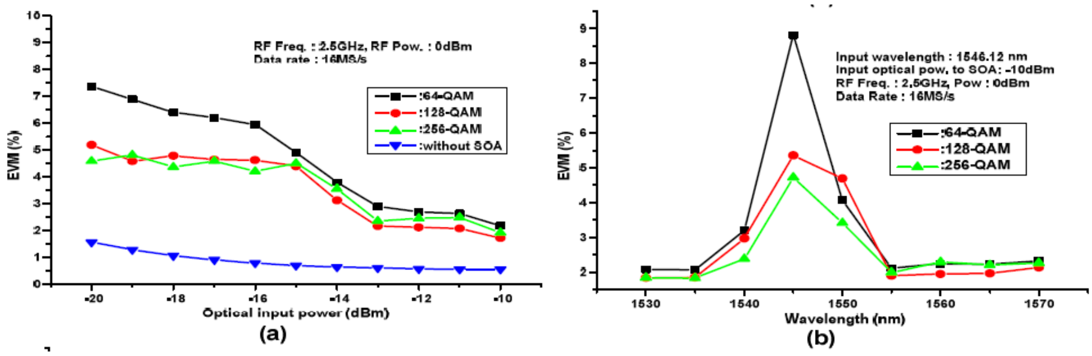

Figure 36: EVM performance of a single RF carrier QAM signal for (a) the input optical power to SOA, (b) the selected passband of the modulated ASE noise

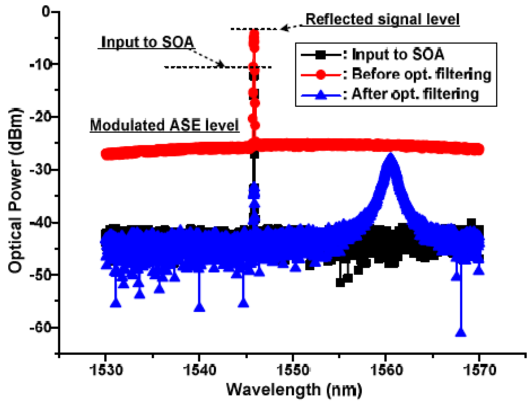

Figure 37: Optical Spectra

Figure 35 shows the configuration of the proposed RoF signal distribution system. An SOA in the remote node (RN) is free running with a certain bias current. When RoF signals (λ0) are injected to the SOA, the radio signals modulate its ASE noise through a cross-gain modulation (XGM) process. Then, the modulated ASE noise is directed to an arrayed waveguide grating (AWG) router.

In general, ASE noise has a broad optical spectrum. Due to that, radio signals can be distributed by the modulated (wavelength converted) ASE noise signals. However, by introducing a tunable optical filter, RoF signals can be routed to particular output ports or network connections can be reconfigured. As shown in figure 35, a label signal on different optical wavelength (λ1) is transmitted together with RoF signals. The label processor takes out the label signal and decodes the label information. In the meanwhile, RoF signals modulate ASE noise by XGM. Then, the modulated ASE noise signals pass an optical tunable filter (OTF) just before the AWG. The OTF is tuned by the label information and filters the broadband modulated ASE signals so that the RoF signals can be routed to the particular ports (or places indicated by the label).

5.5.2 Main outcomes and results

The experimental setup consists of three parts: the transmitter in CO, the RoF signal distributor in RN, and the wireless channel as shown in figure 35. The CO has two optical transmitters; Tx1 and Tx2, those are for radio signals and labels, respectively. The radio signals are Wi-Fi - compliant (IEEE 802.11a/g, 54Mbps, 52 OFDM subcarriers centered at 2.412 GHz), which are generated from the vector signal generator (Agilent, N5182A), and modulate an optical signal (λ0=1546.12nm). After optical modulation, the optical signal (λ0) is combined with the label signal channel (λ1) and then transmitted to the RN.

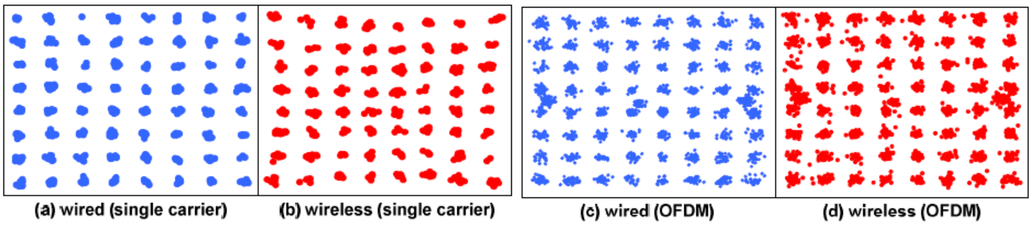

Figure 38: Constellations for (a, b)single-carrier 64QAM, (c, d) multi-carrier OFDM (802.11a/g)

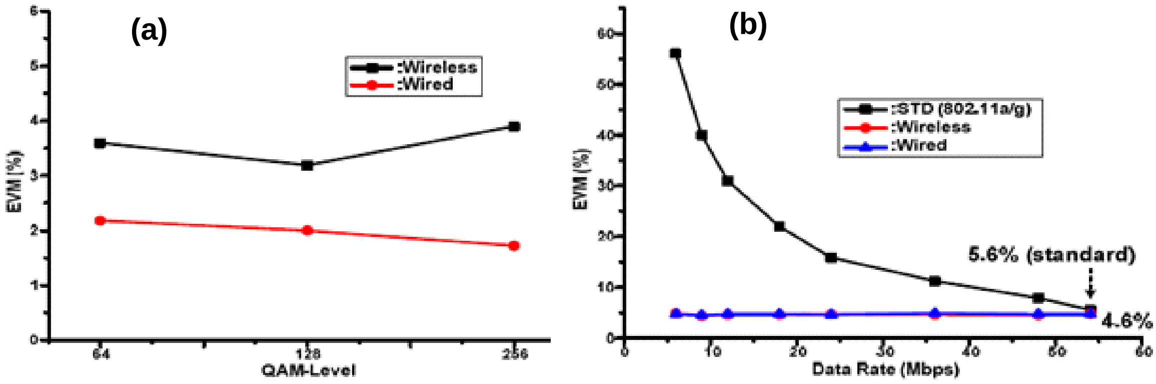

Figure 39: EVM performance after wireless transmission (a) single carrier QAMs, (b) Wi-Fi (802.11a/g)

At the RN, the label processor takes out only the λ1 wavelength and then decodes the label information. However, the label processor is emulated at the moment of the demonstration. The RoF signals (λ0) pass the label processor and are directed to the SOA (CIP, SOA-NLOEC- 1550) which has a small signal gain of 30dB, a saturated output power of 8dBm @ 200mA, and a gain peak at 1542nm @ 350mA. The SOA is biased with a current of 350mA and the generated broadband ASE noise is modulated by the injected RoF signals based on the XGM. To avoid an optical filter to remove the optical seeding signal (λ0) for the XGM, the modulated ASE noise signals are taken at the counter-propagation port with an optical circulator. For reconfiguring network connections, the OTF selects the proper ASE noise band based on the control information from the label processor and then the selected optical band is routed by the AWG.

At the antenna site, the distributed modulated ASE signals get detected and transmitted to a wireless channel through a monopole antenna (Titanis, Swivel antenna with -1dBi gain). After 3m wireless transmission, the Wi-Fi –compliant signals are received at the counterpart antenna and the performance is evaluated by the vector signal analyzer (Agilent, N9020A).

To evaluate the performance of the proposed RoF distribution system, firstly we measured the EVM performance for the wired parts with single RF carrier QAM signals, which have 16MS/s data rate centred at 2.5GHz. Figure 36 (a) shows the measured EVM against the input optical power to the SOA. Three different QAM-levels (64, 128 and 256 –QAM) show almost the same performance. When increasing the optical power, EVM gets better because the cross modulation efficiency improves with optical power. The EVM penalty as compared to the B-to-B case is from the XGM conversion loss. In addition, the system shows quite even performance over the wide wavelength band as shown in Figure 36 (b) since the XGM covers the whole ASE noise band. However, the bad EVM performance around the seeding wavelength is due to the interference between the reflected seeding signal and the selected ASE noise band. As shown in Figure 37, the power level of the reflected seeding light is very high even in the counter propagation configuration, which is different from what we expected. An ad-hoc filtering could improve the seeding light suppressing, thus increasing the usable wavelength range.

We then tested the technique including wireless transmission. Two different types of radio signals are compared in the wireless transmission: single-carrier QAMs with 16MS/s data rate centred at 2.5GHz and multicarrier OFDM (802.11a/g) with 52-subcarrier centred 2.412GHz. In case of wired link in Figure 39**,** singlecarrier QAMs shows better performance than multi-carrier OFDM: 2.6% difference between them. We think the interference between adjacent OFDM carriers causes extra conversion loss during the XGM of the SOA. Nevertheless, the signals are still better than the limitation of 802.11a/g standard; 5.6% EVM is the upper limit for 54Mbps transmission, but 4.6% EVM was achieved in the experiment.

However, when both types of signals were transmitted over the 3m-long wireless channel, the single-carrier QAMs got distorted due to the multi-path fading. Figure 38 (a), (b) show the edge sides of the constellation are distorted after wireless transmission in case of the single carrier QAMs. But, the multi-carrier OFDM signals show almost the same performances even with the multi-path fading as shown in Figure 38(b) and Figure 38(c, d). There is no great difference between wired and wireless cases. These results also show that OFDM-format signals are tolerant of the multi-path fading environments.

5.5.3 Conclusions

For in-building networks, we proposed and demonstrated a new configuration of a flexible RoF signal distribution system. For the proof of the concept, we showed successful distribution of radio signals (single-carrier QAMs and Wi-Fi (802.11 a/g)-compliant OFDM) including a 3m wireless transmission link. The proposed system is based on XGM of an SOA and uses the sliced modulated ASE noise for the distribution. Hence, the system is colourless and has a lot of flexibility. We believe that the proposed system is simple and robust for in-building applications.

6. Conclusions and future plans

Summary of Joint Activities and current status

The following table summarizes the 5 JAs in the framework of WP23 as well as their current status.

Table 10: Summary of Joint Activities and their current status

No.	JA Title	Current status
1	State of the art definition for components supporting FSO networks in motion	A thorough analysis on all the aspects of FSO interlinks like the atmospheric parameters and optical propagation characteristics in nomadic or mobile situation have been carried out. Publication of an on-line book by Intech has been initiated.
2	Converged MAC algorithms for unified optical wireless functionality	Technology challenges have been analyzed and the performance of the DMW protocol a FTTH-based GPON network has been modelled using OPNET.
3	UWB Radio-over-fibre transmission in indoor environments using different media	Comparison of the in-building transmission performance of the OFDM-based (OFDM-UWB) and impulse-radio UWB implementations has been done via experiments and simulations.
4	Optimizing service delivery in a converged hybrid optical-wireless network	The proof-of-principle is given by the extensive simulations done. A handover scenario is expected to be experimentally demonstrated since this is not trivial in the simulation environments used here. The experiments have been initiated and results could be expected in 2011. A joint paper has been published and a second one is submitted.
5	All-optical Routing Architecture of Radio Signals using Label Processing Technique for In-building Optical Networks	A new configuration of a flexible RoF signal distribution system is demonstrated for in-building networks. The proposed system is colourless and has a lot of flexibility. Thus, the proposed system

		is simple and robust for in-building applications.

Publications

The following publications have been presented during the last year of this topical project:

- In the framework of BONE and in collaboration with COST ICO802 and WP13 on access, the publication of an on-line book by Intech on FSO technologies is under preparation. (JA2)
- Marta Beltran, Maria Morant, Joaquin Perez, and Roberto Llorente, "Performance Evaluation of OFDM and Impulse-Radio Ultra-Wideband over Fibre Distribution for In-Building Networks", IEEE International Conference on Ultra-Wideband, Vancouver, Canada, 9-11 September 2009. (JA4)
- Maria Morant, Joaquin Pérez, Marta Beltrán and Roberto Llorente, "Performance Evaluation of In-Building Radio-over-Fibre Distribution of Multi-Band OFDM UWB Signals", 2009 IEEE International Topical Meeting on Microwave photonics, Valencia, Spain, 14-16 October 2009. (JA4)
- B. Huiszoon, J. Aracil, H.D. Jung, A.M.J. Koonen, E. Tangdiongga, I. Tomkos, and C.P. Tsekrekos, "Optical-wireless network with multi-layer reconfigurability", in *Proc. OSA ANIC 2010*, paper AWC2, pp. 1-2, June 2010, Karlsruhe, Germany. (JA5)

Submitted publications

- J. Martínez, C.P. Tsekrekos, I. Tomkos, and B. Huiszoon, "Performance evaluation of a multi-layer reconfigurable optical-wireless network architecture employing digitized RoF", *submitted to Future Network and Mobile Summit 2011 conference*, June 2011, Warsaw, Poland. (JA5)

Motilities (performed/planned)

The last mobilities of the project were planned as follows:

- JA5: mobility action was foreseen at the end of 2010 in order to assist with the experiments. Unfortunately, the simulations took quite some time to finish so the mobility action could not be done.

Future plans (summary from JAs)

1. JA2: Next activities, such as possible new publications, book publications, collection of material, will be carried out in conjunction with the new agreement set between BONE and COST ICO802 and in collaboration with WP13 on Access Networks, WP02 on Teaching and WP01 on dissemination.
2. JA3: Further developing and evaluating algorithms that will be able to allocate optical network resources in a dynamic manner, enhancing the produced algorithms to enable mapping the packets from wireless users to appropriate PON classes and wavelengths, changing the model topology to account for the wireless architecture to be integrated to the current optical model, as well as enabling more efficient integration using an effective mapping mechanism between GPON priority queues and LTE service connections.
3. JA4: Further investigation of the UWB performance over other optical media could be investigated in the future.
4. JA5: The overall work done shall be summarized in a full-size paper, preferably submitted to a high-impact journal (IEEE, OSA, etc.). The JA-members shall strive to achieve concluding results in the first half 2011 pending on availability of (lab-)time and resources.

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