Ref. Ares(2016)1269004 - 14/03/2016

D 2.9

Dissemination Level:

- **Dissemination level:**

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

Abstract:

This deliverable represents a final summary of the architectural work carried out in the DISCUS project and is thus based on material already covered by a number of previous deliverables. It was devised to provide the reader with a reference document for the most updated version of the DISCUS network architecture.

COPYRIGHT

The DISCUS Consortium consists of:

Participant Number	Participant organization name	Participant org. short name	Country
Coordinator			
1	Trinity College Dublin	TCD	Ireland
Other Beneficiaries			
2	Alcatel-Lucent Deutschland AG	ALUD	Germany
3	Coriant R&D GMBH	COR	Germany
4	Telefonica Investigacion Y Desarrollo SA	TID	Spain
5	Telecom Italia S.p.A	TI	Italy
6	Aston University	ASTON	United Kingdom
7	Interuniversitair Micro-Electronica Centrum VZW	IMEC	Belgium
8	III V Lab GIE	III-V	France
9	University College Cork, National University of Ireland, Cork	Tyndall & UCC	Ireland
10	Polatis Ltd	POLATIS	United Kingdom
11	atesio GMBH	ATESIO	Germany
12	Kungliga Tekniska Hoegskolan	KTH	Sweden

Authors:

Name	Affiliation
David Payne	TCD
Marco Ruffini	TCD
Andrea Di Giglio	Telecom Italia
Giuseppe Ferraris	Telecom Italia
Marco Schiano	Telecom Italia
Laura Serra	Telecom Italia
Giuseppe Talli	Tyndall
Xin Yin	IMEC
Lena Wosinska	KTH
Jiajia Chen	KTH
Rene Bonk	ALUD

Internal reviewers:

Name	Affiliation
Marco Ruffini	TCD
David Payne	TCD

Due date:

31/10/2015

TABLE OF CONTENTS

1 INTRODUCTION

This deliverable is written as a stand-alone report describing the DISCUS architecture from concept to improvements and choices made following the learning from all the work packages within the project. Much of the description is therefore a summary of material in existing deliverables, particularly D2.1 and D2.3: although these can be referenced for more detail we have tried to keep this deliverable complete without the necessity to read them in addition.

This report is divided into a number of sections that describe the major aspects of the philosophy and design of the most relevant components of the discus architecture. Section 2 gives an overview of the rational and reasons both for the need for architectural change in order to solve major problems facing future networks and the logical progression to the structure adopted for the DISCUS architectural solution. This is followed in section 3 by a brief description of the specification and how the architecture extended the state of the art as it existed at the beginning of the project. The next three sections describe the technical designs of the major network components namely the LR-PON access and backhaul network, the metro-core nodes and the flat optical core network. The last two technical sections then give an overview of the end to end design considerations and a final summary of the DISCUS architecture design.

2 THE PHILOSOPHY OF THE END to END DISCUS ARCHITECTURE

Finding solutions to the following three major challenges facing future communications networks is the basis of the objectives of the DISCUS architecture:

- To remain economically viable while user bandwidth grows by 1000 times or greater over the next decade
- To reduce power consumption by at last 95% compared to growing today's networks.
- To avoid the digital divide by redistribution and reduction of costs to enable FTTH solutions for sparse rural areas.

We therefore started the DISCUS project with the primary objective of designing a network architecture that can deliver ubiquitous high speed broadband access to all users independent of their geographical location. Furthermore, the topology must target economic viability as user bandwidths grow by at least three orders of magnitude to ~200Mb/s sustained bandwidth in the busy period. This is to be achieved while also improving energy efficiency that will ensure significant power savings over current network configurations (of the order of 95% compared to extrapolation of today's architecture). In addition, the DISCUS architecture aims to deliver core network bandwidth capability to the access edge so that direct connection to the core network is available from any access terminal fitted with the appropriate technology

The DISCUS architecture must also be able to evolve from today's networks and the ability to evolve gracefully will be an important consideration within the design process. It is also important that the DISCUS architecture does not itself become a legacy network and will therefore need to be able to adopt new technologies and systems as they emerge in the future. A key feature of the design to achieve this objective is to have a transparent fibre infrastructure with optical channel processing, filtering etc. only within network nodes where such processing functionality can either be automatically switched in or out of optical light paths, or be by-passed altogether, without the need for installation of such processing equipment within the external plant or re-configuration of external plant. Such configurability within the networks nodes also supports software defined networks (SDN) at all layers within the network including the physical layer.

Efficient high speed broadband communications networks are essential for thriving communities in the modern world. Ideally, all users and all communities should have equal access to high speed broadband so that there is no division of service availability due to customer location. However, many countries still exploit old copper transmission technology and are now in danger of creating a digital divide between those with good copper access close to the operator's electronic infrastructure and those located in more remote areas connected via much longer copper lines.

There are also problems with wireless access solutions that are used to deliver broadband. In particular, wireless base stations must be located so they can capture a sufficiently large number of customers to make their deployment economically feasible. This inevitably leads to more remote areas getting less effective coverage than more densely populated regions with reduced bandwidth capability and quality of service as a result. Nevertheless, even in populous areas with good coverage, bandwidth availability can be variable depending how many users are actually within a particular coverage area at any one time and the spectrum available for that area. Ultimately wireless base stations for broadband services may evolve to femto cells where they are effectively part of the ONT of the fibre to the premises (FTTP) solution (in this report we use the term FTTP, rather than FTTH (fibre to the home) to include all fibre terminations including business premises, radio base stations etc. not just residential customers). In this case femto cells become the tetherless edge of the network in the same way as Wi-Fi is today.

The main problem with FTTP is that of financial viability. First there is the obvious problem of paying for the cost of the network infrastructure and its deployment, but there is a further financial problem arising from the sheer capability of FTTP networks to grow user bandwidth compared to copper and wireless technologies. If FTTP is used to provide the future high speed broadband services that customers require then the bandwidth entering the metro and core networks will have to grow in proportion and the network capacity will need to scale accordingly. Unfortunately, revenue will not scale proportionately and the revenue growth will not cover the cost of the bandwidth provision required. Furthermore, also expected reduction in the price of electronics will not be sufficient to reduce the telecommunications equipment cost fast enough to ensure economic sustainability (Figure 2-1), while another issue is the ever increasing power consumption of the electronic equipment required to service the projected bandwidth growth.

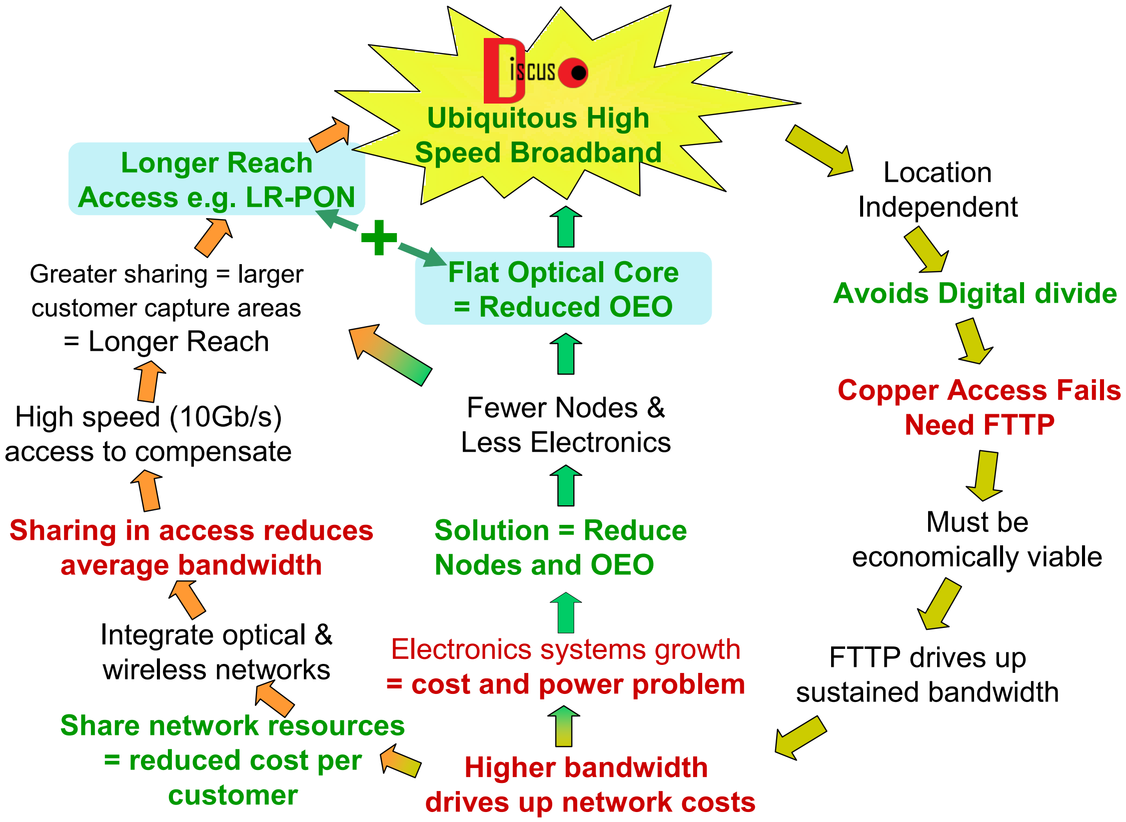


Figure 2-1 The DISCUS architecture - a logical necessity

If it is accepted that ubiquitous high speed broadband is a requirement of a future network and it is also accepted that services will evolve to exploit the capability of FTTP and therefore user bandwidth could grow by at least two to three orders of magnitude, then there is a logical argument that inevitably leads to an architecture that must be similar to the DISCUS architectural proposal. That is, some version of the DISCUS architecture is inevitable and unavoidable if superfast broadband communication is to be at the heart of a modern society. The logical flow that leads to the DISCUS architecture is illustrated in Figure 2-1 and is described below:

Ultimately, the only technology that can deliver ubiquitous high speed broadband is Fibre to the Premises (FTTP).

- We accept that ubiquitous broadband is a major requirement of a future broadband network and is a driving objective.
- Therefore all network services should be available and have equivalent capability at any location of an optical network termination point. This is one of the stated principles for the DISCUS architecture.
- Technologies that are location dependent or local environment dependent such as copper access technology cannot deliver this ubiquitous capability.
- FTTP becomes the inevitable solution for the access network if we want ubiquitous high speed broadband. It is the only technology that can provide equal service capability everywhere.
- But if FTTP is deployed as the universal future solution the network must still remain economically viable.

- It is also apparent that if FTTP delivers only a fraction of its potential service delivery capability, user sustained and peak bandwidths are going to increase and this could be several orders of magnitude compared to today's xDSL access networks.
- With the current network architectures, satisfying higher bandwidth in the core network, in addition to the need to build an FTTP access infrastructure, will significantly increase network costs – both OPEX and CAPEX. As mentioned above, the expected revenue growths are not sufficient to cover this cost increase. Therefore, we need to look at other alternatives for reducing the cost per customer so that the investment required is contained and network growth remains economically viable.
- There are two parts to solving the problem of increasing costs: one is to offset the access infrastructure build investment costs and reduced cost per customer by sharing the infrastructure over as many customers as possible, and at the same time use the lowest cost infrastructure sharing techniques. The second part of the solution is to minimise the number of electronic nodes, network interfaces, routers, switches and the traffic levels they need to process.
- Reducing electronics not only produces huge cost savings but also decreases the power consumption of the network. So the economic drivers also compliment the sustainability drivers and produce a "greener" solution. Removing cost from the backhaul and core networks can also help balance the increased cost of the access distribution network (from the cabinet location to customer) and fibre drop provisioning at the access edge.
- By keeping traffic in the optical domain and enabling transit traffic just passing through core nodes to bypass electronic routers and switches, the number of core network nodes required can be reduced to sufficiently low levels to enable the use of a **flat optical core,** whereby wavelength paths are setup across the network to interconnect the core nodes (or metro-core nodes as we refer to them in the DISCUS architecture). Thus traffic passing through a node stays in the optical domain and is not electronically processed; only traffic originating from or terminating on a metro-node needs to enter the electronic processing layers. Results from the DISCUS project have indeed shown that after a threshold user sustained bandwidth the flat optical core is lower cost than today's hierarchical core designs and remain so with increasing savings as bandwidths continue to grow.
- The flat core network leads us to define an "optical island" as a set of nodes that can be fully interconnected by transparent wavelength routes. For large countries such as the USA it is envisaged that multiple islands will be needed and these islands will be interconnected via a further "higher layer" optical island which interconnects the lower optical island through a small sub set of the metro nodes within those islands. However for European countries we have shown that a single optical island if sufficient and it is only for a Pan European network and interconnection to other parts of the world that would we need an additional interconnecting layer. The structure of the core network will be described in more detail in section 6.
- The strategy for reducing cost per customer/user in the access network is to share the infrastructure over as many customers as possible and to use a common infrastructure for all networks and services including wireless networks.
- Sharing the infrastructure also means sharing the resources including the usable bandwidth. For many existing access solutions, increased sharing would reduce sustained or average bandwidth for users. To compensate for this we propose higher rate systems for the access network for example a minimum of 10Gb/ symmetrical bandwidth Long Reach PONs (**LR-PON**) with options to increase up to 40Gb/s and in addition point to point wavelength circuits of at least 100Gb/s, over the same infrastructure, for larger customers.
- Greater sharing also means covering larger areas to capture larger numbers of customers on to a common shared access network. When this is coupled with the strategy of removing local exchange nodes and electronics from the network, it means that much longer reach

access networks are required: the DISCUS architecture increases this reach to at least 100km.

- The combination of longer reach, higher capacity and greater sharing of infrastructure logically leads to the use of **LR-PON**. So the resulting basic network structure for the DISCUS architecture is therefore **LR-PON** combined with **flat optical core** network.
- The strategy for extending core capability to the edge of the network is to use the wavelength domain and provide wavelength paths across the **LR-PON** common fibre infrastructure. As mentioned above these wavelengths can also be used to enhance access capacity for users connected to **LR-PON** systems. By providing a flexible wavelength domain with physical layer hooks into the optical hardware, flexible and evolutionary paths can be added at a later stage to incorporate new and emerging technologies.

This combination of **LR-PON** plus **flat optical core** is the basic philosophy of the DISCUS architecture which we believe can economically deliver ubiquitous high speed broadband to all users and will ensure all optical points of presence deliver equivalent network and service capability irrespective of geographical location.

The overall DISCUS architecture is shown in Figure 2-2, it employs LR-PON technology in the access and metro or backhaul networks to enable local exchange/central office bypass and closure and elimination of separate backhaul transmission systems. The LR-PON systems terminate on a small number of “metro-core nodes” (MC-nodes) which are interconnected by the flat optical core network which we called an “optical island”.

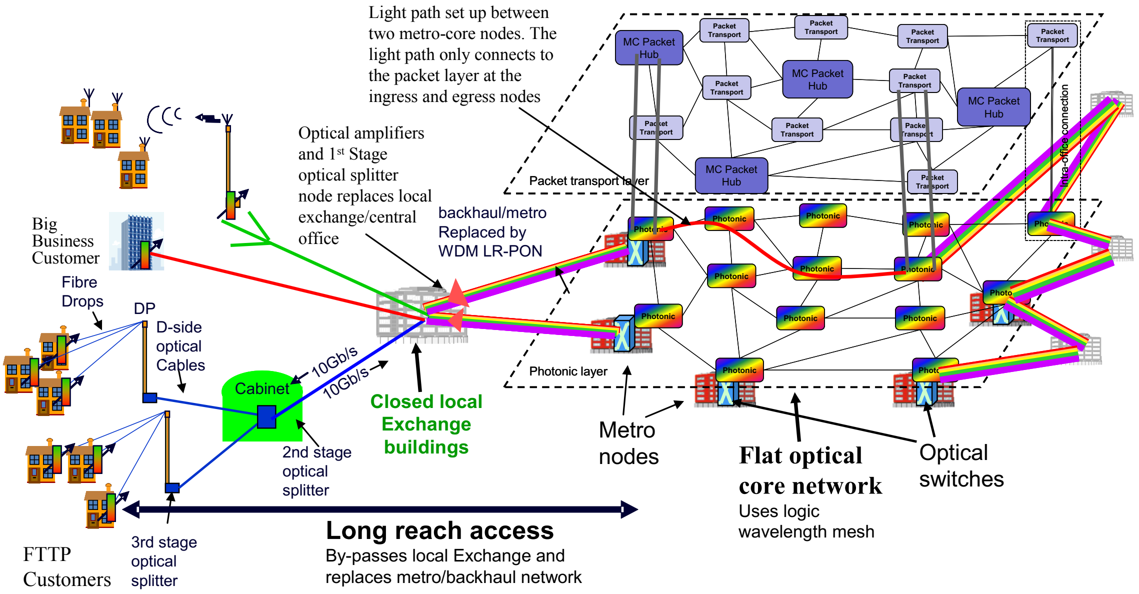


Figure 2-2 The DISCUS end to end Architecture

During the project the definition of what we meant by an “optical Island” was tightened and clarified as some confusion of the exact definition arose. The definition of an optical island is now therefore: a set of metro-core nodes that are fully interconnected via a set of light paths so that any node can reach any other node in the optical island by such a light path. There is no packet processing of the data in the light path except at the ingress and egress nodes that terminate the light path. Light paths will often pass through other nodes on route to the destination node but they stay in the optical layer and also for the majority of light paths will stay on the same wavelength channel/s. However some light paths may need wavelength conversion and possibly regeneration, functions that are allowed within the definition. These “through” light paths, whether regenerated or not at intermediate nodes, are not terminated on the packet processing layers in those intermediate nodes.

In the metro-core node there is an optical circuit switching layer that allows interconnection between core light paths for the traffic on light paths passing through the MC-node. It also enables interconnect of access wavelengths over the LR-PON infrastructure to the terminating and packet processing equipment and also direct connection to core light paths, so that core wavelengths can pass transparently over the LR-PON infrastructure. The optical switching layer can provide fully flexible interconnect and sharing of all metro-node equipment and functions. These basic concepts of the DISCUS architecture are shown in Figure 2-2 with an example light path (shown in red) across the flat optical core network.

During the project detailed work has been carried out on the LR-PON designs and also solutions for sparse rural areas have been designed: these designs are described in section 4. The early work on optically amplified LR-PON focused on EDFA amplifier technology because of the high linearity, high saturated output power and low noise figure requirements. Although EDFA amplifiers remain the focus for the design of the first installed systems, the improvements in linear SOA technology warrants a fresh look at their suitability for LR-PON solutions: this work is described in section 4.3. A major advantage offered by SOAs over EDFAs is the ability to exploit other optical windows in the fibre transmission spectrum.

3 DISCUS architecture specification, targets and state of the art

This section describes the target parameters or specification for the discus architecture and also shows where the DISCUS architecture goes beyond the state of the art established by previous projects such as PIEMAN, OASE and ACCORDANCE. We will start at the access network and work through to the metro-core nodes and then the core network.

As mentioned in section 2, the overall objectives of the DISCUS architecture are to find solutions to three of the major problems facing future networks, i.e. to find economically viable solutions that enable three orders of magnitude or more bandwidth growth while bridging the digital divide to enable sparsely populated areas to have access to the same network capability and services as urban and city areas and at the same time massively reducing power dissipation within the network as the capacity grows.

In D2.1 (and briefly in section 2 above) it is shown that to meet the first challenge - remaining economically viable as bandwidths increase by 1000 times or more over the next decade - two major approaches to the design of the future architecture are required. The first is to minimise electronics systems and OEO conversions: this would be mainly applied to the traffic processing nodes in the network and the backhaul and core transmission networks. The other is to maximise sharing of network resources to minimise cost per customer of the remaining network equipment.

In order to achieve these targets DISCUS adopts an end to end design philosophy which is a major differentiator compared to previous projects which generally tackled problems in only one network area e.g. access, metro or core. By taking an end to end approach DISCUS is attempting to avoid problem transfer where solving a problem in one part of the network only transfers problems to other parts. The solution must also be scalable and evolvable and be able to adapt to future technologies as they emerge.

It was also recognised that ideally for a complete network solution all layers of the network would be considered as part of the design process and would include layers 4 and up in the OSI model. However detailed design of these higher layers was beyond the resource of DISCUS and was therefore out of scope; but in order to enable future evolution of these higher layer and also new transport protocols that could eventually replace legacy protocols such as Ethernet and IP/TCP etc., DISCUS introduced an optical switching layer to separate the physical optical transmission layers from the electronic traffic and packet processing layers. The inclusion of this optical switching layer can enable radically new and even experimental systems to run and operate alongside legacy systems. If these new systems are successful they could grow to gracefully displace the legacy technology which can be allowed to slowly wither and die. It is only by considering the end to end design aspects that such opportunities can be designed into the solutions.

Another major area where DISCUS goes beyond the state of the art of previous projects is to tackle up front the issue of the digital divide, where current broadband roll out and performance favours citizens living in dense urban areas and neglects those living in sparse rural regions. As described in D2.1 and above the rational for the DISCUS architecture lead to the conclusion that long reach access (to eliminate local exchanges or central offices) network interconnected via a flat optical core was necessary to meet the DISCUS objectives. The long reach access technology chosen is long reach passive optical networks (LR-PON). In past projects designs for LR-PON have centred around what has become to be known as the "lollipop" model which has a long feeder fibre length (up to 90km) between the metro-core node and the amplifier node at the old local exchange/central office site and then a relatively short (up to 10 km optical distribution network (ODN). This model works well for urban areas but is not optimal for sparser rural areas where the splitting portion (ODN) of the LR-PON needs to be distributed over larger geographical areas. A focus in DISCUS is therefore to develop designs and fibre splitter layouts that reduce costs and are more suitable for these sparse rural areas. These options are described in more detail in this deliverable in section 4.4

A further development in the DISCUS design of the LR-PON is the dynamic use of the wavelength domain. Initially the C-band using EDFA technology in the amplifier nodes is used but we also introduced the semiconductor optical amplifier (SOA) technology to extend capacity availability outside the C-band to the other fibre windows. The DISCUS LR-PON infrastructure design is also taking into account the need for bespoke network configurations and point to point optical paths at rates up to 100Gb/s and possibly beyond, for large business customers and for those customers requiring special services including Service Provider connections.

At the metro-node the optical switch configuration and the interconnection of the electronic processing equipment forms a major part of the metro-core node design. Options for embedded functionality and stand-alone functions interconnected via "grey" optical ports can be compared via the modelling tools. These features of the architecture go beyond the work of previous projects, for example we can compare the use of separate OLT racks and shelves versus embedded OLTs in the access switch and the use of N to 1 sharing of protection equipment compared with 1+1 protection. The N to 1 sharing for protection can be further augmented by utilisation of the LR-PON dual parenting mechanism to enable traffic off load to minimise standby protection equipment at the metro-core nodes.

The core network is an evolvable hybrid with coexisting fixed grid and flex-grid technologies. Economics and traffic demands will determine the technology of choice. The core network itself is a flat optical core with transparent optical light paths interconnecting the metro-core nodes in a full logical mesh configuration. Although the DISCUS objective is to have fully transparent light paths in the core network wherever possible, sparse regenerators for extremely demanding links are also allowed, although for Europe the use of sparse Raman amplification can eliminate the need for any regenerators

To summarise this section, DISCUS extends the designs of the LR-PON to include all geo-types including sparse rural and flexible wavelength assignment for both bespoke and LR-PON protocol enabled wavelengths.

The metro-core node is a flexible design with an optical switching layer to enable flexible protection mechanisms and graceful evolution including displacement of legacy protocols and technologies.

The core network is a flat optical core with transparent light paths to minimise OEO conversions and packet/traffic processing. It enables the coexistence of fixed grid and flex-grid technologies allowing economics to determine the technology of choice.

These design principles realise the following target performance for the DISCUS network:

- Reduction in buildings housing electronic switching/routing/transmission equipment by closure of the majority of LE/COs and simplification of the core network ~98%
- Reduction in customer network ports (cf. xDSL) ~99.8% (by increasing LR-PON split to 512 ways)
- Reduction in network port cards ~70% (by elimination of metro network and using the flat optical core network design)
- Reduction in network power consumption (neglecting CPE) with respect to Business as Usual (BAU) >95% (from elimination of LE/COs, backhaul transmission systems and flat circuit switched optical core to minimise packet processing)
- 10Gb/symmetrical basic rate per LR-PON (in principle allowing 10Gb/s Peak Information Rate (PIR) if network and customer ports allow)
- 40Gb/s downstream enhanced rate for LR-PON
- 100Gb/s symmetrical for point to point bespoke optical light paths over LR-PON infrastructure using commercial DP-QPSK modulation formats
- Scalable to >1000 times today's ADSL broadband capacity (200Mb/s sustained bandwidth per user).

4 LR-PON OPTICAL ACCESS NETWORK

4.1 LR-PON optical access network

The access network selected for the DISCUS architecture is the Long Reach - Passive Optical Network (LR-PON) which enables sharing of fibre infrastructure as close to the customer as possible using a passive optical splitting element that can fit into existing footway boxes or pole tops at the DP locations. The higher total split of the LR-PON (512 way is seen as the pragmatic split for engineered solutions although in the denser areas 1024 way split could also be used) enables additional splitter points in the optical distribution network (ODN) that increases infrastructure sharing. The long reach allows bypass of the vast majority of LE/CO sites reducing the total number of network nodes with traffic processing equipment by typically a factor 50 for European countries. The long reach also extends the PON infrastructure across the backhaul or metro-access network eliminating the need for metro network transmission systems. This elimination of LE/CO site traffic processing equipment and metro-access network transmission systems produces significant cost and power consumption savings compared to today's network architectures that keep these nodes and systems in place.

At the beginning and during the evolution of the project there were a number of design options for the detailed design of the LR-PON that needed to be considered, these options included:

- Single or two fibre working within the LR-PON (we separated this into two parts the ODN - from the LE site to the customer site - and the backhaul network – from the LE site to the MC-node site).
- M x N splitter rather than just 1XN splitters to enable multiple splitter ports on the network facing side of the optical splitter (these could be used for splitter by pass for selected wavelength bands and test access ports for field staff to aid maintenance and diagnostics).
- The wavelength usage plan.
- The resilience options including N to 1 sharing of protection equipment.
- The amplifier node technology and design.
- The designs for rural areas.

These options are discussed further in the following sections

4.2 Initial DISCUS architecture - single fibre ODN, two fibre backhaul

The initial LR-PON design considered for DISCUS is shown schematically in Figure 4-1 and has single fibre (bi-directional) working in the (ODN) section and two fibre working in the backhaul section. This follows conventional practice for FTTH networks which traditionally is only installed in the access network from the LE site to the customer and is single fibre working. The transmission systems in the backhaul network would use two fibre working with separate fibre for the two directions of transmission. Single fibre working in the ODN has been the de-facto standard for the access network for many years. The original driver came from point to point fibre solutions for the access network where halving the number of fibres in the high fibre count access cables had a major economic benefit. Even for low split PON solutions, such as 32 way GPON and EPON, there is an economic benefit because of the limited infrastructure sharing gained by the low optical split of these systems. However, for LR-PON, which is a very fibre lean solution with a much higher split capability and therefore much higher degree of infrastructure sharing, the additional cost of two fibre working might not be significantly higher than single fibre working and can be offset to some extent by removal of the diplexer devices in the ONT and OLT. However even for LR-PON two fibre working will increase the cost of the ODN infrastructure and is very dependent on the geotype or customer density of the LE area being considered.

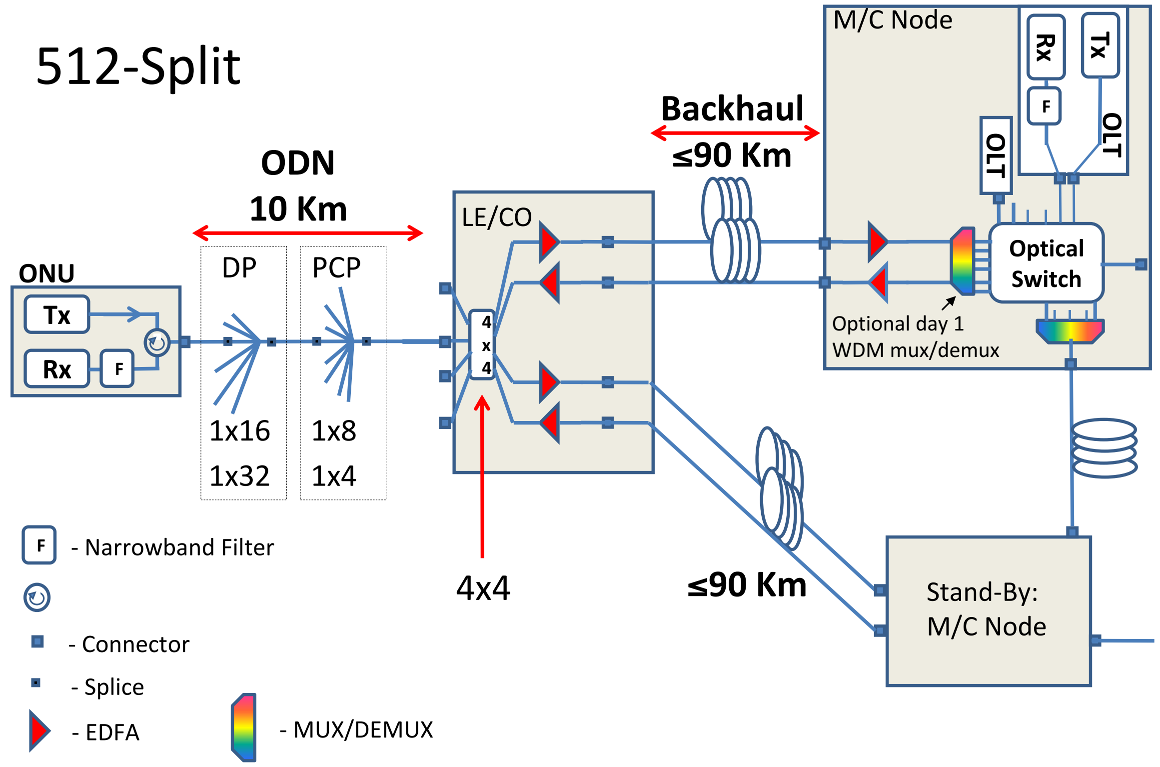


Figure 4-1 Basic LR-PON architecture with single fibre working in the ODN and two fibre working in the backhaul

This LR-PON design shown in Figure 4-1 would typically use 32 way splitters at the DP location and 4 way splitters at the cabinet or primary cross connect (PCP) location. At the local exchange site there would be a 4x4 with up and downstream amplifiers on separate backhaul fibres, which gives the total split of 512 ways. If 1024 ways were to be used it would generally be implemented by increasing the LE split to a 4 x 8 way splitter with the 8 ports facing the ODN.

The size and location of the first splitter (DP splitter) closest to the customer premises affects the distribution network (D-side network) costs and average LR-PON utilisation. A high utilisation is necessary to ensure maximum sharing of the network resources. The size and location of the DP splitter depends on the geotype of the LE site where the LR-PON is being installed, the geotype being determined by the customer density. For the range of geotypes used for modelling the UK network the DP splitter size ranges from 8 way for the sparser rural areas to 32 for the denser urban and city areas. The actual DP size used is a trade-off of cabled fibre cost, optical drop cost, optical splitter size and the housing cost plus splices. Further work in a project running in parallel with DISCUS, but not part of DISCUS, is examining the optimal layout of optical splitter networks for sparse rural areas and shows that a bespoke design fitted to the specific area using even smaller splitters can yield further cost savings for the sparsest geotypes (see [1]).

4.2.1 LR-PON architecture – two fibre working in the ODN and backhaul

The option of two fibre in both ODN and backhaul is shown in Figure 4-2. If a two fibre working design is used in the ODN as well as the backhaul network there is the major advantage that twice the number of wavelengths can be used for service provision compared to single fibre working, this additional doubling of available optical spectrum may be very valuable in the future. Single fibre working in either the ODN or the backhaul network requires the available optical spectrum to be divided into two halves to provide the upstream and downstream wavelength channels, two fibre working avoids this.

However for the mass market solution, even allowing for bandwidth growth of 1000 times, only about 9 wavelengths are required to support all the residential and small business customers connected to a 512 way split LR-PON, and only 18 wavelengths if that split was extended to 1024. This can be accommodated easily in the C-band and given that in the DISCUS project we have shown that linear SOAs can also be used to open up other optical windows, see section 4.3, it is unlikely in the foreseeable future that the increase in available capacity justifies the increased cost of two fibre working, even though it is much reduced for LR-PON solutions. The initial design using single fibre working in the ODN part and two fibre working in the backhaul part of the LR-PON is the selected design option for the DISCUS architecture.

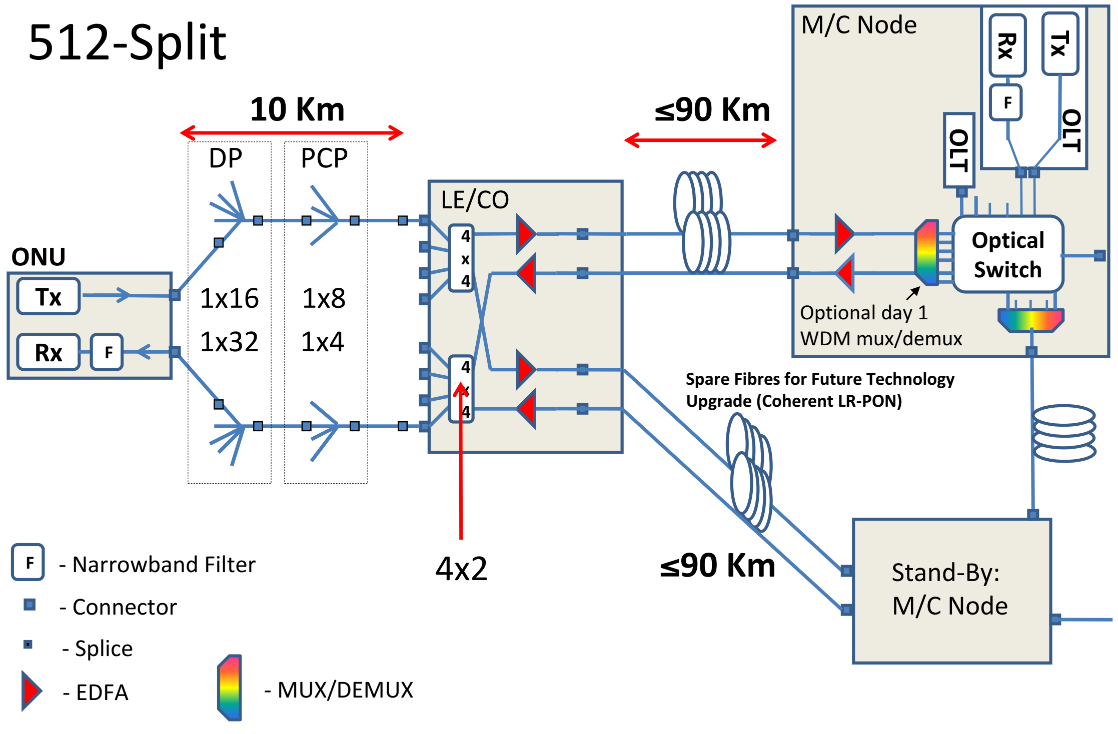


Figure 4-2 LR-PON architecture with two fibre working in both the ODN and backhaul

4.2.2 M x N splitter architectures

An important design issue for the specification of the optical splitter is the number of optical ports on the network side of the splitters. Typical PON designs use 1 x N optical power splitters with only one fibre port on the network side of the splitter. An alternative design would be to use m x N splitters with m fibre ports on the network side of the splitters to provide greater flexibility. This greater flexibility can enable alternative designs and bespoke networks that might require smaller optical split using wavelength bands assigned for those networks. Providing a 2xN splitter would enable the spare network side splitter port to be used as a test access port for field staff even if no further ports are implemented for the alternative PON designs that by-pass some of the split of the LR-PON infrastructure.

However these additional splitter ports add cost to the ODN infrastructure and if connected back to the MC-node will also increase cost of the backhaul cables. The actual costs will depend on the customer density and number of customer sites in the LE area where the LR-PONs are being installed.

Local Exchange Name	Geo-type	2xN Splitters 1-fibre ODN	2xN Splitters 2-fibre ODN	% increase 2 fibre ODN	1 x N Splitter	2 x N Splitter	4 x N Splitter	% increase for 2 ports	% increase for 4 ports	Total sites	Site Density
Castlemartin	Sparse	£1,152.27	£1,305.84	13.3%	£1,073.53	£1,152.27	£1,349.07	7.3%	25.7%	272	5.3
Port Isaac	Rural 3	£908.43	£1,008.09	11.0%	£849.92	£908.43	£1,091.19	6.9%	28.4%	958	26.4
Sapcote	Rural 2	£542.38	£613.45	13.1%	£524.07	£542.38	£602.15	3.5%	14.9%	2944	145.9
Littleborough	Rural 1	£488.06	£576.87	18.2%	£458.73	£488.06	£573.91	6.4%	25.1%	8876	220.6
Stroud	Urban 3	£281.95	£287.33	1.9%	£273.29	£281.95	£319.16	3.2%	16.8%	12014	508.3
Southwick	Urban 2	£162.48	£139.30	-14.3%	£156.74	£162.48	£183.93	3.7%	17.3%	6633	992.6
Erith	Urban 1	£101.68	£143.23	40.9%	£95.53	£101.68	£120.76	6.4%	26.4%	9829	1898.8
Stamford Hill	Metro	£79.22	£110.91	40.0%	£70.95	£79.22	£103.02	11.7%	45.2%	25674	3701.2
North Paddington	City	£57.71	£87.05	50.8%	£50.89	£57.71	£70.03	13.4%	37.6%	12272	7043.4

Table 4-1 Example of relative costs for representative LE areas for the 9 geo-type classifications used for the UK network modelling.

The data in Table 4-1 shows examples of the relative costs affecting the ODN of adding additional network side splitter ports. The 3rd and 4th columns also show the relative costs of single fibre working compared with two fibre working in the ODN. These were calculated for the 2xN splitter option.

The ODN costs for the varying network splitter port counts for each geotype is plotted in figure Figure 4-3. It shows that although increasing the number of network side splitter ports to 4 does have a significant impact on the ODN costs, increasing from 1 to 2 ports has relatively small impact and that this extra cost could be justified for the significantly increased access provided to field staff for diagnostic and maintenance activities. This could help reduce operational costs and speed up time to repair in the event of failures, due to damage to the external plant.

Figure 4-3 also shows the large change in cost per customer when comparing very sparse rural areas with dense urban and city areas.

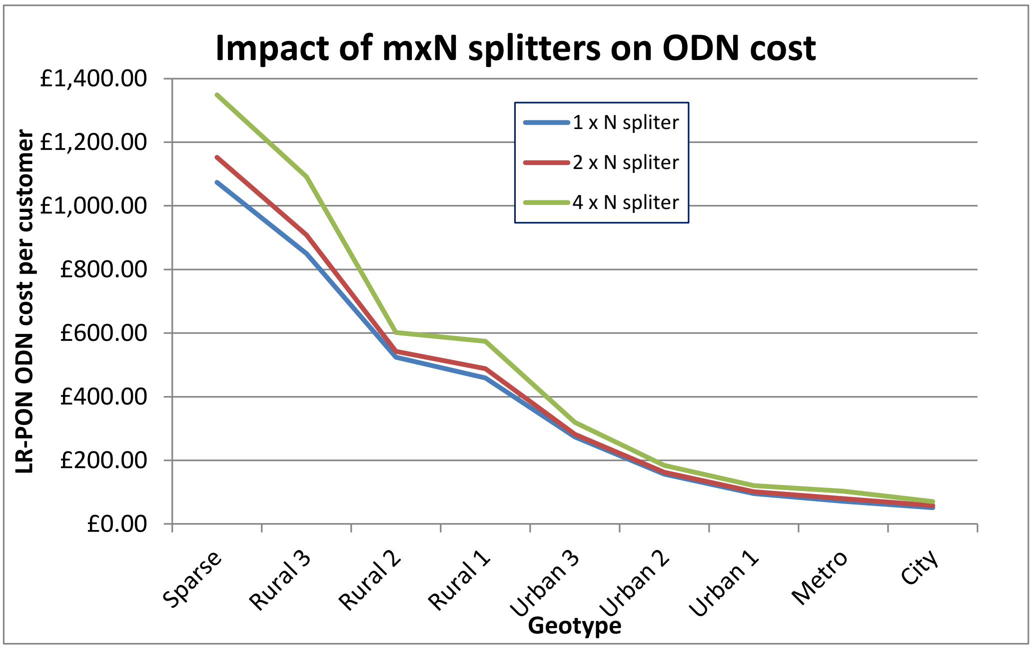


Figure 4-3 Variable ODN costs by geotype and network side splitter ports

4.2.3 Growth by increasing Wavelengths

The LR-PON designs shown in Figure 4-1 and Figure 4-2 show a WDM device in the metro core node connected to the up and down stream fibres of the LR-PON. If it is important for the operator to invest the absolute minimum capital expenditure for the initial system installation, then this could be omitted until customer demand requires the wavelength upgrade of the LR-PON. In this way only the minimum and simplest infrastructure for a single wavelength LR-PON is provided at day one.

At first sight it may be thought that if WDM devices are required at some future time then they must be fitted at day one to avoid major service interruptions when they are fitted. However this is not the case as the LR-PON basic design will have dual parenting protection and the secondary, non-traffic carrying, path to the standby metro-core node can be upgraded first without any service disruption. Once this has been completed the primary, working path can be switched to the upgraded standby path with minimal disruption and then that original primary path can be upgraded in turn. A version of this process has been described in section 3.2.3 of D2.3. Also we have shown that the protection switching time can be kept very short [2] and service disruption will largely go unnoticed. Another alternative is to use the optical switch in the metro node to switch WDM devices to the access fibre when required; this would also allow upgrades to respond rapidly to demand when and where it arises, therefore matching expenditure directly to demand. It should be noted that this latter alternative is a different configuration from that shown in Figure 4-1 and Figure 4-2 where the WDM device is inserted between the optical switch and the LR-PON backhaul fibre.

As previously discussed the initial design of the LR-PON would use EDFAs at the optical amplifier nodes placed at the old LE sites. We also now propose staying with single fibre working in the ODN for the mass market deployment of the LR-PON FTTP network to gain the cost benefits from that network design which would outweigh the capacity advantages gained by two fibre working for the foreseeable future. This does however mean that the available C-band operating window must be divided into two parts, one for upstream transmission from customer to the MC-node and the other for downstream transmission from MC-node towards the customers. Initially we adopted the simplest approach of simply splitting the C-band into two halves, possibly with a guard band between the two wavelength bands to relax the demands on the optical band pass splitter design.

However more recently, following consideration of wavelength referencing for dynamic wavelength assignment and non-linear crosstalk, (when mixing high speed phase modulation systems with on-off keyed, direct detection, LR-PON optical signals) the idea of using wavelength channel interleaving has become the favoured option. This option allows adjacent downstream channels to reference accurately the upstream transmitted wavelength from the ONU without expensive wavelength lockers being required and without the need for Auxiliary Management and Control Channel (AMCC) methods. Also 100Gb/s channels would be spaced at least 100 GHz away from adjacent 10Gb/s channels travelling in the same direction. This reduces non-linear crosstalk effects over the distances of LR-PON systems enabling coexistence of 100Gb/s DP-QPSK channels and 10Gb/s OOK adjacent channel interferers with the full dynamic range of the 10Gb/s channels for a 512 way split LR-PON, (see section 4.8.2). Wavelength interleaving of the upstream and downstream channels can be achieved with interleaved AWG devices rather than band pass filters and because these devices are highly shared on LR-PON network the small cost penalty has negligible impact on the economic viability of the system.

4.3 LR-PON OPTICAL POWER BUDGETS

The optical power budget of the LR-PON determines the reach, split and bit rate for a give modulation scheme. Compared to today's standardised PON, the longer reach and larger total split (number of supported users) of the DISCUS LR-PON is enabled by the use of optical amplifiers both at local exchange sites where in the upstream direction they act as a line amplifier and in the downstream direction they act as a power amplifier so the there is sufficient optical power to drive the large split ODN. Optical amplifiers are also required at the metro-core node as a pre amplifier in the upstream direction and again as a power amplifier in the downstream direction to increase the optical launch power. As addressed in other parts of the projects, the greater the optical split the greater the sharing of fibre infrastructure and network technology and systems including the optical amplifiers. This reduces the cost per customer and provides a means of transferring capital expenditure from the upper reaches of the network to the final drop and customer termination while maintaining overall economic viability. The long reach of the access part of the DISCUS architecture enables consolidation of the core network and reduces the number of metro/core nodes required to reach all the customers. This is a key enabler for the flat optical core which, as bandwidths increase becomes the increasingly lower cost than hierarchical core networks which are necessary to support core network with a larger number of core nodes.

Due to the introduction of optical amplification, on top of the power budget (commonly used in today's PON design), the optical signal to noise ratio (OSNR) rather than just received optical power level becomes one of the important system limitation. The power budget and OSNR are closely interlinked and need to be considered together in the overall system design. In the upstream direction the PON channel is mainly limited by OSNR, which is reduced by the amplified spontaneous emissions (ASE) noise from the optical amplifiers. In the example of the lollipop architecture described in section 4.7, the OSNR limitation for the upstream can come from both the access part of the network before the first amplifier, where there is a large loss due to the large split, and from the backhaul section, where fibre lengths of 80-90km can also introduce considerable loss before the amplifier in the metro/core node. A careful design of the gain and consideration of the noise figures of both amplifiers is necessary in order to not degrade the OSNR and not incur non-linear impairments in the long backhaul fibre section. In the architectural solution targeted for rural, sparsely populated areas using a chain of amplifier nodes (section 4.4) the OSNR limitation is mainly caused by accumulation of the ASE in the chained optical amplifiers. On the other hand, the performance of the downstream is power budget limited for all architectures due to the large loss introduced by the large split ratio. In order to reach the ONU receiver with power above its sensitivity, the launched power from the local exchange is required to be relatively large, which, as explained later, can be problematic for the optical amplifier used in the local exchange.

In terms of the type of optical amplifiers used in the LR-PON, Erbium doped fibre amplifiers (EDFAs) are an obvious candidate due to the low noise figure (typically 5-6 dB for commercial modules), moderate cost and off-the-shelf availability. EDFAs with fast gain transient stabilisation, which would be required for the upstream EDFAs, are also commercially available (see D5.4 for details). Linear SOAs (with high output power, low gain and relatively low noise figure) have been rediscovered in the last few years due to their ability to amplify signals of various modulation formats in 10 THz windows over the entire spectral range from 1250 nm up to 1600 nm by tuning the gain of the active material, at reasonable cost and without adding significant distortions. The DISCUS consortium investigated these linear SOAs as optical amplifiers located inside the remote node. Despite having lower performance compared to the EDFAs they have been studied as an evolutionary approach which can open the operation of new wavelength bands outside the C-band see deliverable D4.11, section 6.2).

Examples of power and OSNR budgets for both solutions using EDFAs as optical amplifiers can be found in the Appendix of deliverable 5.4, while considerations on the power budget of the SOA version of the lollipop LR-PON can be found in D8.5. The analysis of the power and OSNR budget has been performed under the assumption that within DISCUS the linear burst-mode receiver (LBMRx) technology developed by the Tyndall research group will be employed. The LMBRx requires 15 dB OSNR at dynamic range of 20dB to achieve BER=10^{-3} (at 10Gb/s). Hence, for this initial study we used 15dB as the minimum (end of life) OSNR target. Another assumption in this analysis is that FEC will be used in the upstream. FEC is assumed also in the downstream direction where we also consider that an APD is used in the ONU receiver with a worst case sensitivity of -28dBm at 10^{-3} BER. All the component losses used are derived from the GPON standard in the ODN and from datasheets of commercial components for the ODN, amplifier node and backhaul link. The results from the power and OSNR modelling suggest that a split of 512 can be supported, with on-off keying (OOK) modulation of the optical signals at 10Gb/s in both directions, by both architecture variants (lollipop and open-ring) and both optical amplifier types (EDFAs and SOAs).

It should be noted, however, that in the EDFA-based lollipop case the launched power from the LE into the access section is quite high (+15dBm) due to the high split ratio, despite using an APD receiver in the ONU. One potential concern is Stimulated Brillouin

Scattering (SBS) which can be a serious problem if narrow linewidth optical sources are used with modulation schemes such as OOK that have a significant carrier component in the transmitted optical signal. SBS limits the effective launch power that can be used but it can be mitigated by techniques such as dithering of the optical carrier which effectively broadens the optical line width without incurring additional dispersion penalties. The 4x4 splitter in the LE reduces the non-linearity concerns and this could be increased to an 8x4 to further reduce non-linear impairments. The other important issue for such high channel power is that the aggregate output power of the EDFAs has to be able to support all the channels. Considering 20 active channels with +15dBm/ch means that the total aggregate power for the downstream EDFA is +28dBm, while if we consider 40 channels the aggregate power is +31dBm. Despite being achievable with commercially available EDFAs, these are really high aggregated output powers, which will require more expensive EDFAs and might also require personnel with specialised training. The issue is not present for the open-ring because of the lower split ratio supported by the amplifier node, which requires lower launched power. Similarly in the case of the SOAs, due to the distributed gain after the 4x4 splitter, the required channel power is lower.

A similar issue is also present in the upstream direction for the EDFA-based lollipop regarding the aggregated output power of the EDFAs in the local exchange. In this case the OSNR budget limits the minimum power of the upstream launched in the backhaul. The upstream operated in burst-mode presents a burst to burst dynamic range, which due to the non-uniform loss in the ODN could be up to 14dB for 512 split. This means that, while the majority of the channels present instantaneously an average nominal power in the middle of the dynamic range, there is the possibility that some channels present the highest power in the dynamic range. Considering the case presented in D5.4, which is a worst case due to the 90km backhaul, the nominal average power at the output of the local exchange EDFA is around +8dBm per channel. The total aggregate power in case of 40 channels at nominal power would be +24dBm, which is already a challenging for commercial EDFAs with fast gain stabilisation. Due to statistical multiplexing it is very unlikely that all channels will present the maximum burst power (which would require an aggregate power of +31dBm), hence, as explained in D5.4, it may be possible to use EDFAs with lower aggregate output powers. The open-ring architecture does not present this issue since the fibre spans between the amplifier nodes are shorter and the EDFA output powers are lower.

4.4 RURAL OR SPARSE POPULATION SOLUTIONS

The difficulty for conventional PON designs in sparse rural areas is connecting a sufficient number of customers to the PON system in order to get adequate sharing of the physical infrastructure and achieve a low cost per customer. A further problem is the longer distances between splitter nodes and customers requiring longer cable lengths with higher fibre count which also increases cost per customer. In deliverables D2.1 and D2.3 we considered novel architectural options for the LR-PON that utilise a "chain" of amplifier nodes. While the basic idea was described in D2.1, D2.3 explored in details the options to implement efficiently the protection path towards the protection M/C node. In particular it is recognised that most metro/aggregation networks are deployed today in rings. The chain of amplifier nodes can be considered to be part of a ring, hence utilising efficiently the fibre configuration already deployed.

Two different architectures for the amplifier nodes and fibre configuration were considered in D2.3 and are reported here in Figure 4-5 and Figure 4-6. The first one presented in Figure 4-5 reutilises the same amplifier node configuration of the lollipop LR-PON structure. The fibre interconnection between the amplifier nodes is however more complex with four fibres required between the amplifier nodes for each LR-PON chain while only two fibres are required from the primary and secondary metro-nodes to the closest respective amplifier nodes. The inner amplifier nodes also require the use of a 4x8 splitter/combiner while outer amplifier nodes closest to the primary and secondary metro-nodes requires only a 4x4 splitter/combiner. Protection switching is also more complex than for the simple "lollipop" LR-PON model used for dense areas due to the increased number of failure modes that can occur. In the event of a break anywhere in the primary path all the amplifier nodes would switch over to the secondary path. The upstream amplifiers in the secondary path need to be off to avoided multipath propagation and an amplified loop, an example of such a loop is shown by the path highlighted in red in Figure 4-5. The need to turn off the amplifiers in the protection path (to avoid the risk of amplified loops) reduces "fault coverage" because the protection path cannot pass light unless the amplifiers are bypassed with an out of band wavelength pass filter. This makes monitoring of the protection fibre path difficult when the protection path is in the "off" state. Monitoring of protection paths is an important operational requirement in order to maximise "fault coverage" and minimise the risk of switching to a faulty protection path.

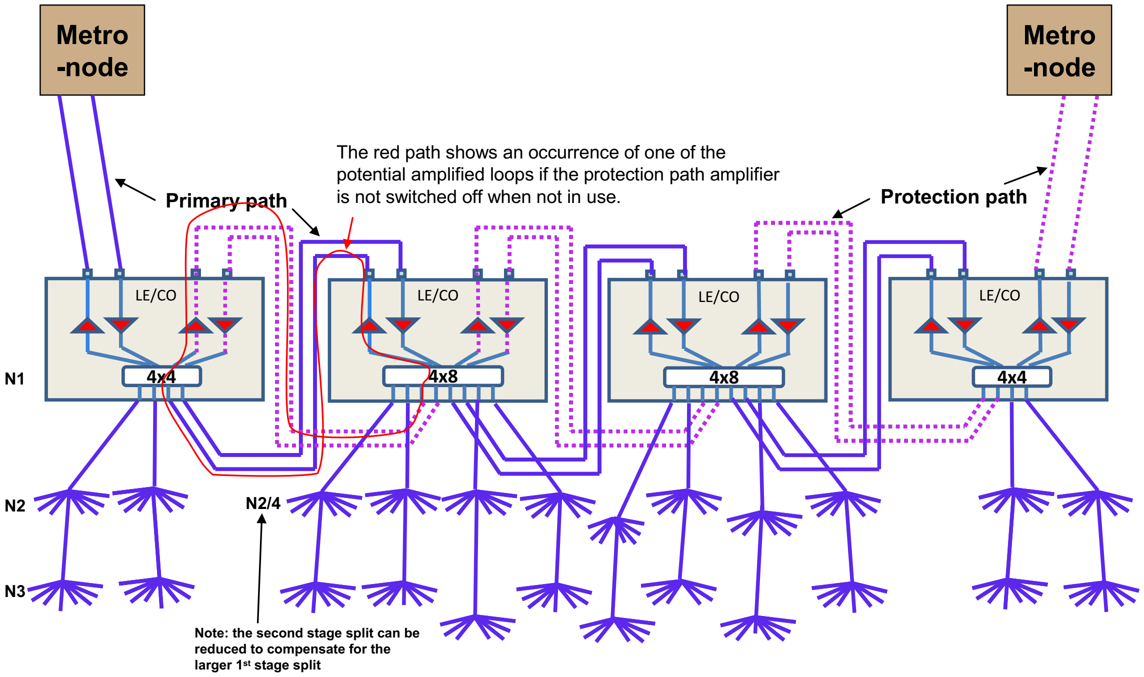


Figure 4-5 Chain configuration of distributed amplifier structure

An alternative LR-PON chain model for rural areas is shown in Figure 4-6. The node design is a little more complex than chain model of Figure 4-5 but has the advantage that the protection fibres can be monitored while the system is in the normal working state. This is an interesting option and builds directly on more conventional ring topologies. There are additional components in the amplifier node which will add cost, but the advantage that the protection fibre paths are used by the working paths means that full fault coverage is possible.

The operation is more complex than the conventional LR-PON configurations and will therefore be described in more detail. There is a mix of single fibre and two fibre working in the feeder fibre sections with single fibre working in the ODN part after the amplifier nodes. Referring to Figure 4-6, which also shows the up and downstream wavelength bands in various parts of the network to aid clarity (the downstream band is arbitrarily shown as green and the upstream band as red). Here we show and describe for simplicity the option of splitting the up and down stream bands into two bands, but the principles also would apply to interleaved up and downstream wavelengths which is now the favoured option, as described previously. It can be seen that the fibres from the metro nodes (both working and protection) to their nearest amplifier node are two fibre working with each fibre carrying only the upstream or downstream wavelength bands. The ODNs are all single fibre working carrying both up and down stream wavelength bands in all fibres. The intermediate feeder fibre between first and last nodes in the chain now also carry both up and down stream wavelength bands which is different from the configurations shown in Figure 4-5. This is because the upstream wavelengths from the ODN are combined via the coupler with the downstream wavelengths from the metro-node. The intermediate amplifiers therefore have to support both upstream and downstream wavelength bands whereas the upstream amplifiers towards the metro-nodes only need to carry the upstream wavelength band and the downstream amplifiers into each ODN only need carry the downstream band but require band filters to block the upstream bands from the adjacent ODNs. Similarly the upstream amplifiers at the ends of the chain into the metro-core nodes may also need optical band pass filters to block the downstream wavelengths band from the distant metro-core node when the standby metro-core node is used for monitoring purposes (these filters could be left out and the upstream amplifier could be used to transit both up and downstream wavelengths to the standby metro-node for monitoring purposes.).

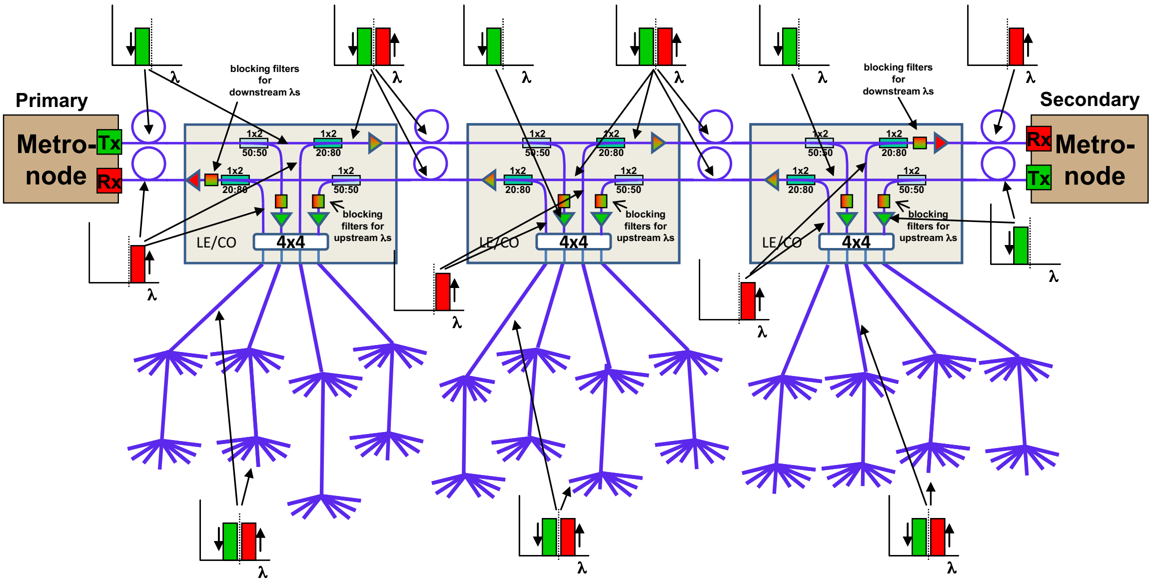


Figure 4-6 Alternative LR-PON chain model or “Open Ring” design for rural areas

Although there is wavelength mixing between upstream wavelengths from the local ODN and the ODN of the previous amplifier node there will be no wavelength collisions for LR_PON wavelengths as they are avoided by the LR-PON protocol, in this configuration all the amplifier nodes in the chain form a single LR-PON controlled by a single instance of the LR-PON protocol, so only 1 ONU is transmitting an upstream burst at any instant of time.

There will be constrains on the number of amplifier nodes and the total chain length. In general the number of amplifier nodes should be kept as small as required to serve the targeted rural area, the greater the number of amplifier nodes in the chain the greater will be the cost per customer due to less customers sharing amplifiers and other components, typically there would be no more than three or four amplifier nodes per chain. The ODN split and reach can be traded off as discussed in D2.1 where approximately each factor of two reduction in split can provide ~10km increase in ODN reach. The longest path length from a metro-node through the chain to the furthest ONU should be less than 125km. This is currently the design limit on the LR-PON protocol we are considering within the DISCUS project, increasing RTT of the LR-PON while at the same time meeting XGPON delay targets will add significantly to PON overheads and reduce payload efficiency. The total sum of split on all ODNs in the chain should be <=1024 (again this is a design limitation decision for the LR-PON protocol).

The structure of the remote node can be seen more in details in Figure 4-7. The PON ODN entry point is a 4x4 splitter combiner, which is the first splitter in the ODN the total split will be a trade-off of reach and distance with an overall constraint of a total split for all ODNs in the chain of 1024 as mentioned above. Typically each node could support 4x32=128 or possibly 4x64=256 users in a four node chain (a four node chain with 256 split at each amplifier node is technically challenging but is possible).

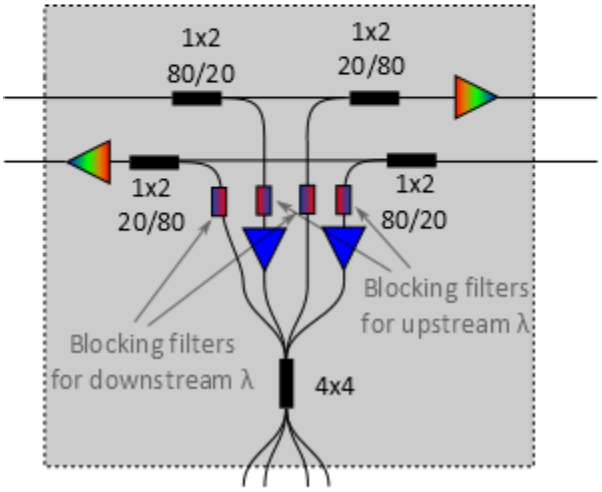


Figure 4-7 Amplifier node design for the alternative "Open Ring" LR-PON design for rural areas

Internally the 4x4 splitter would be used to connect the 2 downstream drop ports and the 2 upstream add ports. The open ring fibre entry points for the upstream channels are 1x2 combiners. Combiners with 80/20 split ratio can be used to reduce the add loss for the upstream (80% port introduces ~1dB). The exit points from the open ring fibres for the downstream channels are also 1x2 splitters which could also be asymmetric 80/20 to help the power budget. In this case the 20% port could be used for downstream channels drop and the lower loss 80% for the path forwarded to the next node. A filter is required to remove upstream channels, added by previous nodes, in the path of the downstream channels dropped to the PON ODNs, as they would waste optical power of the downstream amplifier and might also interfere with upstream traffic due to Rayleigh backscattering and reflections in the PON ODNs. A filter is also required on the upstream add path to remove the reflected downstream power in the ODN due to Rayleigh backscattering and localised reflections. Due to the relatively high launched power of the downstream channels in the ODN, the reflected power could be comparable to the power of the upstream channels at the add point and hence compete for the gain and power of the inline amplifiers.

The RN contains 4 optical amplifiers, which is the same number used in the remote node of the structures shown in Figure 4-1. The total amplifier count for the LR-PON would of course be higher compared to the "lollipop" architectures since multiple RNs are chained, but, due to advantage of the distributed amplification, lower output power is required from the amplifiers (for details see the power budget). This could be advantageous if cheaper, lower power, optical amplifiers can be employed. Two optical amplifiers are located after the upstream add point and just before the output of the RN. These two in-line amplifiers compensate for the power loss to the next amplifier and the nominal input power of the channels to the next amplifier is kept constant. Another two optical amplifiers are located between the downstream drop and the 4x4 splitter to boost the power of the downstream channels before entering the high loss PON ODNs. Less launched power is required compared to the lollipop structure due to the lower split targeted per PON ODN.

As an example the power and OSNR budget has been calculated for this architecture with 4 RNs each separated by 30km of fibre, with 4x32=128 users connected to each node giving a total of 512 users. In terms of upstream performance the estimated minimum OSNR is 19dB which has ~4dB margin over the performance expected from the BM receiver (see D2.1). This is also achieved with maximum per channel powers of +4dBm at the output of the EDFAs which means that relatively lower power EDFAs can be used compared to the lollipop (ref. D2.1). In terms of downstream performance the limiting factor is the power at the ONU receiver, which can be maintained to -26.6dBm using per channel EDFA launched power of +8.6dBm, also lower than the lollipop (it should be noted that an APD receiver and FEC are assumed for the downstream). The calculations for this architecture show margin, which could be used to add more RNs (increasing the total number of users supported) or to increase the number of users supported by a single RN (at the expense of requiring higher EDFA powers for the downstream).

4.5 LR-PON RESILIENCE OPTIONS

The resilience study is of key importance for LR-PON in DISCUS network architecture because a highly-branched access segment needs to serve big areas, where a single failure may affect a large number of end users. Furthermore, a cable cut in LR-PON may destroy a large amount of traffic, which makes the outside plant protection very crucial. In D2.2 and D2.3, we have reported the work on reliability assessment and resilience schemes carried out in Task 2.4 (interacting with Task 4.3 optical layer supervision and management). The methodology for the reliability performance analysis was described, and the feeder section including OLT and feeder fibre connecting the DISCUS metro/core node and the first splitting point was identified as a critical segment, where the protection should be provided in the first place in order to improve the reliability performance in LR-PON. With this in mind, we proposed a ring topology in order to protect the feeder section in a cost-efficient way. A special focus was on the rural deployment, where multiple stages of amplifier nodes are needed to support ultra-long reach. In this final deliverable of WP2, the latest work on LR-PON resilience options will be reported, where we put a particular attention on offering low latency and high connection availability in order to enable DISCUS LR-PON to support mobile services. Moreover, working together with Task 4.3 we propose a novel optical layer supervision scheme that can perform full monitoring for LR-PON, which can be compatible with our previous work on cost-efficient and reliable ring based LR-PON architecture. This section includes two parts: 1) cost-efficient and reliable PON-based architecture supporting multipoint coordination transmission for mobile networks, and 2) full monitoring scheme for LR-PON.

4.5.1 Cost-efficient and reliable PON-based architecture supporting multipoint coordination transmission for mobile networks

The exponential growth of mobile traffic mainly driven by multimedia services and increasing number of connected devices brings new challenges for mobile network operators in terms of providing high capacity solutions with good quality of service. In this regard, coordinated multipoint (CoMP) transmission and reception 9 is introduced to enable the long-term evolution (LTE) evolved nodes B (eNBs) to efficiently exchange the cell information and/or user data among a cluster of adjacent nodes through mobile backhaul/fronthaul networks. It has high potential to improve the network throughput and spectral efficiency, in particular at the cell edges. In the 3GPP standards two interfaces are defined at eNB, namely S1 and X2. S1 is for the communication between eNB and the central aggregation switch in the mobile core network while X2 is a logical interface for direct information exchange between base stations. To support the emerging 5G services, such as road traffic safety and mission-critical control, the implementation of CoMP needs to meet the strict latency constraint and high reliability requirement on the link between the X2 interfaces[7]. Depending on the type of transmission techniques used for CoMP, the delay requirement is between less than 0.5 msec (using common public radio interface-CPRI) and 10 msec [8]. Moreover, the connection availability should higher than 4 nines (99.99%) in order to guarantee high reliability performance. The DISCUS LR-PON, which has ambition to not only accommodate fixed broadband customers but also support mobile services, has a difficulty to fulfil such stringent latency and reliability requirements. Due to the long distance in LR-PON the propagation delay itself may exceed 1ms (~RTT for transmission in a 100km fiber link). The work presented in [9], proposes to use a passive optical network (PON) based architecture, where a splitter-box containing several splitters and diplexers is employed to directly interconnect base stations. However, in this scheme the direct connectivity is limited to the eNBs belonging to the same PON. Moreover, the cluster size is fixed and cannot be dynamically changed in time. Paper [10] presents another backhaul solution for CoMP system based on the wavelength division multiplexing (WDM) PON, which passively interconnects the eNBs. This scheme needs one extra wavelength at each optical network unit (ONU) for interconnecting the eNBs, which is costly. Moreover, this solution requires arrayed waveguide grating (AWG) in the remote node which is not compatible with splitter based PONs considered in DISCUS architecture. Regarding reliability performance, without the protection in distribution fibre section, the connection availability hardly reaches 4 nines. To the best of our knowledge, there is no proper architecture that can satisfy the latency and reliability requirements of multipoint coordination transmission in mobile networks

In this regard, we propose a PON-based high-capacity architecture supporting CoMP by providing direct connectivity between neighbouring cells without any intermediate electronic processing [11]. Our scheme offers low latency for CoMP transmission and compatibility with the splitter based PON architectures. Furthermore, the proposed architecture supports dynamic clustering of eNBs, meaning that the cluster size and border can adapt to users' movements in order to provide sufficient capacity at each point of time, even in the locations with high density of customers. End-to-end protection is also provided for each cell without any significant investments.

Figure 4-8 (a) shows an example of the physical topology of the proposed architecture including nine PONs where each OLT is connected to four ONUs by a splitter. The upstream data sent by each ONU is broadcast to all other ONUs in the same PON via a specific configuration of the splitter, where an isolator is used to connect two ports on the OLT side. Each ONU is connected to the splitter of its own PON as well as the splitter belonging to one of the adjacent PONs, which helps to broadcast the data sent by each ONU to the cells in the neighbouring PON in the vertical direction (e.g., connection between PON B and PON E in Figure 4-8(a). Each splitter is also connected to the two other adjacent splitters in order to support direct inter-PON connections between ONUs of the neighbouring PONs in the horizontal direction (e.g., connection between PON E and PON F)). As shown in Figure 4-8(a), the data sent by the ONU in PON E (in black), can be broadcast to all the ONUs of PON A, B, C, D, F and H. The splitters can be either located in the same remote node (RN) or placed in different locations. The structure can be easily extended in both directions to cover any area size. Figure 4-8(b) presents virtual overlay connectivity among X2 interfaces provided by the physical topology shown in Figure 4-8(a), where each dashed circle represents all the connected neighbouring nodes of the eNB located in the centre. The ONUs in the Figure 4-8(a) and their equivalent eNBs in Figure 4-8(b) are represented via the same colour. The neighbouring connectivity can be extended in all directions, and it is compatible with the honeycomb structure of the cellular networks. Figure 4-8(c) illustrates the proposed ONU tailored for the physical topology shown in Figure 4-8(a). In order to have enough capacity as well as separate the data of the S1 interface from the X2 interface, an additional wavelength (λi) is applied to interconnect X2 interfaces (i.e., inter-base station (inter-BS) communications) which dictate the need of an extra pair of transceivers at each ONU. Band filters are responsible for separating wavelengths for the inter-BS, downstream and upstream traffic, respectively. Optical switches are added to support the switching between two fiber ports of the ONU.

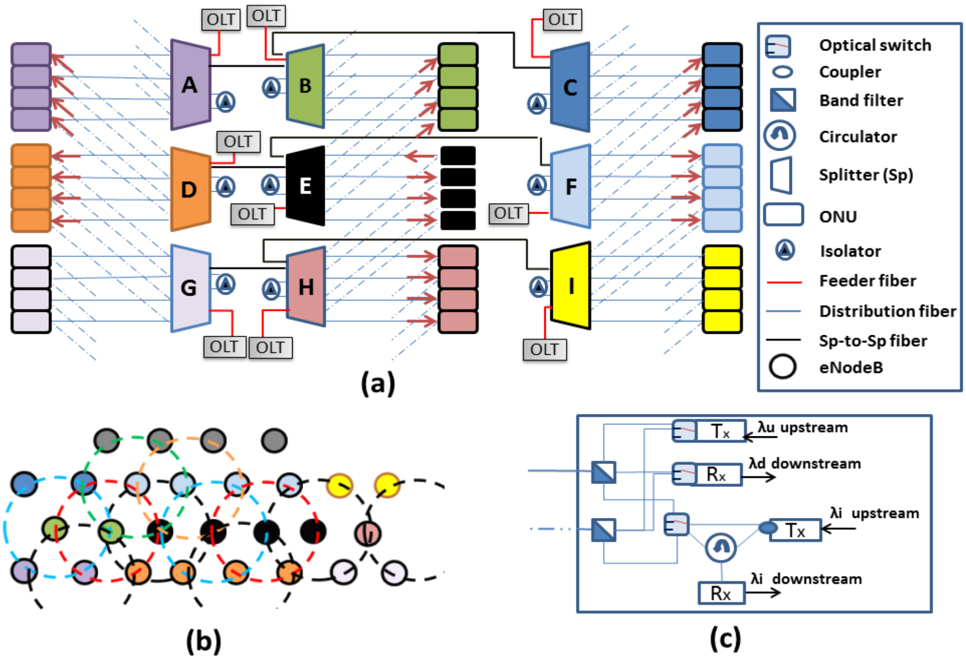


Figure 4-8 :(a)Proposed architecture, (b)virtual X2 topology pattern, and (c)proposed ONU structure

The upstream traffic from the ONUs utilizes time division multiple access (TDMA) scheme to avoid collisions in the shared medium, which is widely used in the TDM based PONs. In scenarios where high capacity and low delay are required (e.g., in case of CPRI), WDM technology can be used for inter-BS communications, where a dedicated wavelength can be assigned for each cluster. The architecture and connectivity is still the same as Figure 4-8(a) and (b). However, tuneable receivers and lasers should be placed in the ONUs for the inter-BS communications. It should be noted that the proposed scheme also offers end-to-end resiliency from each cell towards the core network considering the fact that each ONU is connected to two adjacent PONs. Moreover, in order to compensate for power loss of the upstream signal caused by passing the splitter twice, the amplifiers can be added to the ONU in the scenarios with a high splitting ratio.

Figure 4-9 present the analytical results evaluating performance of the proposed scheme (referred to as BH1) and comparing with the conventional PON architecture, where all the data and control signals from the ONUs have to be sent to the OLT in a multi-point to point manner (referred to as BH2). Figure 4-9 shows the average delay related to the inter-BS communication including both propagation and processing delays (0.1 msec in average per active node is assumed) for different cluster sizes and various feeder fiber (FF) lengths. As the inter-BS traffic in case of BH1 is not passing the OLT, the length of FF does not affect the delay. In case of BH2, the communication between ONUs belonging to different PONs with their OLTs located either in the same central office (CO) or in other places needs to be provided. This means that when the cluster size grows, the number of involved active nodes (e.g. switches, OLTs, etc.) in the connection between eNBs increases. Therefore, the delay can be reduced considerably by using our proposed scheme compared to BH2. Moreover, in our scheme the delay is nearly independent of the cluster size, because the active nodes are eliminated. Figure 4-10 shows the connection unavailability from the OLT up to each cell considering various FF lengths, which is calculated based on the method and input data presented in [12]. Thanks to the embedded resiliency of the proposed scheme, its connection availability is always better than BH2 and independent from the length of FF. According to the results in Figure 4-10, connection availability in BH1 (our scheme) is higher than 99.99% while in BH2 the availability is much lower (unavailability much higher) and dependent of the feeder fiber length.

In addition to the above mentioned improvements, keeping the inter-BS traffic local can alleviate the amount of traffic passing the active nodes and the FFs. Then it is possible to use the switches and OLT transceivers with lower capacity, which in turn brings lower cost and energy consumption. These benefits are clearly shown in Figure 4-11 and Figure 4-12 where the equipment cost and power consumption related to the backhauling of 24 eNBs are presented. In case of BH2, the OLT needs to support both traffic from S1 and X2, and hence it needs 10Gbps transceivers to handle the same amount of traffic as BH1 utilizing GPON 2.5 Gbps transceivers at the OLT. This assumption is valid when calculating the cost and power consumption of the switches handling traffic in the CO or metro node. For the input data we refer to [13]. It can be seen that the cost and energy consumption is always higher in conventional PON-based architecture compared to the proposed one and the difference is increasing with larger cluster size. Due to full connectivity offered in the physical layer in our scheme, the expenditures and energy consumption are independent from the cluster size.

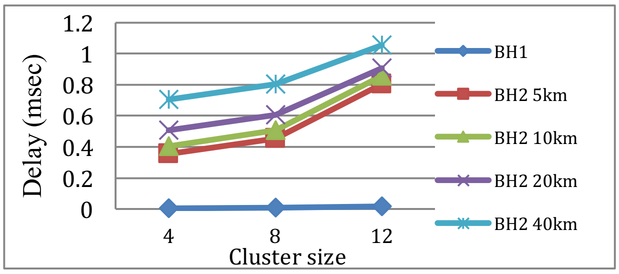


Figure 4-9 Average delay for inter-cell traffic (msec)

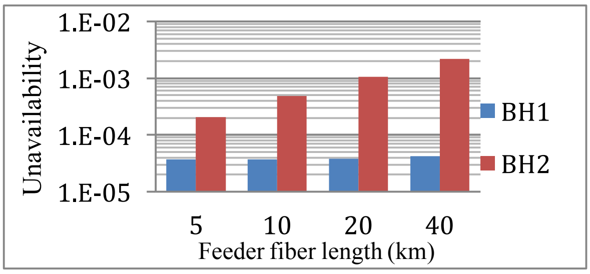


Figure 4-10 Connection availability

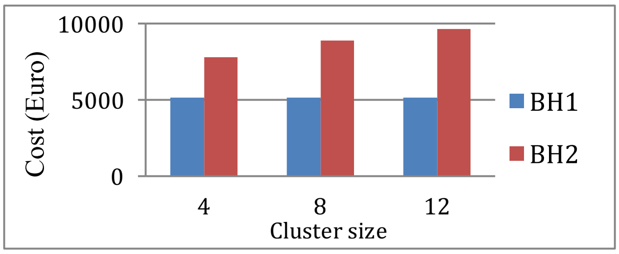


Figure 4-11 Equipment cost for 24 eNBs (Euro)

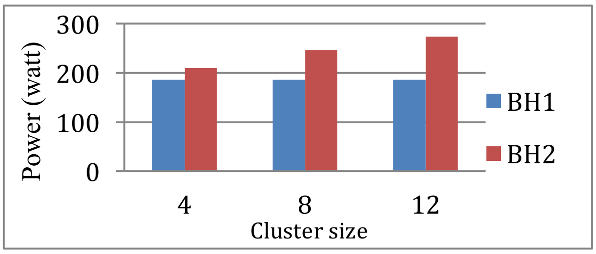


Figure 4-12 Power consumption for 24 eNBs (Watt)

4.5.2 Full monitoring scheme for LR-PON.

One of important advantages of DISCUS LR-PON extends the coverage from the traditional 20 km to 100 km and beyond, which in turn reduces the number of Central Offices (COs) in the field, offering a high potential on cost saving [14]. Figure 4-13(a) depicts open ring based LR-PON topology that has been reported in the previous DISCUS deliverables D2.2 and D2.3. In this structure, feeder fibres for different LR-PONs share the same cable ring leading to low infrastructure cost while offering high reliability [14]. Meanwhile, with the exploding of the traffic demand and the emergence of the 5G services, optical access networks not only require large network capacity, but also need to support multi-service environment for handling business broadband access and mobile X-haul as well [15]. These "important customers" for the network providers typically are willing to pay more to avoid long time service interruption. Therefore, it becomes vital to offer high reliability performance in the access network segment. In this regard, an effective and fast system for fault detection and localization is highly required to minimize network unavailability particular for distribution fiber segment, where protection is not always provided in DISCUS LR-PONs.

We have recently proposed an efficient solution for monitoring the feeder ring of DISCUS LR-PONs in [16],[17]. The proposed technique uses a "dark fiber" to detect and localize the major faults (e.g. fiber cut, bending, seepage) which simultaneously affect all the data carrying fibres in the same feeder cable. Meanwhile, newly developed multi-wavelength Bi-Directional Transmission Reflection Analysis (nλ-BD-TRA) approach, makes it possible to outperform many other monitoring methods (e.g., Optical Time Domain Reflectometry OTDR) with respect to measurement time, system complexity and dynamic range. However, it should be noted that more than 80% of PON failures could occur in the distribution segment close to the user end [18]. To the best of our knowledge, there is no existing scheme that can fulfil the distribution section monitoring in ring-and-spur LR-PONs. In this regard, we propose a novel fault supervision system for the first time realizing full monitoring functionality, i.e., covering both feeder and distribution sections in LR-PON. Moreover, considering Time/ Wavelength Division Multiplexing (TWDM) feature driven by FSAN, our proposed scheme can be compatible for both power-splitter (SPL) and wavelength-splitter (e.g., Arrayed Waveguide Grating AWG) based PON structures.

The schematic diagram of the proposed monitoring system is shown in Figure 4-13(b), where a *1xN* AWG as a first splitting point and several *1xM* power splitters (SPLs) as second splitting points in LR-PON are used [19]. A 2λ-TRA scheme [16],[17] is employed as the monitoring technique thanks to its good performance on fault localization. To realize full monitoring functionality, in the proposed scheme the 2λ-TRA unit is implemented at the Remote Node (RN) covering both the Feeder Fiber (FF) ring and Distribution Fiber (DF) segment by means of a *1x(N+1)* Optical Switch (*OS*). After receiving a fault alarm triggered by the network layer (indicating the information whether the failure occurs in the feeder section or a certain drop link), the *1x(N+1)* OS switches the monitoring signals either to the feeder ring or to the corresponding drop port that contains the faulty branch.

The feeder ring monitoring scheme has been included in the previous DISCUS deliverable D4.13. In this deliverable we focus on the monitoring procedure of the distribution section, which is combined with the feeder ring monitoring scheme reported in D4.13 to realize full monitoring of DISCUS LR-PON. As shown in Figure 4-13(b), the 1st stage splitting point at RN can be bypassed by the monitoring signals using filters. This stage of splitting point can be either an SPL or an AWG to be compatible with different types of PON architectures. The TRA monitoring signal is launched at the 2nd stage of splitting points (i.e., *1xM* SPL as shown in Figure 4-13(b)) and therefore simultaneously interrogates *M* distribution fibres. The size of the 1st stage splitting point determines the number of monitoring ports. For LR-PONs, the 1st stage and 2nd stage splitting points are not always at the same RN. In that case, our monitoring scheme can be implemented at the 1st splitting point, still covering the full distribution segment. This monitoring scheme involves active devices in the field. It should be noted that in LR-PONs, the 1st splitting points are often kept active due to the installation of amplifiers for reach extension [18]. Moreover, since fiber ring is used for feeder section, the fault monitoring information can still be transmitted to the CO though the protection path in case of a fiber cut in the feeder segment.

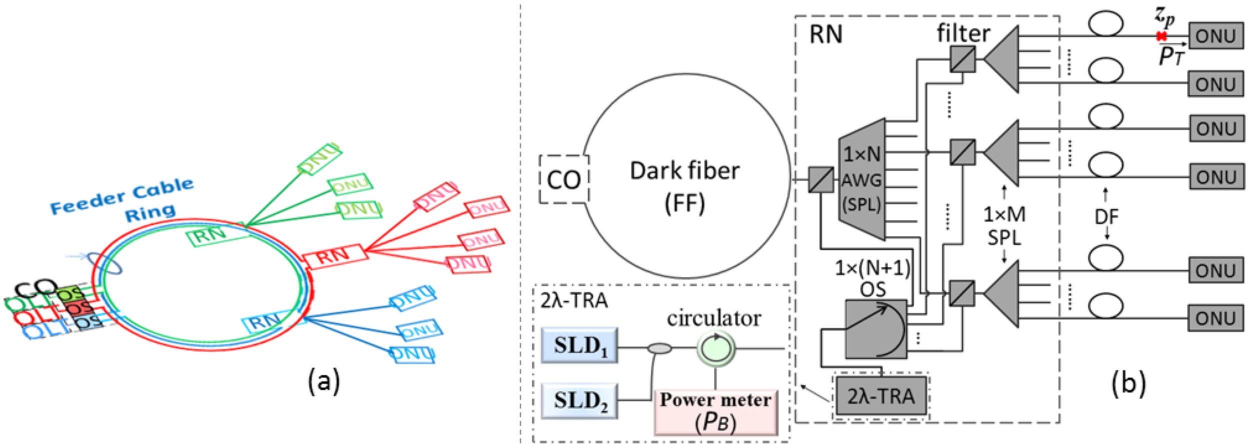


Figure 4-13 (a) “Ring-and-spur” LR-PON (b) Schematic diagram of the proposed monitoring (OS: optical switch, OLT: optical line terminal, ONU: optical network unit, CO: central office, FF: feeder fiber, RN: remote node, DF: distribution fiber, SPL: splitter, SLD: super luminescent diode, AWG: arrayed waveguide grating)

If a fault occurring in a distribution fiber is detected by the network layer, the *1×(N+1)* OS is switched to the corresponding monitoring port. Then the 2λ-TRA fault monitoring is triggered. A continuous-wave light emitted by a super luminescent diode (SLD_1 at λ_1) is launched into the *M* distribution fibres through the *1xM* SPL. Let us consider *M*=4 and the fiber lengths of the 4 DFs are given by L_1, L_2, L_3 and L_4, respectively. The transmitted power P_{T1j} (*j*=1 to 4) are measured by the four ONUs, respectively (ONUs are capable of measuring the received powers [20]) and the Rayleigh-backscattered/reflected power (P_{B1}) integrated all along the 4 fibres is measured by the power meter included in the 2λ-TRA unit (see Fig.6b). By switching the source from SLD_1 to SLD_2, we can obtain the corresponding transmitted power (P_{T2j}) and backscattered power (P_{B2}) at wavelength λ_2. For a fault occurring in a fiber, the insertion loss (*IL*) of the event is typically wavelength-sensitive (e.g. bending) while the return loss (*RL*) is not obviously affected by the wavelength according to our previous experimental verifications [21]. In the following, we denote the return loss of an event by *RL* [dB] whereas IL_i [dB] represents the insertion loss at λ_i. The event location is given by z_p (distance measured from the splitter side). Let us define P_{T0i} as the reference (without any fault) transmitted power corresponding to the faulty DF (It is rare to have more than one faulty DFs for a monitoring port and hence we consider a single faulty DF case) and P_{B0i} as the reference power backscattered/reflected by the four DFs. They are changed into P_{Ti} and P_{Bi} in the presence of an event. Since $P_{Ti}=P_{T0i}\cdot$ 10^ ($-IL_i/10$), IL_i can be calculated by measuring P_{T0i} and P_{Ti}. The normalized power reflection coefficient R_i ($i=1@\lambda_1$, $i=2@\lambda_2$) can be expressed as in Eq.1. It should be noted that the rigorous equation is quite long (where parameters such as directivity, *IL* and *RL* of all devices in the field are considered). In order to simplify the whole formula, Eq.1 only presents the contribution of the Rayleigh back scattering effect.

$$R_i = \frac{P_{Bi}}{P_{B0i}} = \frac{RAY(z_p) + 10^{-\frac{ILi}{5}} \times [RAY(L_1) - RAY(z_p)] + T_i^2(z_p) \times 10^{-\frac{RL}{10}} + RAY(L_2) + RAY(L_3) + RAY(L_4)}{RAY(L_1) + RAY(L_2) + RAY(L_3) + RAY(L_4)}, \qquad (1)$$

where T_i is the fiber transmission coefficient depending on the fiber attenuation coefficient α and can be expressed as $T(x)=exp(-\alpha x)\mathrm{T}(\Delta x) = e^{-\alpha\Delta x}$. Since α varies with the wavelength, different wavelengths will lead to distinct transmission coefficient. RAY_i is the Rayleigh backscattered power coefficient that is expressed as: $RAY(x)=S\cdot\alpha_S\cdot(1-exp(-2\alpha x))/(2\alpha)$, in which α_s is the Rayleigh scattering coefficient and is proportional to $1/\lambda^4$ and S is the capture coefficient [21] (also λ dependent). The insertion loss of the splitter is a common factor in both P_{Bi} and P_{B0i}. It therefore does not affect R_i.

Since α, α_s, L and other parameters (e.g. directivity of the circulator, *IL and RL* of the switch, filter and splitter) are known, and since P_{Bi0}, P_{Bi}, can be obtained by measurements, the problem of localizing the event (i.e. determining z_p) finally consists in solving two equations (Eq.1 for i=1@λ_1 and i=2@λ_2) with two variables (z_p and RL).

To verify the proposed monitoring scheme, an experimental set-up based on a 1×4 splitter is implemented. The lengths of the four fibres connected to the splitter are 6.6km, 3.6km, 5.23km and 2.2km (measured by an OTDR), respectively. In this experiment, a fiber break is introduced in the first drop fiber at three different locations (z_p). The SLDs used in our experiment are operated at 1564.6 nm (SLD_1) and 1307.5 nm (SLD_2) with 57.9 nm and 80.4 nm linewidth, respectively. The input power (P_0) is 12.79mW for SLD_1 and 10.73 mW for SLD_2. For comparison, the event localization has also been measured by an OTDR, which has a localization accuracy of 10 m (i.e., a pulse duration of 100 ns has been selected in order to get a necessary dynamic range to compensate for the splitting loss). The experimental results for fiber break are presented in Table 4-2. A good agreement between the OTDR measurements and the 2λ-TRA scheme has been achieved (with a maximum localization difference of 6.6m), confirming its capability of localizing an event in the distribution section with high accuracy.

Table 4-2 Comparison between the measured z_p by OTDR and the 2λ-TRA solution

OTDR	Z_{p1}	Z_{p2}	Z_{p3}	2λ-TRA	Z_{p1}	Z_{p2}	Z_{p3}
	0	1.711km	6.6km		-6.6m	1.7106 km	6.596km

This experimental study was conducted using two SLD sources (i.e., λ_1: 1550nm and λ_2: 1310nm) that were available in our lab. However, since the distribution section monitoring is carried out together with data transmission, we have to avoid using the same wavelength for the monitoring and data signals. In this regard, 1260nm and 1650nm can be considered as two monitoring wavelengths in practice. Utilizing the simulation methodology described in [16], we consider the inaccuracy of the power meters and calculate the expected localization errors and standard deviations (STDs, which can be considered as localization resolution) as a function of the event RL along a 5 km-long distribution fiber under two different wavelength combinations (i.e. 1550nm+1310nm and 1650nm+1260nm). z_p was set to 2km. IL_i have infinite values in case of a fibre break.

In Figure 4-14 it is clearly shown that in most of the cases the evaluated two wavelength combinations provide almost the same localization accuracy (e.g. less than 5m when RL>35dB and less than 80m when RL<27dB). However, one may notice that when the *RL* of an event approaches 30dB, the expected localization error of both wavelength combinations show a peak. Thanks to the large *RL* values of fiber bending and fiber breaks (according to [21], fiber breaks and bending always have *RL* larger than 33 dB and 75 dB, respectively), which are the two major events to be monitored in the telecommunication networks, the localization inaccuracy (peak value) at 30dB-*RL* may not influence the proposed monitoring scheme. Therefore, our scheme is suitable for monitoring data carrying fibres in distribution segment using "data-transparent" wavelengths, like 1260nm and 1650nm.

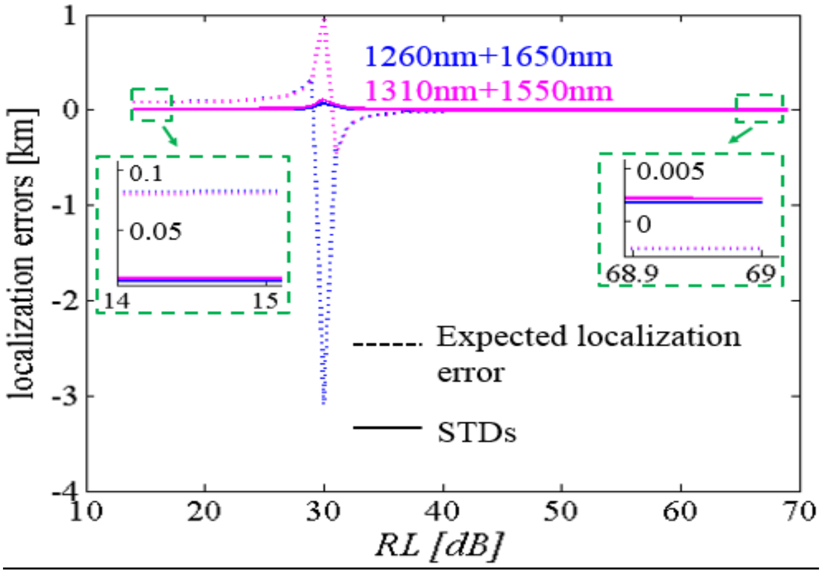


Figure 4-14 Calculated localization errors when a fiber break is introduced in the DF

4.6 Amplifier Remote Node Design Including Solutions for Very Low Latency Wireless Link Integration

The amplifier remote node can be used on one hand to amplify the downstream (DS) and the upstream (US) data signals and on the other hand to include special functions to offer a flexible and future-proof network design, e.g. supporting systems requiring very low latency in the access network between the customer and the first processing node such as mobile front hauling. Optical amplifiers are employed within such remote nodes to increase the low power levels of both the DS and the US signals. This way, the reach-extending amplifier node is an important feature of the access network to enable bypassing of the local exchange (LE) equipment required for today's copper and short reach access networks. The amplifier node will be placed at the location of today's LE site where electrical power is available. However, a major objective of the DISCUS architecture is to enable closure of these buildings. This approach seems reasonable for almost all applications and services except for very low latency solutions requiring a total latency of few milliseconds only as currently discussed in the framework of 5G wireless networks. The DISCUS access architecture offers all kind of flexibility and may also adapt to these changing circumstances that may be faced in the future. Thus, the DISCUS architecture allows for including the necessary equipment into the LE or even at other locations, e.g. as part of the optical distribution network (ODN). Very low latency solutions may also occur even closer to customer locations and they may be attached to particular PONs only in which a service provider or customer demands for these services, e.g. HF trading centres. In this way the mass market FTTP customers can benefit from the economics advantages enabled by the long reach PON while systems requiring the additional terminations closer to the customer for the low latency, bear the cost of that equipment and are not subsidised by the mass market FTTP customers.

Key features for the design of the remote node in addition to the optical design parameters are: management, power feed and/or battery pack up, maintainability, upgradability, reliability and cost.

In this section, we update the work on the remote node design presented in the DISCUS deliverables D2.1, section 2.7 and D2.3, section 3. First, we briefly remind the reader of the already existing solutions and afterwards, we update the remote node design for very low latency applications

4.6.1 *Brief Summary of Deliverable D2.1 and D2.3 on the Remote Node Design*

The optical amplification section of the remote node is shown in Figure 4-15 for the DISCUS network case of a single ODN fibre and two feeder fibres for the DS and US. The additional 2 fibres in the feeder section are used to establish a physical protection path to the backup M/C node. The different output branches of the 4 x 4 splitter in feeder (backhaul) direction are used to separate the up- and downstream paths, which are connected to separate fibres in the feeder section as explained (or 2 x 4 splitter if single fibre working was used in the feeder fibres). The different output branches of the 4 x 4 splitter in ODN direction carry up- and downstream data signals simultaneously, but in opposite directions.

The optical parameters of the Erbium-doped fibre amplifiers (EDFA) and the semiconductor optical amplifiers (SOA) that can be employed in the remote nodes are discussed in detail in the DISCUS deliverable D4.3 and short summaries can be found in D2.1, D2.3 and D4.2.

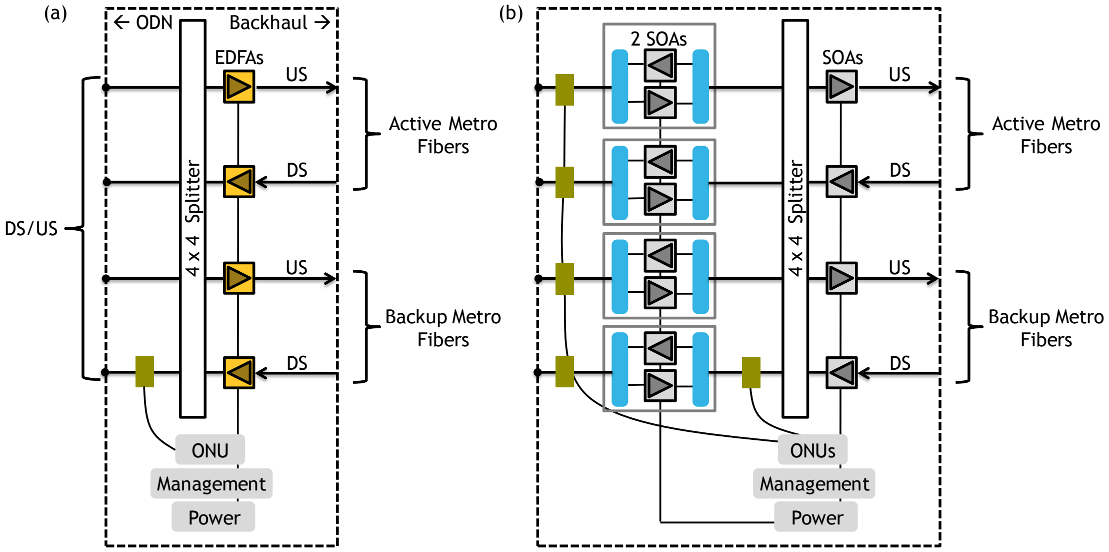


Figure 4-15 Amplifier node for conventional LR-PON with single fibre ODN and two fibre backhaul. In (a) the amplifier node comprises 4 EDFAs for upstream and downstream amplification and in (b) the amplifier node comprises 12 SOAs (parallel cascade of linear SOAs).

Figure 4-15 shows an example of two amplifier remote node configuration employing either EDFAs (a) or SOAs (b). The downstream signals are launched into the amplifier node at which either a single EDFA (a) or first a single SOA is used to amplify the data signals. In (a), no further downstream data signal amplification is required, because of the use of a high gain EDFA. In (b), behind the 4 x 4 splitter 4 additional SOAs are employed for amplification in DS direction. This SOA cascade is employed to achieve the required accumulated gain. The upstream signals are transported over the ODN and launched into the amplifier node (4 x 4 splitter). Here, either a single gain-controlled EDFA (a) or a cascade of SOAs is used to amplify the signals.

Management/maintainability: In the case of using EDFAs as introduced in Figure 4-15(a) an optical tap is placed on the ODN side of the 4 x 4 splitter to access the optical signals for operations and maintenance supervision. The tapped optical signals are fed to what is essentially an optical network unit (ONU) and enables management messages to be passed between the amplifier node and the optical line termination (OLT) at the metro-core node. The optical tap can be very low loss as the optical signal power level at this point will be high. Contrary, in the case of using SOAs Figure 4-15(b) 4 optical taps are placed on the ODN side of the 4 x 4 splitter to access the optical signals for operations and maintenance functions. The use of more than a single tap and a single ONU function is required to monitor the functionality of the amplifiers in upstream and downstream direction, respectively. The optical taps can be low loss as explained for the EDFA case.

Energy/power consumption: in general a LE site will support a number of PONs systems and it would be expected that the amplifier remote node will be modular and able to flexibly accommodate a number of amplifier modules to serve the LE site. This gives the opportunity of sharing some components such as power supplies and battery back-up systems and possibly the management ONUs on a shared protection basis to improve reliability of the node.

The EDFA-solution requires the use of 4 EDFAs per amplifier node. A typical high gain EDFA has a power consumption in the range of 15 W or even higher. Since only two of the four EDFAs are switched on (the remaining two EDFAs are for protection purposes), the total power consumption is expected to be in the range of 30 W. In comparison, the SOA-solution requires the use of 12 SOAs per amplifier node. A typical medium gain SOA has power consumption in the range of 2-5 W. Since 10 of the 12 SOAs are switched on (the remaining two SOAs are for protection purposes), the expected total power consumption is in the range of 20-50 W. Thus, the power consumption of both solutions seems to be in a similar range.

Cost: The EDFA-solution requires 4 high gain EDFAs compared to the 12-medium gain SOAs required for the SOA-solution. It is anticipated that the cost of each of these specific EDFAs is significantly higher than that of discrete SOAs. Additionally, the SOA-solution requires a higher number of monitoring taps and monitoring ONUs. However, the SOA-amplified splitter has high potential to be integrated into a single chip containing the SOAs, the splitter as well as the taps for monitoring. It is expected the SOA amplified integrated-splitter can be cost competitive with the stand-alone EDFA solution and has the advantage of opening up additional wavelength windows for future expansion.

4.6.2 Wireless Integration into Service and Space Converged Access Network

The DISCUS consortium focuses on the implementation of a heterogeneous access network space offering access for wireless as well as wired residential, business and enterprise customers. The network architecture is based on a high-split access network with a transparent outside plant, a massive consolidation of central offices to few metro/core nodes eliminating the metro space and enabling a flat core network. The overall DISCUS approach for the integration of the wireless and wired services is based on a point-to-multi-point (PtMP) PON approach.

In a centralized radio access network (RAN) architecture, see [22],[23] and deliverable D2.7, section 2.1 and section 2.2 for details, the digital baseband processing hardware (baseband unit: BBU) is moved from the base stations to a common central location, serving a large group of remote radio heads (RRH) that then do not need much more hardware other than RF electronics. The BBUs and RRHs are connected by high speed digital fronthaul links for transmitting digitized IQ samples. The centralized RAN concept offers cost savings by allowing for relaxed hardware specifications (environmental hardening is needed for only few components), by requiring smaller footprint and less power consumption of outdoor equipment, by sharing infrastructure in the BBU location, by simplifying repair and maintenance and by easing system upgrades. In addition to these CAPEX and OPEX benefits, the centralized RAN architecture also eases implementation of advanced radio transmission techniques that have been considered for helping improve RAN coverage, bit rate and throughput by way of intercell cooperation. In the DISCUS fronthaul approach, see deliverable 2.7, section 3.3 for details, the wireless base stations are co-located with optical line terminations (OLT) and the RRH are collocated with the optical network units (ONU). This way, a unified access and metro (aggregation) network is constructed that allows the structural convergence (at a later stage also functional convergence by the implementation of BBU cloud functions) with a physical layer supporting heterogeneous access for fixed and mobile services. A massive base station hoteling at the M/C node can enable a cost-attractive mobile fronthauling solution. The fronthaul approach incorporation into the DISCUS TWDM-PON offers the possibility of centralization of radio access network functions into the M/C node in which traffic aggregation, switching and routing towards the DISCUS core network or to the Internet may be achieved at the same site. The optical transport between BBU and RRH is currently enabled by using the common public radio interface (CPRI) approach. The constant and high data rates that are generated by the CPRI encoding (IQ sampling of analogue rf signal) in the DISCUS scenarios for 2020, i.e. the 1 Gbit/s IP peak traffic on the air interface per sector causes the need for CPRI compression (factor of about 1/3, e.g. from 30 Gbit/s to 10 Gbit/s) enabling the use of a dedicated 10 Gbit/s TWDM-PON wavelength per sector (requiring one ONU per sector). Additionally, an Ethernet encapsulation may be advantageous before transporting the signals over the PON for further switching and processing. The additional process may be required at the OLT site to encapsulate and even switch Ethernet frames from/to the BBU.

For the current CPRI fronthaul approach, the analogue radio signals are digitized in the same format as they are transmitted over the air (except for down/up-conversion), requiring a fixed line rate on the transport link, regardless of how much valid information is actually conveyed. The RRH in this architecture remains most simple, incorporating mainly RF electronics. Instead, when splitting the wireless processing chain at a point, where the resulting interface capacity is dependent on the amount of data to be transmitted over the air (user data or auxiliary signals like pilot tones), then the user traffic dynamics can be taken advantage of, such that the optical link capacity benefits from statistical multiplexing effects. In the processing chain, there are multiple such split points conceivable, moving the atomic processing functions more to the central or more to the remote site. For obvious reasons these architectures can be called midhaul with dual site processing or split processing. At the last point in downlink direction, where the user data statistics still take effect, the interface capacity dynamically ranges from zero (for no traffic) up to about 20 % of the CPRI rate in case of fully loaded radio channels, see deliverable 2.7, section 2.3. In the DISCUS midhaul approach, see deliverable 2.7, section 3.4 for details, flexible-dual site processing enhancements in base stations may improve the flexibility and cost-efficiency of the former architectures, by reducing the bit rates required between antenna sites and processing units, as well as reducing the cost and improving the flexibility of mobile functions in the network by using virtualization in general purpose platforms. Assuming a target average user rate of 1 Gbit/s, an air peak rate per sector of > 10 Gbit/s (maximum peak rate per user) is required so that a CPRI rate of about 150 Gbit/s per sector can easily be required. Applying the concept of mid-hauling a rate of 30 Gbit/s results which can be addressed by either higher TDM rates per wavelength channels, e.g. by using duobinary modulation with 25...40 Gbit/s in upstream and also in downstream direction. The mid-haul remote radio heads (RRH+) at the antenna site may also contain functions to establish Ethernet transport and aggregation functions. In general TWDM-PON channels comprise the functionality to transport Ethernet packets which are either just encapsulated into the burst or are split into pieces and encapsulated step-by-step. To avoid latency restrictions, the dynamic bandwidth allocation (DBA) algorithms need to be adapted accordingly. Additionally, the processing units located within the M/C node comprise the functionality to flexibly and efficiently allocate bandwidth to different RRH+ units. The processing unit enabling cloud RAN is directly connected to the OLT ports. Contrary, the processing unit could also become part of the L2/L3 switch/router configuration so that the OLT ports may be used flexibly and that they are not reserved for the wireless services.

The transport and networking mechanisms require achieving the strict timing requirements in fronthaul and midhaul links, such as total latency, timing accuracy and jitter accumulation. In the process of standardization, it will be of paramount importance to accommodate these fundamental radio requirements on the transport network side. While timing information can be provided by additional means such as GPS, SyncE or IEEE 1588v2 protocols, the latency constraints will need appropriate measures during processing in the network nodes.

In current LTE solutions, the latencies are not constrained by the fronthaul protocol, but rather by the chosen radio access technology (RAT). Among the current radio access technologies, LTE imposes the most stringent requirements on transport latencies. They result from the uplink hybrid automatic repeat request (UL-HARQ) process, in which the BBU must indicate within 4 ms to the user equipment (UE) to retransmit an erroneous packet. The typical latency budget left for the fronthaul transport segment for carrying antenna data is of the order of a few hundred microseconds with the actual numbers varying from vendor to vendor based on implementation considerations. This transmission latency relates to the round trip time from the RRH/RRH+ to the BBU and return, including travel time over the fibre as well as signal processing time in the optical system equipment. Depending on the optical transmission technology, the fibre length between BBU and RRH/RRH+ is thus limited to below 20 km (with very low processing delays: up to 40 km assumed within DISCUS including a 10 km ODN length). Whereas with UMTS these constraints can be more relaxed, it is expected that for some applications in future 5G radio networks the latency constraints will be even tighter.

In deliverable D4.10 and 4.11, the DISCUS consortium has shown that for example in the UK 50 % of all customers can be covered by a M/C node to customer distance of 40 km and 90 % of the customers are 75 km away from the M/C node. Additionally, it was shown that for example in Ireland almost all customers (99.9 %) are located within a 10 km distance from the LE and just very few customers are further apart. Thus, the DISCUS fronthaul and midhaul approach covers most of the customers without violating the latency requirements (in case of violation a backhaul approach is used in DISCUS networks). However, very low latency requirements (below 1 ms) are currently in discussion for different applications at 5G, for interactive services or for improving the efficiency of CoMP (cooperative multi-point) techniques. Short optical links are thus needed on the x-haul network, by interconnecting neighbouring remote sites on a local passive optical mesh network (solutions presented in section about bespoke networks) or by placing small active nodes in the neighbourhood of remote sites (e.g. into the local exchange) offering local compute and/or higher layer processing capabilities. The latter could e.g. help reduce the latencies in IPsec secured transmission which currently involves processing deep in the core network, thus inducing latencies of more than 20 ms.

In the following, two possible solutions for very low latency links that are incorporated into the DISCUS network architecture are presented showing that the DISCUS infrastructure is also capable of enabling this functionality. We refer to a latency scenario in which we distinguish “gold” (very low latency), “silver” (low latency) and “bronze” (moderate latency) requirements. The “gold latency” requires the establishment of local peering partners in the ODN and either in the local exchange (remote node) or in the street cabinets. The “silver latency” requires the use of a peering partner in the M/C node (up to 40 km separation) and the “bronze latency” requires a peering partner to be located at neighbouring M/C node (>80 km separation).

In the following, we focus on the incorporation of the “gold latency” solution into the DISCUS network architecture, i.e. first a fronthaul solution is presented (DISCUS 2020 vision) and afterwards a midhaul solution is discussed (DISCUS vision for beyond 2020).

4.6.3 Wireless Integration into LE Sites for Very Low Latency Links in DISCUS Architecture

The first solution focuses on the DISCUS 2020 network vision as introduced in deliverable D2.7, section 3.3. In the following, we describe the centralized RAN approach only. In Figure 4-16, the incorporation of wireless equipment into the remote node / LE is shown. We use an overlay of DWDM-channels in O-band to establish a connection between the “gold latency” BBU and the RRU. Edge processing is included in the RN and a backhaul communication can be established to the M/C node reusing the DISCUS fibre access infrastructure.

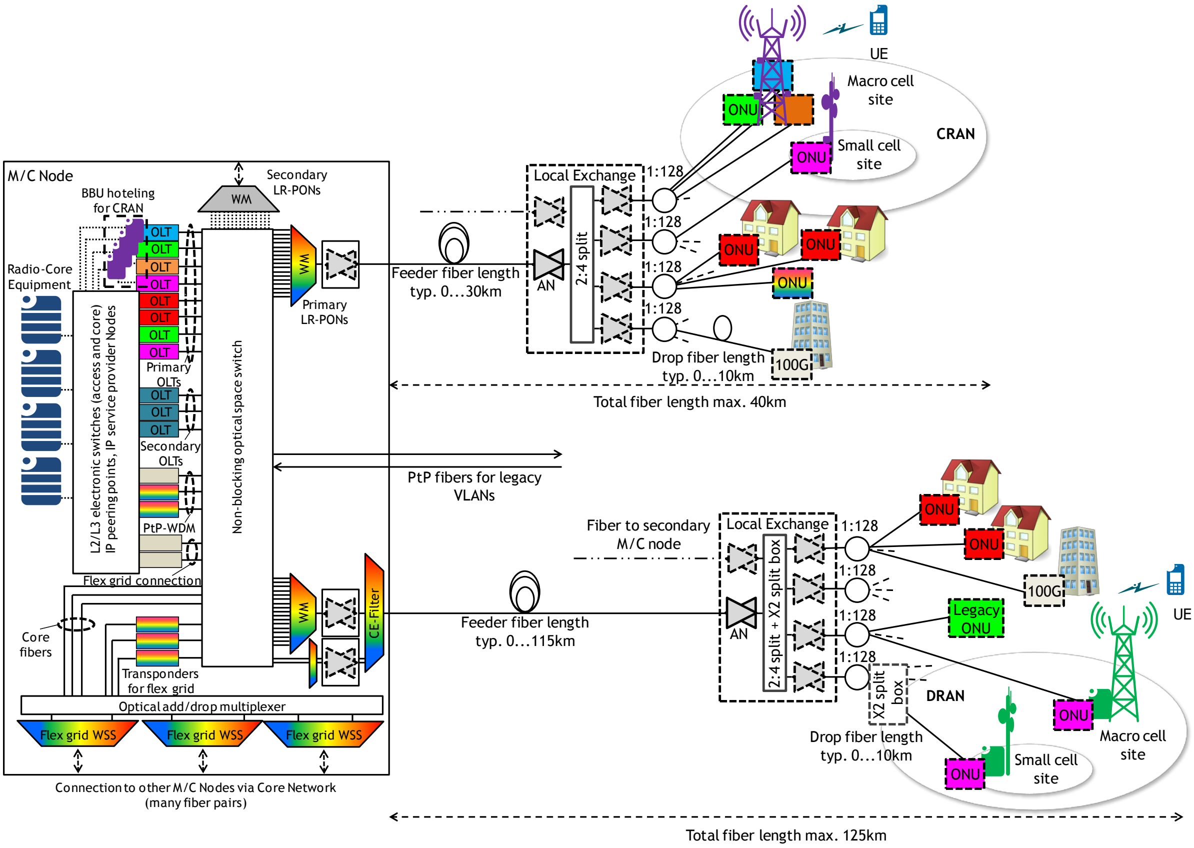


Figure 4-16 Particular DISCUS access network scenario including wireless and wireline convergence accounting for different latency requirements. The local exchange contains beside amplification of the data signals also few BBUs and local processing functionality. The overall network approach comprises distributed-RAN (not shown), centralized-RAN, "core-bandwidth" transmission over PtP-WDM channels, co-existence of DISCUS TWDM-PON with legacy PON systems and higher speed PON applications (DB-TDM-PON or coherent PON).

A detailed sketch of this first solution is shown in Figure 4-17 for the remote node in (a) and the antenna site in (b). The DISCUS access services such as residential TWDM-PON, PtP or high speed TDM-PON for business users and "silver and bronze latency" wireless links (via TWDM-PON on dedicated wavelength using compressed CPRI over PON) as well as "core-bandwidth over PON" systems are transported as usual in C-band.

The "gold latency" solution may be established with an overlay using another wavelength band of the same fibre, i.e. the O-band. In Figure 4-17(a) in DS direction a power splitter (tap) is used to drop the signals towards an ONUs that is used for the backhaul communication for the very low latency link. The backhaul communication in the US direction can be designed accordingly. In case the ONU bandwidth is not sufficient then a PtP high-speed link can be established. The fronthaul solution requires a modified RRH that uses either dedicated antennas for the different services or a specific band of the wireless resources to distinguish between the different latency requirements. LTE-A standards already support aggregation of carriers to serve a user device from different bands and different sites. The "gold latency" optical link makes use of a PtP DWDM O-band transceiver that is part of the RRH, see Figure 4-17(b). The O-band signals from different RRHs can be combined with the DS and US from the legacy DISCUS PON by a C-/O-band diplexer per antenna site. The native CPRI signals are sent with DWDM over the passive and transparent ODN towards the remote node. There, these O-band wavelengths are separated from the C-band, amplified and directed towards the BBUs by means of an interleaver, e.g. working on a 100 GHz grid for uplink (UL) and downlink (DL), see also Figure 4-17(c). Note in Figure 4-17 we show the C-band split into two bands for up and downstream transmission however we now favour that band also using interleaved up and downstream channels.

The remote unit comprises also an edge processing unit that may perform local compute and higher layer processing capabilities as well as possibly offering local content and application capabilities. The virtualization of BBU functions may allow minimizing the processing in the remote node. Thus a further reduction in latency as well as in processing needs and energy consumption seems possible. For example, specific functions that are not required for a very low latency link may be placed into the M/C node to minimise the amount of equipment and functionality at the remote nodes.

This way, mobile devices are connected to different radio end points in the network (RN, M/C nodes) depending on the service needs. The processing of different wireless services is also performed at different locations in the DISCUS networks even though they share some common fibre links, i.e. the PON. However, a persistent logical control channel can be maintained independent of the specific solution to facilitate adding and dropping links and to address time synchronization issues.

The second solution focuses on the DISCUS vision beyond 2020 as introduced in deliverable D2.7, section 3.4. In the following, we focus on the midhauling approach using dual-site processing. In Figure 4-18, the incorporation of wireless equipment into the remote node is shown. We use an overlay of a TWDM-PON in O-band to establish a connection between the virtualized BBU cluster and the RRH+ (including the analogue-to-digital processing up to the access to the individual user traffic as well as Ethernet encapsulation). Edge processing is included into the RN and a backhaul communication can be established to the M/C node reusing the fibre access infrastructure.

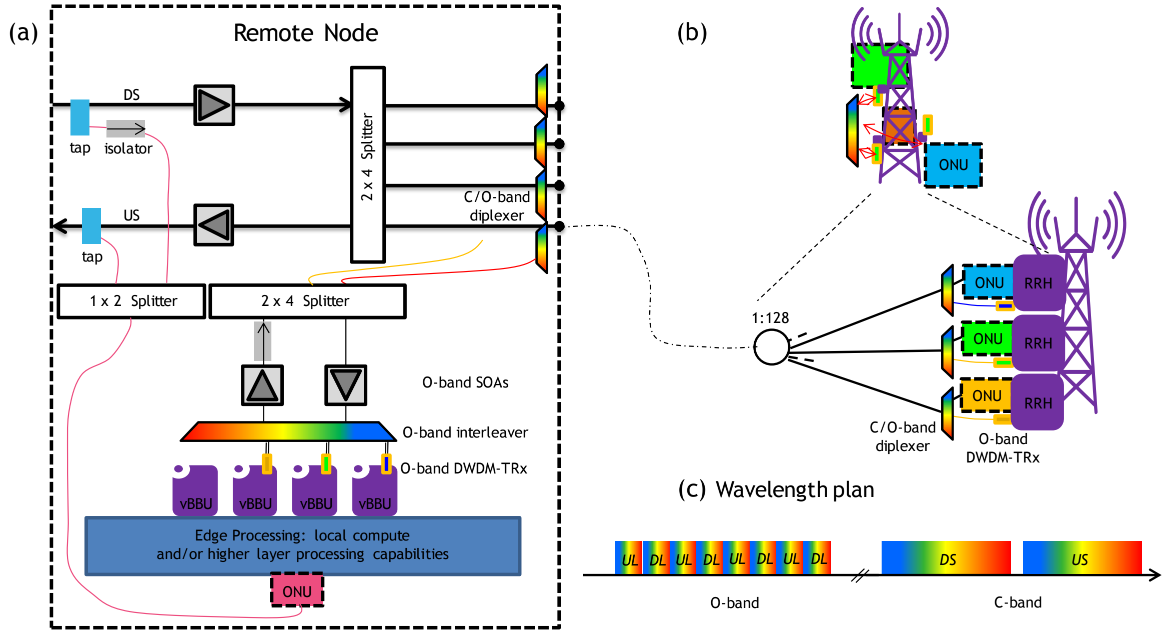


Figure 4-17 Detailed architecture of Figure 4-16 to realize very low latency fronthaul links. The remote node configuration is shows in (a), the antenna site is shown in (b) and the wavelength plan to overlay the very low latency links using O-band transceivers on top of the legacy DISCUS PON applications located in C-band is depicted in (c).

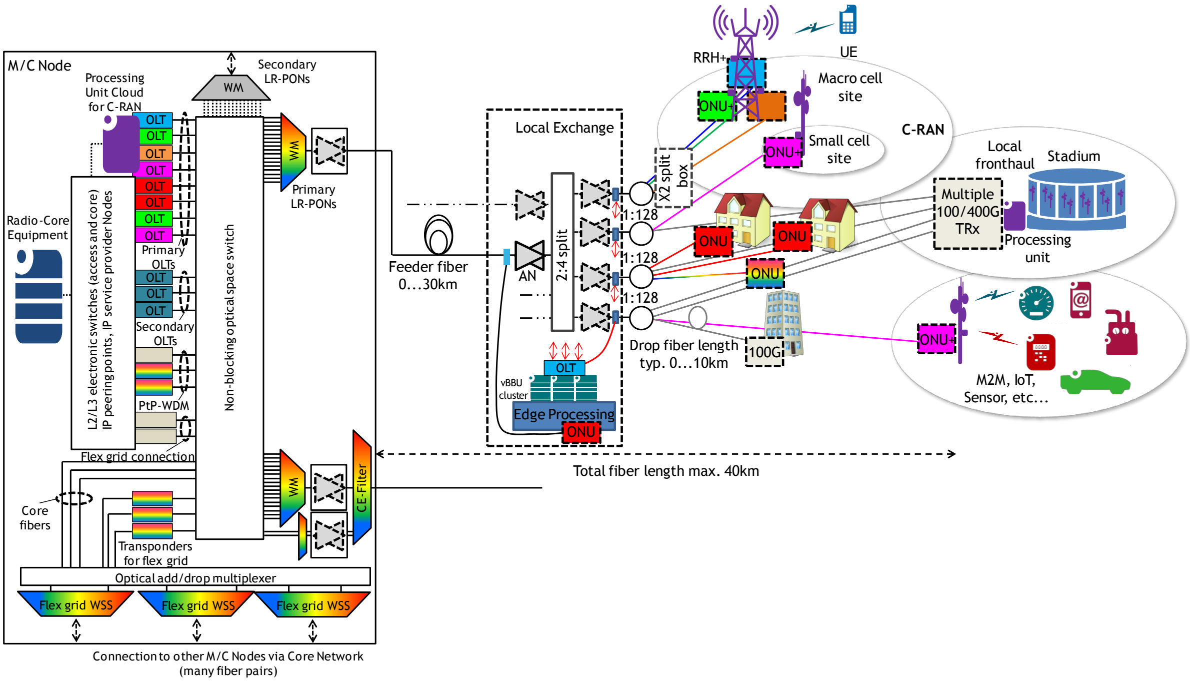


Figure 4-18 Particular DISCUS access network scenario showing details of the top part of Figure 4-16 including wireless and wireline convergence for a possible future network including a 5G vision and accounting for different latency requirements. The local exchange contains beside amplification of the data signals also a virtualized BBU cluster and local processing functionality.

A detailed sketch of this second solution is shown in Figure 4-19 for the remote node in (a) and the antenna site in (b). The "legacy" DISCUS access services ("silver and bronze latency" wireless links (RRH+ dual-site processed wireless signals with access to individual user data and benefit from statistical multiplexing transported via TWDM-PON)) are transported as usual in C-band. The "gold latency" solution may be established with an overlay using another wavelength band of the same fibre, i.e. the O-band.

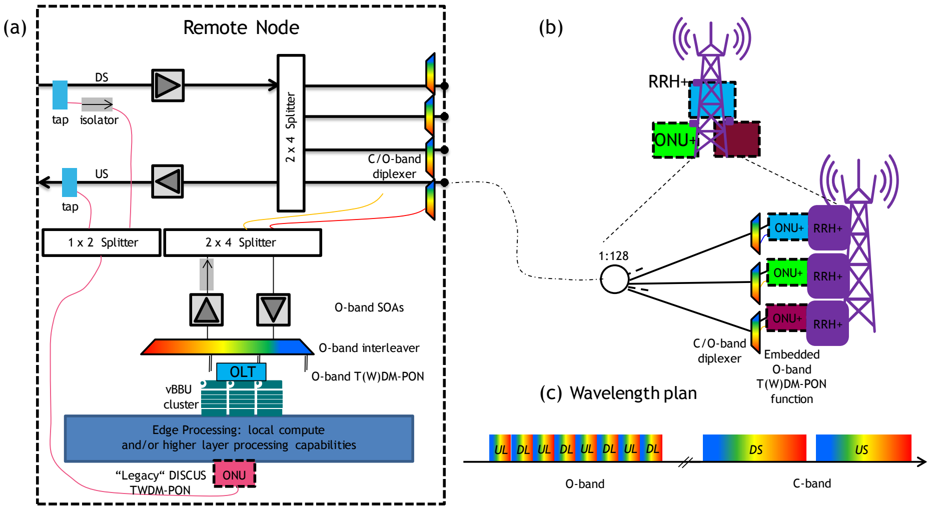


Figure 4-19 Detailed architecture of Figure 4-18 to realize very low latency midhaul link. The remote node configuration is shows in (a), the antenna site is shown in (b) and the wavelength plan to overlay the very low latency links using O-band T(W)DM-PON on top of the legacy DISCUS PON services located in C-band is depicted in (c).

In Figure 4-19(a) in DS direction a power splitter (tap) is used to drop the signals towards an ONUs that is used for the backhaul communication for the very low latency link. The backhaul communication in the US direction can be designed accordingly. Again, if the backhaul capacity is exceeding the 10 Gbit/s or even 40 Gbit/s (high speed DISCUS T(W)DM PON solution), a dedicated PtP high-speed transceiver can be used. The midhaul solution does not necessarily require a modified RRH+ (direct access to user data could enable direct Ethernet switching for different latency requirements towards the different optical transceivers). However the use of either dedicated antennas for the different services or a specific band for the wireless resources to distinguish between the different latency requirements are also applicable. Here, the "gold latency" link makes use of a high-speed T(W)DM (e.g. using duobinary modulation) that is operated in O-band. The additionally required O-band transceivers are incorporated into the ONU+ that is connected the RRH+. The O-band signals from different RRH+'s can be combined with the DS and US from the legacy DISCUS PON by a C-/O-band diplexer per antenna site (it could also be part of the ONU+). The use of a T(W)DM-PON becomes possible because of the access to the individual user data at the RRH+ that also enables direct access to the different services. These data signals are sent via the O-band T(W)DM-PON across the passive and transparent ODN towards the remote node. There, these O-band wavelengths are separated from the C-band, amplified and directed towards the virtualized BBU cluster by means of an interleaver, e.g. working on a 100 GHz grid for uplink (UL) and downlink (DL), see also Figure 4-19(c). The remote unit comprises also an edge processing unit.

In order to guarantee constant bitrates on the client interfaces and to avoid jitter accumulation caused by random access to the PON, the TDM/TDMA channel must be operated in fixed bandwidth mode with DBA switched off (dynamic bandwidth assignment). Each ONU is assigned multiple slots per TC layer frame (transmission convergence layer frame = 125 µs), thus reducing the buffer time in the end equipment on either end of the link to only a few ten microseconds. The quiet windows in upstream direction, which are required for ranging and registering new ONUs (new RRHs), have to be as short as possible. For these short optical links, the ranging window can be reduced to the duration of a single TC layer frame or even less. Likewise, the equalization delay for the ONUs must be reduced. So altogether, for fibre links of up to only a few kilometres length (more generally: up to only a few kilometres of differential distance between any two remote sites on the network), the total latency can be reduced to below 100 µs per direction: buffering for accommodating the slot sequence per frame (30 µs), compression/decompression (20 µs), FEC encoding/decoding (5 µs), travel time (5 µs/km) and buffering for ranging windows (e.g. 20 µs); the values in brackets are given as examples. It should be noted that timing and synchronization issues of the wireless network as well as at switches and router processing may occur that could be addressed by the above mentioned standards and / or have to be considered as part of further research projects.

4.7 40GB/S DOWNSTREAM FOR LR-PON

This section serves as an update to the 40 Gb/s downstream study reported previously in D2.1 and D4.1. As the demand for broadband services continues to rise, such as business users and mobile backhaul applications, the investigating on >10 Gb/s single-carrier downstream links is recently gaining a lot of interest (e.g. in IEEE NG-EPON initiative [3]. As usual cost and technology feasibility are the main concern when increasing the single-carrier downstream line rate from current 10 Gb/s to 40 Gb/s. For instance, the full service access network (FSAN) group has proposed NG-PON2 based on a time and wavelength division multiplexed passive optical network (TWDM-PON) over a splitter-based optical distribution network (ODN), i.e., by stacking downstream rate of 10 Gb/s at 4 or 8 wavelengths. One major reason of this choice was that higher serial rate TDM-PONs were believed not cost-effective due to the foreseen technology limitations at that time. In D2.1, we proposed a 3-level electrical duobinary modulation to reduce the bandwidth needs of the OLT transmitter and ONU APD receiver. We chose 3-level electrical duobinary because its implementation for modulation and demodulation is simple, and because its degradation of receiver sensitivity relative to NRZ is minimal (~3dB at BER=1E-3). The proposed modulation reduces the downstream channel bandwidth requirement to ~20 GHz, which allows for a low-cost DFB-EAM (distributed feedback laser-electro absorption modulator) TX at OLT and a 25 Gb/s APD at ONU. Due to the reduced bandwidth, 3-level electrical duobinary will also serve to further improve the CD tolerance of the 40G downstream. Furthermore, detailed simulation and studies have conducted and reported in D4.1 for the proposed 40Gb/s 3-level electrical duobinary modulated downstream.

Based on the results of D4.1, in WP5, IMEC and III-V has focused on the development of low-cost 40 Gb/s downstream PON subsystems at both OLT and ONU. In WP8, two physical-layer test-beds have been built in IMEC to evaluate the performance of both APD (Figure 4-20) and SOA (Figure 4-22) based schemes. The experiments results have been fed back into the system power and OSNR calculation and summarized below.

- **Case 1: 40Gb/s downstream using 3-level duobinary modulation and APD-Rx**

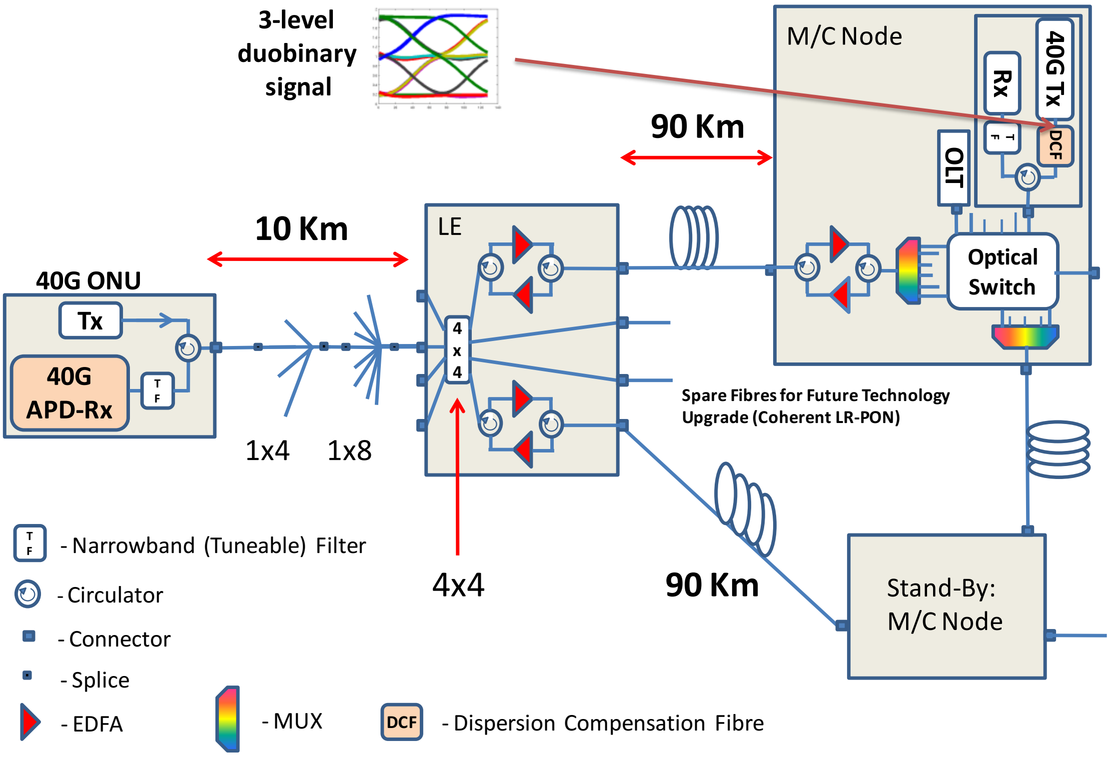
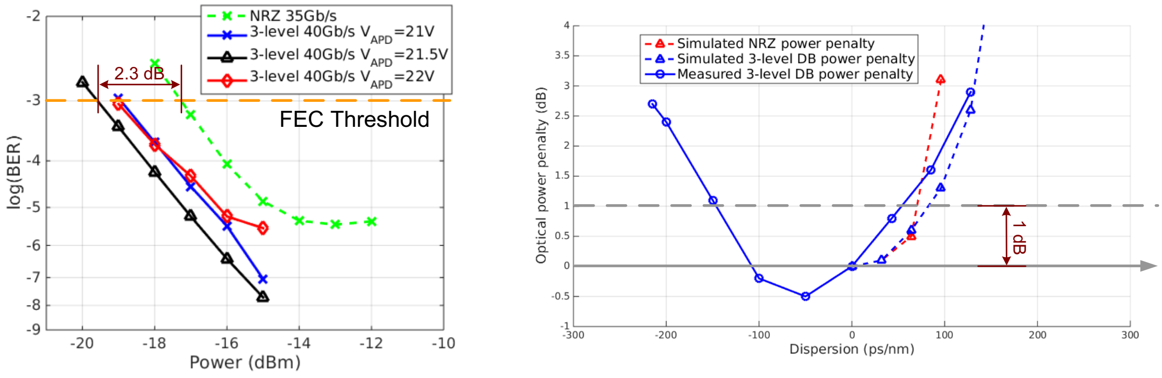


Figure 4-20 Power budget scenario 1: 40Gb/s downstream path using APD-Rx with 3-level duobinary modulation

In the downstream test-bed [4] at the OLT a compact and low-cost DFB-EAM transmitter optical sub-assembly (TOSA) is modulated by an on-off keying (OOK) return-to-zero (NRZ) signal. The ONU receiver consists of a front-end APD-TIA receiver optical sub-assembly (ROSA) and a custom 3-level duo-binary decoder IC. The linear APD-RX converts the received input into 3-level modulated signal. After three level duo-binary decoding, one of the four de-multiplexed outputs was fed into a BER analyser for real-time BER measurement.



(a) (b)

Figure 4-21 (a) measured 40 Gb/s 3-level duo-binary downstream BER versus NRZ. (e) measured link power penalty in terms of dispersion in comparison of simulation results.

The measured sensitivity of the 40 Gb/s 3-level detection was -19.6 dBm at BER=1E-3 and it showed a sensitivity improvement of 2.3 dB with respect to 35 Gb/s NRZ transmission (see Figure 4-21(a)). Next, we have evaluated the 40 Gb/s 3-level duo-binary link as a function of dispersion. The measured power penalties versus various dispersion values are shown in Figure 4-21(b) together with simulated results in D4.1.

Given a differential reach of 10km, the nominal dispersion length should be chosen as the mean of the distance of the shortest and the longest reach. In this case, the resulting maximal power penalty was less than 1 dB in the range from -137 ps/nm to +63 ps/nm, which is able to support more than 10 km of SSMF (assuming a dispersion value of 17 ps/nm/km) in ODNs.

Table 4-3 Optical power margin including dispersion penalty for 40G downstream with APD-Rx

	Standard FEC (pre-FEC BER=1E-3)	Strong FEC (2dB improvement)
128 split	0.5	2.5
256 split	Negative margin	Negative margin

Taking the measurement results and power budget calculation in D4.1, the final power margins including dispersion penalty are shown in **Table 4-3**.

- **Case 2: 40Gb/s downstream using pre-amplifier SOA in ONU**

In order to improve the optical budget, a semiconductor optical amplifier (SOA)-preamplifier with a PIN ONU receiver can be employed. In this case, the minimum received power at the input of the PIN-Rx is of importance as the link is not OSNR limited.

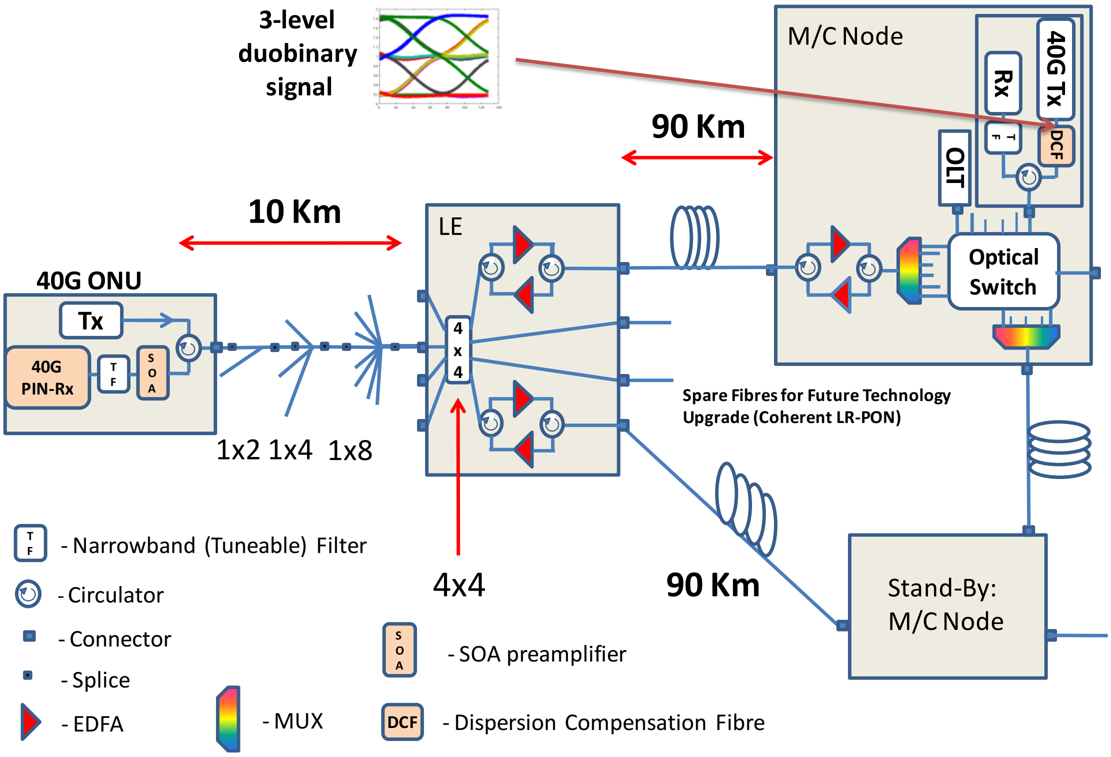


Figure 4-22 Power budget scenario 1: 40Gb/s downstream path using SOA+PIN-Rx with 3-level duobinary modulation

In addition to the APD-Rx, a PIN-TIA [5] was assembled by III-V Lab, which consists of a PIN photodiode from III-V Lab and a linear TIA developed in IMEC. We then measured the bit error rate (BER) of the PIN-TIA assembly for NRZ and 3-level duobinary inputs. The measured sensitivity for the 3-level duobinary detection was -12.6 dBm at BER=1E-3.

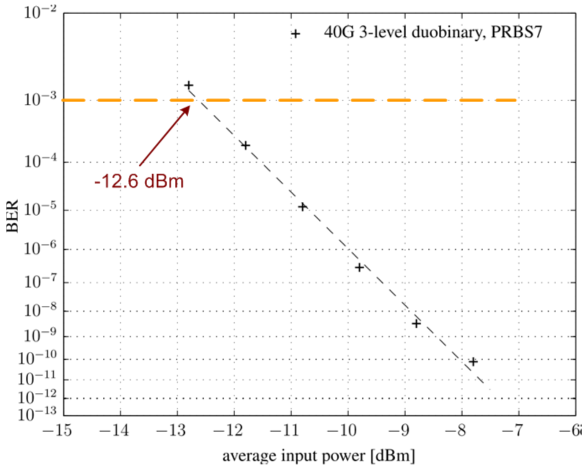


Figure 4-23 measured BER of the 40 Gb/s 3-level duo-binary downstream with PIN-Rx

Table 4-4 Optical power margin including dispersion penalty for 40G downstream with PIN-Rx

	Standard FEC (pre-FEC BER=1E-3)	Strong FEC (2dB improvement)
256 split	0.85	2.85
512 split	Negative margin	Negative margin

With this measurement result, we also updated the final power margins including dispersion penalty for SOA-preamplified PIN-Rx in **Table 4-4.** Based on the updated power and OSNR budget calculation, an APD receiver would support a 90km backhaul, a 10km ODN and a 128-way split while a SOA-PIN receiver would allow for an upgraded split ratio of 256 at 40Gb/s.

To accommodate the reduced split compared to the target 512 for the 10Gb/s LR-PON the amplifier node splitter could be by-passed by exploiting additional network side splitter ports for splitters placed at the cabinet location as discussed in section 4.2.

4.8 100GB/S POINT TO POINT TRANSMISSION OVER LR-PON INFRASTRUCTURE

An important aspect of the DISCUS network architecture is the implementation of the “principle of equality” concept, that is, all optical terminations anywhere in the network have equivalent connection capability independent of their geographical location. This is achieved by a flexible use of the wavelength domain, with wavelength channels capable of carrying a wide range of services and capacities. Thus, for example, the same access infrastructure could deliver in parallel 10 Gb/s passive optical network (PON) services, as well as point-to-point core services (40Gb/s, 100Gb/s or higher) to business customers located at any point within the network. Hence, this requires that the long-reach PON (LR-PON) has the capability to offer such capacities to a few selected customers without disrupting the on-going time division multiple access (TDMA) traffic to and from the conventional customers attached to that network and that the high capacity link is also resilient against the impairments created by the TDMA traffic, such as, for example, linear and non-linear cross-talk.

There are different possible solutions to transport capacities of 100Gb/s per channel in today's optical networks depending on the specific application. OOK modulation at 100Gb/s is very challenging both from the optical impairments point of view, but also very importantly for the electronic components needed to drive the optical components and receive the optical signals. For this reason the majority of the 100Gb/s solutions use a number of tributary channels, at a fraction of the full 100Gb/s rate, which are then multiplexed into a single optical channel. For example a solution that is currently employed in short-reach applications to implement the 100GE standard uses inverse multiplexing of several high-speed data streams over different wavelengths. Other solutions for short reach employ multilevel modulation formats, for example 4-level pulse amplitude modulation (PAM4), in order to reduce the symbol rate while maintaining the same bit rate. Orthogonal frequency-division multiplexing (OFDM) is also being considered in order to reduce even more the symbol rate and to be able to transmit high bit rates using low bandwidth components.

The requirements of core and metro networks are however different and alternative solutions are currently being implemented to transport 100Gb/s channels in these parts of the network. To the best of our knowledge DP-QPSK with digital coherent receivers is currently the only commercial solution for 100Gb/s in core and metro systems. Despite the higher cost of transmitter and receiver compared to other solutions (i.e. inverse multiplexing), DP-QPSK allows the transmission over metro and core distances (and over legacy fibre infrastructure) with a high spectral efficiency since it can be transported in 50GHz channel grids (or even narrower).

There are currently no commercial solutions targeting the metro-access type of network reaches that DISCUS is addressing. However, we have chosen to implement the 100Gb/s channel using the same solution used in of metro and core networks. There are several motivations for this choice:

- Despite being used in the LR-PON this solution would target large business customers, hence the cost constraints are less stringent compared to residential access and a relatively more expensive solution could potentially be used
- The technology is readily available today, hence it is reasonable to assume that larger volume markets and associated cost reduction will have developed on the timescales of a likely DISCUS network deployment
- The maximum reach targeted in the DISCUS LR-PON is around 100km which can be easily supported by DP-QPSK, while short-reach technologies would not be able to support these reaches
- The DP-QPSK channel is compatible with the DISCUS dense wavelength division multiplexing (DWDM) 50GHz spacing channel plan

- The DP-QPSK transponders are designed to be compatible with legacy links designed to operate at 10Gb/s, hence since the DISCUS LR-PON is designed to carry the 10Gb/s PON links it should support the DP-QPSK channel from an OSNR budget point of view

4.8.1 Dual-polarization quaternary phase-shift keying with digital coherent receiver

DP-QPSK with digital coherent reception has been shown to be able to transport 40 Gb/s over legacy 10 Gb/s links as it has the same tolerance to optical signal to noise ratio (OSNR) and higher tolerance to chromatic dispersion (CD) and polarization mode dispersion (PMD) [24]. Commercial solutions also exist that can carry 100 Gb/s over legacy 10 Gb/s links [24]. By using the capabilities allowed by the DSPs in the digital coherent receiver it is possible to deploy a 100 Gb/s channel on the same LR-PON designed for 10 Gb/s non-return-to-zero (NRZ) links. For example CD and PMD compensation for links of thousands of kilometres can be carried out in the DSPs of commercial line cards and strong forward-error-correction (FEC), using for example soft-decision decoders, can be also implemented in the DSP in order to improve the OSNR tolerance of the 100Gb/s link [24],[25]. DP-QPSK also helps to reduce the requirements on electrical and opto-electronic components because it requires a symbol-rate of only ¼ of the bit-rate.

4.8.2 DP-QPSK channel performance over the LR-PON

The results presented in D2.3, Section 6, analysed the performance of a 100Gb/s DP-QPSK channel transmitted over the DISCUS LR-PON infrastructure. The results presented in D2.3 focused on the downstream link in the “lollipop” configuration for densely populated areas and considered the linear impairments of the link, e.g. OSNR degradation, CD, and PMD. The results confirm the preliminary design consideration, presented also in D2.1, that the 100Gb/s DP-QPSK channel can support the linear impairments introduced by the LR-PON link. As expected the ONSR and power levels targeted for the 10Gb/s PON channels are compatible with the performance of DP-QPSK channel for all the considered architectures (lollipop and open ring) and also for both directions of propagation (up- and downstream). The CD and PMD introduced by the relatively short LR-PON links (compared to metro and long-haul systems) can also be easily supported by the DP-QPSK channel provided an adequate number of taps is used in the CD compensation finite impulse response (FIR) filters and constant modulus algorithm (CMA).

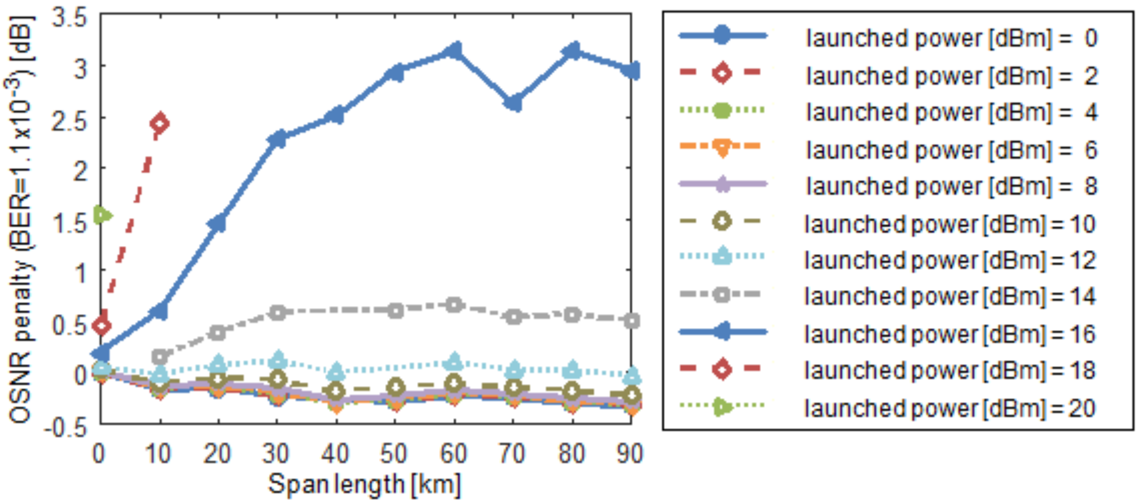


Figure 4-24 OSNR penalty as a function of the span length for different values of the DP-QPSK channel power launched into the backhaul fibre for the "Lollipop" architecture

Deliverable D8.3 focused on the modelling of non-linear distortion and cross-talk in the fibre propagation that could impair the 100G DP-QPSK channel in the DISCUS LR-PON architectures. The major issue for the overlay of a 100Gb/s DP-QPSK channel in the DISCUS LR-PON is the possible presence of co-propagating 10Gb/s NRZ neighbouring channels that could create strong crosstalk distortion on the coherent channel. Especially in the upstream direction the 10G NRZ channels could present a much higher power than DP-QPSK for certain intervals of time due to the burst-to-burst dynamic range. A numerical analysis has been performed as a function of the NRZ channel power and for channel spacing of 100GHz and 50GHz for the two LR-PON architectures considered for DISCUS, "lollipop" and "open ring" (for details of the exact configurations, power budgets and modelling tools please refer to D8.3).

Figure 4-24 shows the performance of the DP-QPSK channel in terms of OSNR penalty as a function of the span length (when the neighbouring NRZ channels are disabled) for different values of launched power into the backhaul fibre. From these curves it is clear that the 100G DP-QPSK channel do not presents visible penalty in comparison to the back-to-back case (at 0dBm) as long as its launched power remain below 10-12dBm. Since the highest launched power in the backhaul link is +5dBm in the "lollipop" downstream, this confirms that self-phase modulation (SPM) has a negligible impact on the system performance up to these launched powers.

Figure 4-25 shows the upstream symbol error rate (SER) for the "lollipop" architecture as a function of the power of the two interfering NRZ channels with 50GHz and 100GHz spacing launched into the 90km backhaul fibre and for different split values ranging from 128 to 1024 (the minimum required dynamic range of the NRZ channel corresponding to a 128-split PON is also indicated). For the 50GHz channel spacing case (solid lines and symbols) it is clear that the DP-QPSK channel would not be able to operate below the FEC limit of 1.1×10^{-3} at the highest power of the NRZ channel dynamic range. XPM is the main contributor to performance degradation for NRZ launched powers above approximately 0dBm, even though for high split-ratios its effect is less pronounced as the system becomes more strongly OSNR limited. Similar trends are seen for the 100GHz spacing case (dashed lines + open symbols) where, as expected, XPM impairments occur at higher powers (+5dBm and above). Nevertheless, the performance is still limited and can only extend to the full NRZ dynamic range for a 128 split.

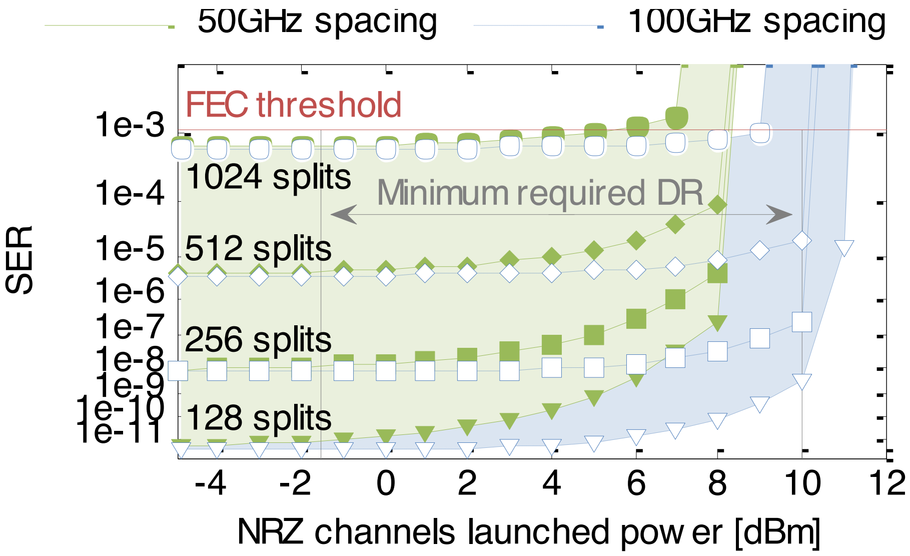


Figure 4-25 "Lollipop" upstream SER as a function of the NRZ channels launched power for different split cases.

Regarding the downstream performance (not reported here), results indicate that up to 512 split can be supported for both 50GHz and 100GHz spacing. In particular, it is found that for launched powers of +5dBm into the backhaul fibre the BER performance present nearly negligible penalty in comparison to lower powers, and only for greater launched powers the penalty becomes significant. Despite the high launched power in the ODN fibre (around +9dBm for 512 split) the maximum length of 10km is not enough to create substantial impairments on the DP-QPSK channel.

Figure 4-26 shows similar results for the "open ring" architecture. In this case, the split ratio in the ODN is fixed to 128, while the number of nodes in the chain is varied from 3 to 6 (corresponding to 384 users to 768 users per LR-PON) with backhaul links of 30km of fibre. The total LR-PON length is hence varied from 100km (3×30+10km) up to 190km (6×30+10km). The latter transmission distances are unlikely to be of practical interest, but are shown here as a worst case. For both 50GHz (solid lines and symbols) and 100GHz (dashed lines + open symbols) channel spacing cases the onset of XPM impairments is at significantly lower NRZ launched powers compared to the "lollipop" system due to the fact that here XPM-induced penalties accumulate over the various spans. However, in this case the DP-QPSK channel is below FEC threshold for the entire dynamic range of the NRZ channel for both 50 and 100GHz channel spacing.

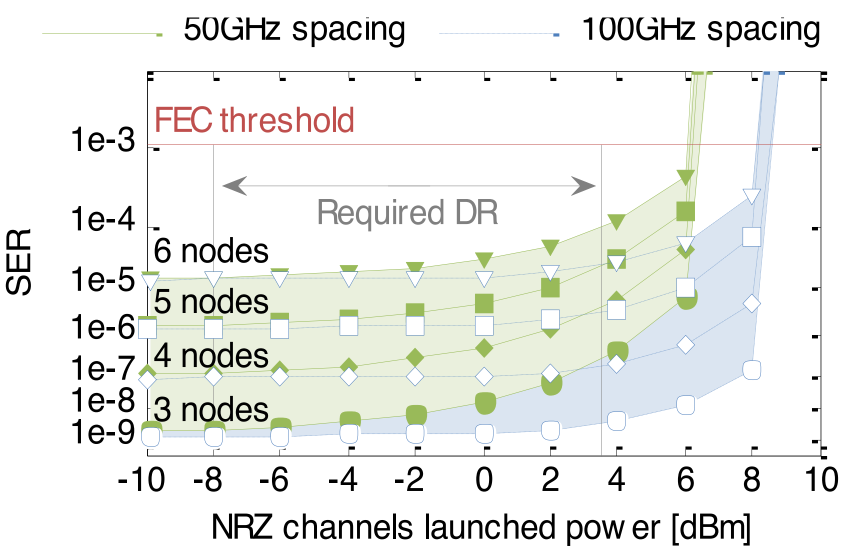


Figure 4-26 "Open ring" upstream SER as a function of the NRZ channels launched power for different number of nodes.

Regarding the downstream performance (not reported here), results indicates that up to 6×30km links (+10km in the ODN) can be supported in both channel spacing cases with adequate margin. Despite the multiple spans in the system the launched powers in both the backhaul and ODN fibres are lower compared to the "lollipop" case and hence the impairments caused by the fibre non-linarites are smaller.

The largest source of penalty in these results is believed to come from XPM which impairs the carrier phase estimation (CPE) algorithm in the coherent receiver DSP [25]. While the XPM-induced penalty on the 100Gb/s channel does not represent a limitation for the "open ring" case, it could compromise the implementation of "lollipop"-type architectures if the 10Gb/s NRZ channels are operated with their full potential dynamic range. However, this issue could be resolved by the introduction of active power levelling on the NRZ channels as well as on the DP-QPSK channel.

As part of task 8.4, the performance of a commercial 100G DP-QPSK transceiver are characterised in the two LR-PON configuration chosen for the DISCUS demonstrator. The results are reported in deliverable D8.4.

4.9 OLT CONFIGURATION OPTIONS

The content of this section is a summary of the material that has been reported in deliverable D4.11, section 3.2. In this section possible OLT configurations are discussed for the case that DS and US interleaving is selected as the wavelength scheme.

In Figure 4-27 four possible OLT realizations are visualized. In Figure 4-27(a) the M/C node is equipped with an interleaver filter at the input/output for all DS/US wavelength channels. The input interleaver filter guarantees that all DS channels are multiplexed to the output fibre and that all US channels are not launched into the DS optical amplifier. In this case the wavelength channels of the DS can be separated by e.g. 100 GHz which is also the separation between the US signals. Both US and DS signal bands are amplified by two separated optical amplifiers handling up to 50 wavelength channels simultaneously. A second interleaver filter (with 100 GHz wavelength band separation) combines/separates the DS and US channel bands. The interleaver filter is connected to the WM filter. This WM filter separates the US wavelength channels and it combines the DS wavelength channels. This is performed in a way that always pairs of DS and US channels separated by 50 GHz are filtered into an identical band. This can be achieved with a WM filter having a spectral grid of 100 GHz (e.g. flat top arrayed waveguide grating (AWG)). The centre of the WM is spectrally located between the desired US and DS wavelength channels. Thus, the US signal enters the OLT and the DS signal leaves the OLT by means of the identical filter channel and the optical space switch. Following, a DS and US separation filter (diplexer) is required which can be realized by a DWDM filter with a pass-band for the US signal to further suppress other US channels or in case of already acceptable separation, a CWDM filter can also be used. The receiver comprises an APD (or a PIN), the linear burst-mode receiver (LBmRX) front-end and the electronic dispersion compensation (EDC) all are able to detect a 10 Gbit/s burst-mode on-off-keying (OOK) signal. The transmitter comprises a 10 Gbit/s externally modulated laser (EML) that can consist of a distributed feedback laser (DFB) section and a following an electro-absorption modulator section which is also able to generate 10 Gbit/s OOK signals. The spectra at the right part of the figure show the spectral content of US and DS signals at some locations within the M/C node.

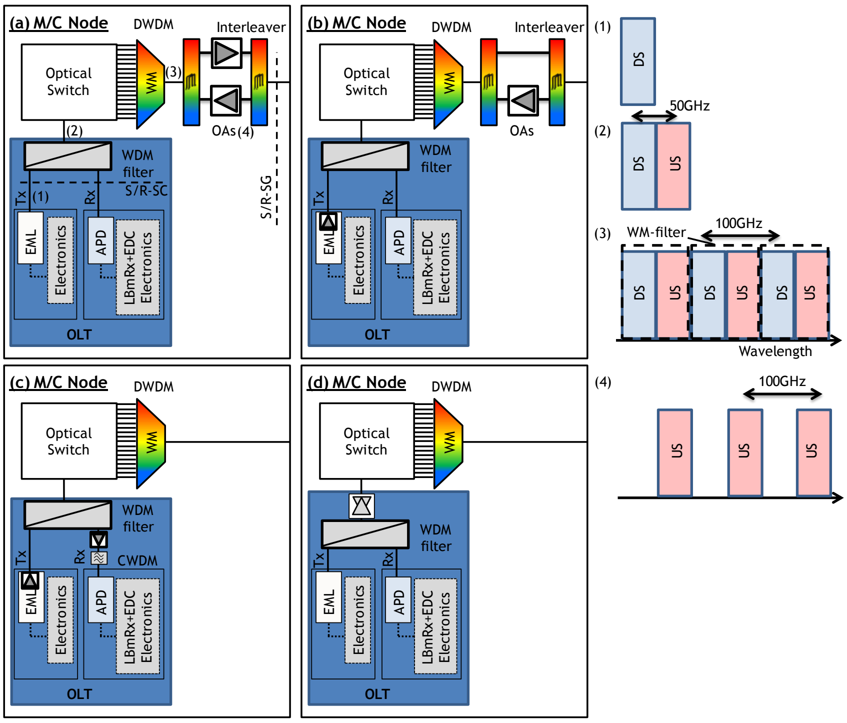


Figure 4-27 Various OLT realizations for the TWDM-PON using the example of interleaving of the US and DS channels

Figure 4-27(b) can be distinguished from Figure 4-27(a) in terms of the fact that each EML chip also comprises an integrated SOA for individual DS amplification.

Figure 4-27(c) can be distinguished from Figure 4-27(b) in terms of the fact the each OLT comprises now two optical amplifiers. The optical amplifier for the DS signal is, as described in (b), collocated, co-packaged or monolithically integrated with the EML. The optical amplifier for the US signal is located behind the diplexer and in front of the APD

(PIN) another noise reduction filter is required (e.g. CWDM filter). In this case, the two interleaver filters can be removed from the M/C node.

Figure 4-27(d) can be distinguished from Figure 4-27(c) in terms of the fact a single bi-directional optical amplifier can be used to amplify the US and the DS signal simultaneously. The need of an additional receiver filter behind the optical amplifier depends on the spectral width of the diplexer filter.

4.10 BESPOKE NETWORKS SOLUTION OVER LR-PON INFRASTRUCTURE

The content of this section is a summary of the deliverable D4.11, sub-section 3.3.2. The implementation of an optical backhauling network for cooperative multi-point (CoMP) in LTE-Advanced networks faces two major challenges: latency constraints and bandwidth requirements. In sub-TWDM (TDM)-PON systems the communication between neighbouring nodes usually has to be via the central OLT. In LR-PON architectures with total fibre length up to 125 km the latency constraints could hence become a blocking argument. Also the bandwidth requirements (which depend on the details of the CoMP approach taken) can become severe, since in LR-PONs with high number of nodes the X2 interface will request a large fraction of the upstream bandwidth, in addition to the user data via the S1 interface.

The architecture shown in Figure 4-28 allows for circumventing these restrictions (see also DISCUS deliverable D4.3) and is particularly useful with LR-PON applications. It realizes a bespoke network, here a local mesh, on a conventional PON ODN.

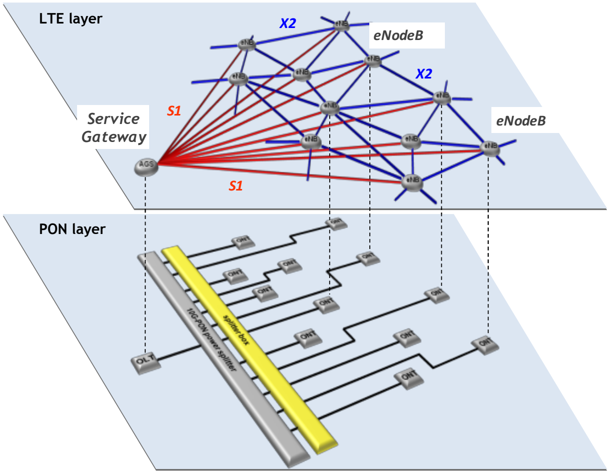


Figure 4-28 Mapping of LTE-Advanced with next-neighbour communication for CoMP to underlying PON fibre infrastructure. Nearest neighbour connections are established by yellow splitter-box next to the PON power splitter

On the LTE layer the desired backhauling topology is shown: red links for S1 between eNB's and S-GW, blue links for X2 between neighbouring eNB's. The S1 interface can readily be realized by employing a TDM-PON system as shown on the PON layer in Figure 4-28. Since deploying additional fibres between eNB's is usually no option, an additional "splitter box" (yellow) is attached to the PON power splitter. It serves for redirecting optical signals from one eNB to its nearest neighbours. These signals are transmitted by additional dedicated transceivers in the eNB's operating in a wavelength band different from the TWDM-PON, PtP-WDM or high-speed PON "bands".

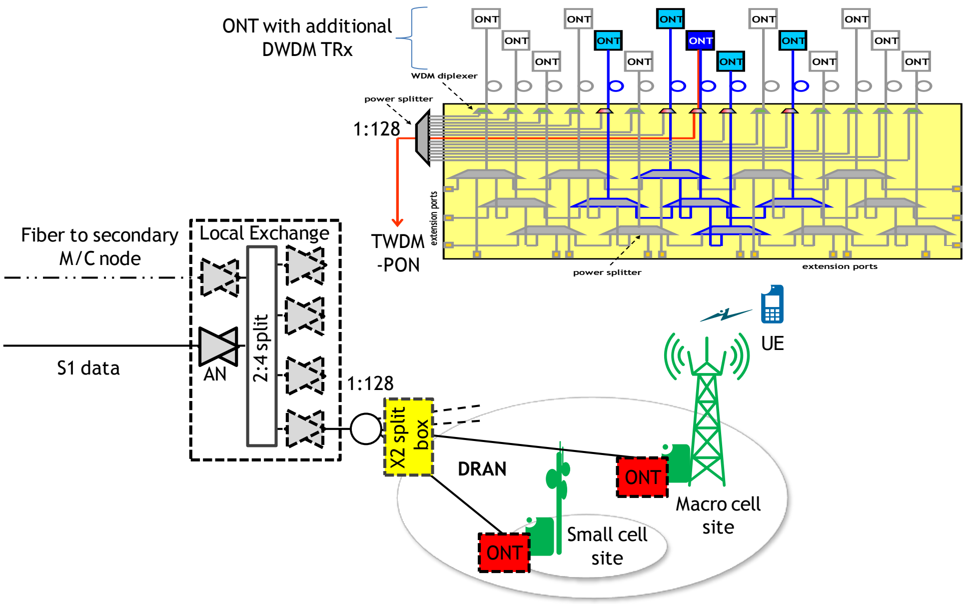


Figure 4-29 Example architecture of yellow splitter box from Error! Reference source not found.. **Implementation of power splitters along with waveband diplexers in a common box (top) is shown. The TWDM-PON system for the S1 connections is attached via the power splitter on the left side of the box. (coloured links and splitters highlight the elements and connections needed for connecting the dark blue ONT. The ONTs are the optical frontends in the respective eNodeB's).**

The internal architecture of the splitter box is shown in Figure 4-29 together with the location within the DISCUS network. The required topology for X2 is exemplified for nodes on a square grid on the top right in the picture. The trapezoidal elements attached to each node are 1:4 power splitters. Each ONT (eNodeB) is connected only to its nearest 4 neighbours. The structure can arbitrarily be extended into either direction without challenging or modifying the optical power budget on each cluster of interconnected nodes. In reality a number of splitters (here 15) are collected in a X2 split box (yellow) and the S1 interfaces are implemented by the TWDM-PON system being attached via diplexers as shown in the figure. The loss budget of the links for the X2 interface can be bridged without requiring optical amplifiers for split factors up to 1:8 per ONT, i.e. for up to 8 neighbours attached to each eNodeB using typical DWDM-TRx. Note that multiple such splitter boxes can be connected to form a virtually infinite "X2 cloud" around the last splitter stage (4 x 128) in the TWDM-PON DISCUS network.

It should be added that the X2 interface for backhauling purposes is a particular example to locally connect customer sites by a bespoke network. This solution may also be used for other applications too.

5 THE METRO-NODE CORE DESIGN

This chapter includes a description of the final overall DISCUS metro/core node structure and design. Figure 5-1 shows an abstract view of functions as well as the associated interfaces to control plane that should be included in final DISCUS metro/core node architecture. It can be seen that the high-level view (i.e., the main elements of DISCUS metro/core node) are kept almost the same compared to the preliminary one reported in D6.1, in order to well accommodate the DISCUS supported network services. The minor difference is introduced to access MPLS switch, where the reference Layer 2 functional blocks are generically called. During the course of the project, our major efforts have been put to refine the detailed design of each element. The recent updates are presented in this chapter.

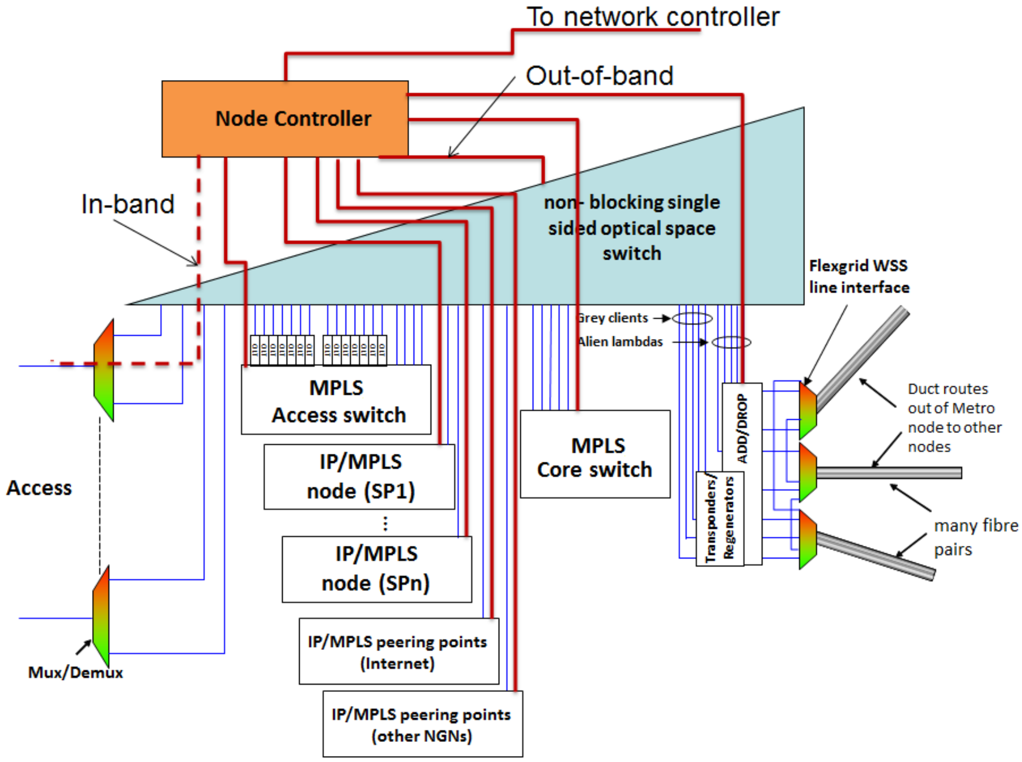


Figure 5-1: An abstract view of final DISCUS metro/core node architecture as well as the required interface for control plane

5.1 THE OPTICAL SWITCH LAYER (Polatis)

The optical fabric of the metro/core node has been described in detail in D6.2 and D6.3. The purpose of this section is to summarise those discussions and to describe the work done since after D6.3.

5.1.1 Optical switch architecture

Using Polatis' [26] technology to provide a 192 port single sided optical crossbar switch, a single sided 12288 port switch fabric can be built in a folded Clos architecture [27].

Figure 5-2 shows the folded Clos architecture with g single sided edge switches each with g ports and m single sided centre switches, each with g ports. We partition the edge switches with m internal connections and n external connections, so $n+m < g$, and then Clos' theorem asserts that $m = 2n-1$. We define the total number of ports $N = ng$.

To have strictly non-blocking, we need to keep $3n -1 < g$. So the maximum value for n is $(g+1)/3$, which gives us $N = g(g+1)/3$ and $m = 2(g+1)/3 – 1$ which constrains g to keep m a whole number. Using g = 192 and p+1 = 192, give us $2N$ = 12288 ports.

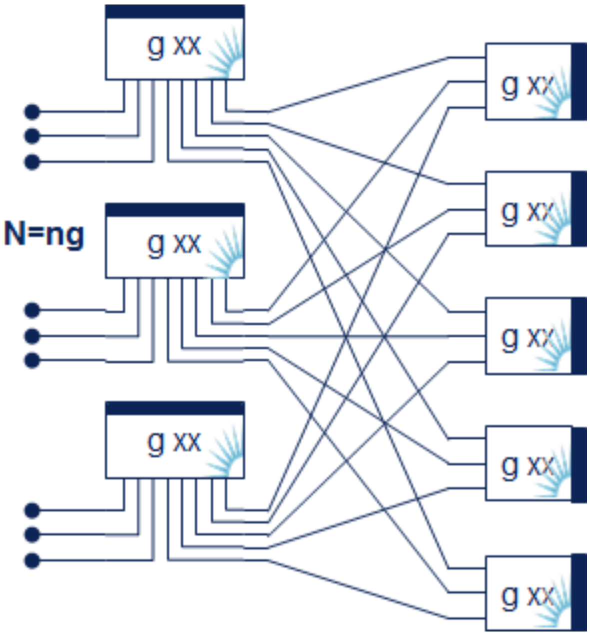


Figure 5-2: Strictly non-blocking single sided Clos switch composed by single sided edge and centre switch matrix

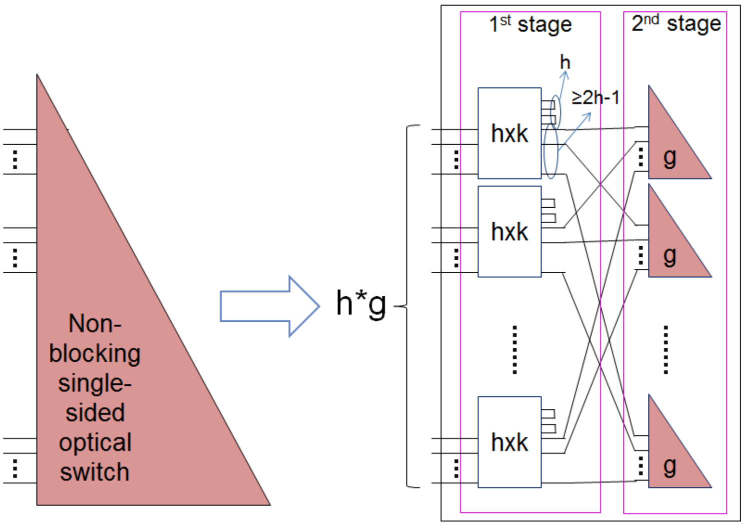


Figure 5-3: Strictly non-blocking single sided Clos switch composed by double sided edge switch matrix and single sided centre switch matrix

Figure 5-3 shows an alternative solution of the folded Clos architecture with g double sided edge switches each with hxk ports and n single sided centre switches, each with g ports. We partition the edge switches with h internal connections (each pair is connected, see the figure above) and n external connections (to connect centre switch). Clos' theorem asserts that $n \geq 2h-1$ in order to have strictly non-blocking. We define the total number of ports $N = h*g$. Considering the total number of ports of each switch matrix is up to 192, $N=12288$.

Hitless scalability was also addressed in D6.2. There are two standard approaches to scale a strictly non-blocking Clos switch, “edge fill” and “centre fill” (assuming the single sided matrices are not themselves scalable). With edge fill, the centre stage is completed initially, and the incomplete edge gains switches to scale. With centre fill, the edge stage is completed initially, and the incomplete centre gains switches to scale. With interchangeable centre and edge switches, it is clear that starting with the smaller centre stage filled and the larger edge stage incomplete gives the lower initial cost, although the final cost remains constant.

5.1.2 Control of the Optical switch

The OpenFlow protocol was proposed in D6.2 as an open SDN standard that would deliver a consistent external interface, while allowing the control architecture to change over the lifetime of this project. In D6.3, three functions were identified for the optical switch:

1. Connect input to output port
2. Read power at given port
3. Trigger alarm for power below threshold

The OpenFlow interface available for the optical switch is built against the OpenFlow v1.0, using circuit switching extensions (v0.3). The circuit switch extensions enable Function 1. Power monitoring for a given port is not a standard feature, and needs to be implemented as Vendor extensions to the port_status message. The alarm state for a port can be signalled using the port state field (OFPSS_LINK_DOWN). With the future implementation of OpenFlow 1.4, all three of these functions are available as standard features.

In D6.3 a multi-module path router was proposed. This software component computes paths through the Clos architecture, between two external connections. In D6.3 two possible locations for the router were mentioned in the context of SDN:

1. the router is part of the optical switch (in DISCUS this the Polatis switch) and the switch presents a single SDN agent on a “shelf controller” with only the external connections,
2. the switch presents one SDN agent for each module in the switch, presenting internal and external connections, and the router is an application in the SDN runtime used by the SDN controller to compute the paths. The SDN controller then configures the path using the multiple SDN agents.

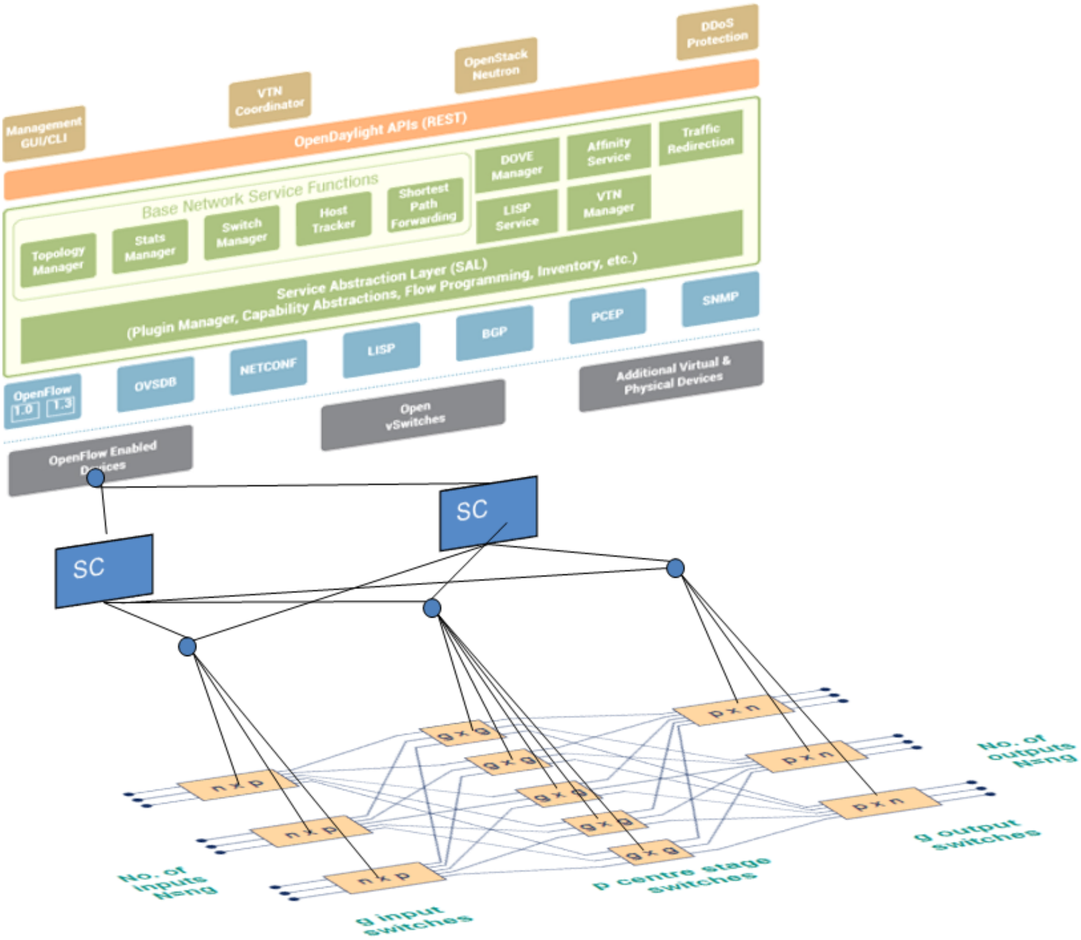


Figure 5-4 Shelf controller architecture for a multi-module switch fabric

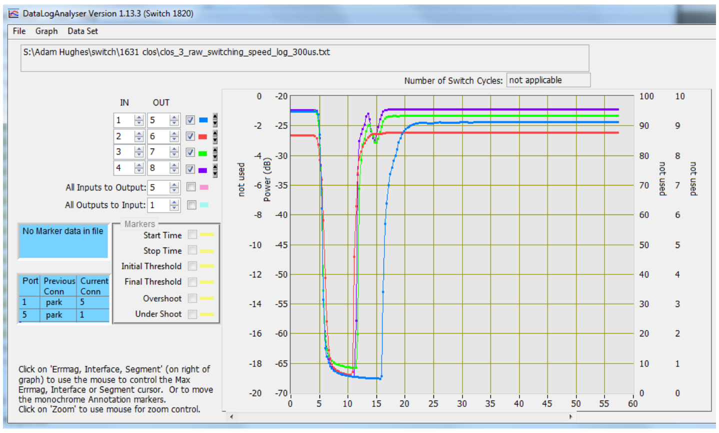
In the context of this project Polatis have implemented the first option, with the routing algorithm part of the "shelf controller" software (see Figure 5-4), because it makes the Clos switch fabric (the component switches plus shelf controller) become a more easily controlled SDN resource.

The multi-module router described in D6.3 has been implemented and tested as a component of the switch fabric, which has been reported in Milestone 19.

A rudimentary 3-stage optical switch was realized from seven available Polatis Optical Cross Connect (OXC) modules to prove the embedded routing algorithm and was shown to perform as predicted. The synthesised strictly non-blocking Clos architecture and routing algorithm worked as designed, allowing non-blocking connections between endpoints. Measurements of insertion loss and switching speed are in line with expectations (4dB of insertion loss and 20ms of switching time). The routing algorithm has been run successfully in simulation mode for 100x100 ports. Further work is in progress to test the algorithm against fabric sizes up to 12,000 single- and double-sided switch ports, and to test the control of larger numbers of components.

A 4x4 test switch was built using seven available component switches, with sizes ranging from 24x24 to 96x96. For testing purposes, we modified configuration files to create two input layer switches of 2x3, three centre stage switches of 2x2 and two output stage switches of 3x2. The positions of the active fibres within the switch were chosen to make the physical connection process and the software configuration (path map) as simple as possible. The switch functioned as a fully-connected three stage 4x4 switch. Insertion loss data and switching speed data was gathered for a representative set of cases.

The switching speed results showed connection times similar to those for a single module switch (measured 9 ms to 20 ms as shown **Figure 5-5** below). In one or two cases the switching trace showed a clear discontinuity, indicating that two of the component switches are completing the transitions at slightly different times. It is possible that in some of the measurements, only one or two of the switching components are actually switching because the routing algorithm preferentially uses the paths it finds first.



DataLogAnalyser Version 1.13.3 (Switch 1820)

S:\Adam Hughes\switch\1631 clos\clos_3_raw_switching_speed_log_300us.txt

Number of Switch Cycles: not applicable

IN	OUT	
1	5	☑
2	6	☑
3	7	☑
4	8	☑

All Inputs to Output: 5 ☐

All Outputs to Input: 1 ☐

No Marker data in file

Port	Previous Conn	Current Conn
1	park	5
5	park	1

Markers
Start Time ☐
Stop Time ☐
Initial Threshold ☐
Final Threshold ☐
Overshoot ☐
Under Shoot ☐

Click on 'Errmag, Interface, Segment' (on right of graph) to use the mouse to control the Max Errmag, Interface or Segment cursor. Or to move the monochrome Annotation markers.
Click on 'Zoom' to use mouse for zoom control.

Figure 5-5: Light levels when switching all four paths

5.1.3 *Photonic switching and add/drop functionalities supporting core network services*

The metro/core node transport technologies and architectures have already been identified and discussed in D7.1 (photonic switching functionalities) and in D6.1 (optical line interfaces) for supporting the core network services. In this sub-chapter we revise those architectural choices based on the latest information on reference networks size and dimensioning data. The proposed metro/core node photonic switching and add/drop functionalities dedicated to core network are based on Wavelength Selective Switches (WSSs) and Multicast Switches (MSs) as shown in Figure 5-6.

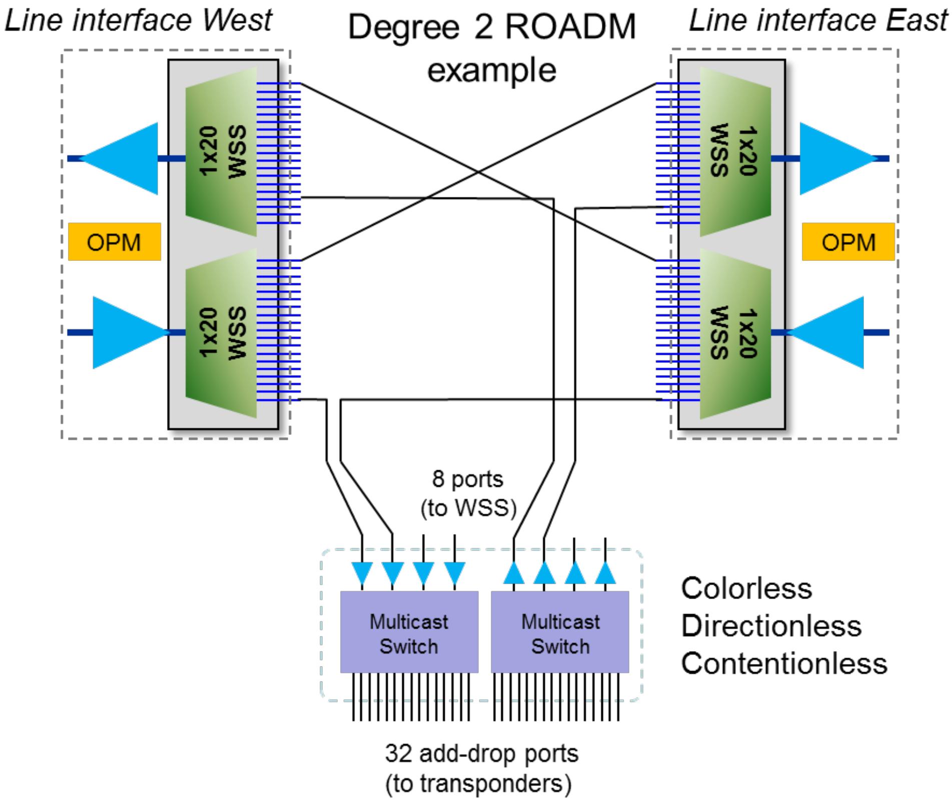


Figure 5-6: Example of Degree 2 ROADM of the photonic switching and add drop functions implemented by Wavelength Selective Switches and Multicast Switches. Only one add-drop block with 32 ports is shown in the picture, but additional blocks can be added if more add-drop ports are needed

This simple architecture has been selected among the ones proposed in D7.1 for the following reasons:

- It provides Colorless Directionless Contentionless (CDC) add/drop (A/D) thus enabling optical restoration without any wavelength blocking constraint in the end nodes;
- It provides flex-grid spectrum management functions improving the efficiency of spectrum utilization;
- The number of WSS and MS ports is compatible with the tentative dimensioning of the largest metro/core nodes of one of the most challenging DISCUS reference networks.

The last point deserves a further comment. A UK reference core network with 73 nodes is currently under study and some preliminary dimensioning data are available. In such a network the larger node has degree 7 and the number of add-drop ports required in some nodes is very large. Therefore we have decided to use 8x32 MS which recently have become commercially available.

From preliminary dimensioning results it also appears that in the most challenging traffic scenario, an optical bandwidth broader than the C band is required (see deliverable D7.7). Therefore we plan using WSS components with 100 nm bandwidth that can be built by three conventional WSS each covering 1/3 of the bandwidth [28].

The cost model of these components is taken from IDEALIST project [29] and is shown in Table 5-1.

The cost model and power consumption of these components are estimated scaling the cost and power consumption of the corresponding C band components as shown in Table 5-1.

Table 5-1 Cost and power consumption model of the photonic components

Item	Cost (ICU) (*)	Power consumption (W)	Number of elements in MC nodes
Dual WB WSS 1x20/20x1 (**)	1.5	60	1 for each line interface
Dual Multicast Switch 8x32 (**)	1.3	45	1 for each group of 32 transponders (***)
WB Raman Amplifier (**)	0.8	100	2 for each line interface

(*) the Idealist Cost Unit (ICU) is the reference cost unit of the IDEALIST [29] cost model and corresponds to the cost of a 100 G coherent transponder

(**) this component is not included in IDEALIST cost model and its cost has been estimated by TI

(***) additional components are required if the number of add-drop ports is larger than 32

The cost and power consumption model of the boards actually used in core network equipment that incorporate the described components is shown in Table 5-2.

Table 5-2 Cost and power consumption model of the photonic equipment boards

Item	Cost (ICU)	Power consumption (W)	Notes
Line interfaces	3.1	260	1 dual WB WSS and 2 WB Raman amp.
Line amplifier	1.6	200	2 WB Raman amp.

5.2 PACKET PROCESSING LAYERS INTERCONNECT

As described in deliverable D6.1, for a network provider the main requirements are for connection-oriented transport capabilities that can be achieved with the MPLS-TP (Packet Transport) framework. Its main characteristic is to have the control plane separated from the data plane. On the contrary, the MPLS framework (developed for L2/L3 switches and routers composing the service provider network) foresees an IP distributed control plane that does not allow creation of a Label Switched Path (LSP) with connection-oriented characteristics. This approach also represents the main evolution foreseen for next generation PONs. For these reasons, in D6.1 we have considered hybrid equipment called MPLS/MPLS-TP access switch and MPLS/MPLS-TP core switch, because they had to support at the same time the MPLS-TP core-oriented network services inside the network provider (NP) DISCUS network and the MPLS end-user oriented services between the OLT and the SP node.

The evolution of the SDN control plane concept allows us to generically re-name these equipment as the MPLS access switch and the MPLS core switch, because there will be no substantial difference between the MPLS and MPLS-TP approaches, in the sense that the DISCUS T-SDN control plane orchestrates, together with the service provider SDN control plane, can create an end-to-end LSP in a connection-oriented manner, according to the packet transport solution, both in the NP and SP domain.

It should be noted that MPLS grooming is preferred here rather than OTN grooming because of the native packet nature of data traffic, collected by LR-PONs. Ethernet framing is used since it is cheaper and standards over 10Gbit/s rates implement Forward Error Correction (FEC) over Ethernet frames. In some cases when using the appropriate modulation format, FEC usage might be mitigated. Where MPLS produces LSPs that reach huge bit-rate, then super-channel bitrate variable transponders (S-BVTs) are used to carry this traffic over multiple carriers.

Regarding the MPLS access and core switch designs, we must consider the MPLS protocol stack needed to support the end user services over all the DISCUS network (i.e. from the SP node border to the ODNs of the LR-PON), as already described in D6.1 and D6.3 deliverables. To summarize, the MPLS LSP is created inside the SP network and on the access switch connected to the Optical Distribution Networks (ODNs), thus identifying the SP and the access switch connected to the SP customers. Furthermore the VLAN, that in the specific case matches one-by-one with the MPLS Pseudo Wire (PW), identifies the service for each SP and for each OLT port. Therefore, the access switch manages VLANs, PWs and LSPs, while the core switch only manages the LSPs.

The detailed functional blocks design of the MPLS access switch, as described in D6.1, is represented in Figure 5-7, it shows the integration into the Access switch of the OLT and NT cards functionalities, and their evolution towards MPLS that properly matches the access switch design described in the same deliverable. Note that this implies an access switch with embedded OLT cards although the physical separation of the OLTs with smaller switches in separate shelves that interconnect to a larger access switch is also possible (as is often the case for OLTs today).

VLANs from/to ODN are mapped/de-mapped into MPLS PWs on the OLT card that has switching capabilities both at Ethernet level (MAC addresses and VLANs) and at MPLS PW level (for traffic switching between ODNs belonging to the same OLT card, or shelf). For the embedded OLT case, all the OLT cards inserted into the access switch are connected by an electrical backplane to the Network Terminal (NT) cards, where MPLS PW switching is available (for traffic switching between ODNs belonging to different OLT cards) as well as MPLS LSP switching (after LSP encapsulation/de-capsulation) to/from the SP service node or to/from the MPLS core switch or directly to/from the photonic layer.

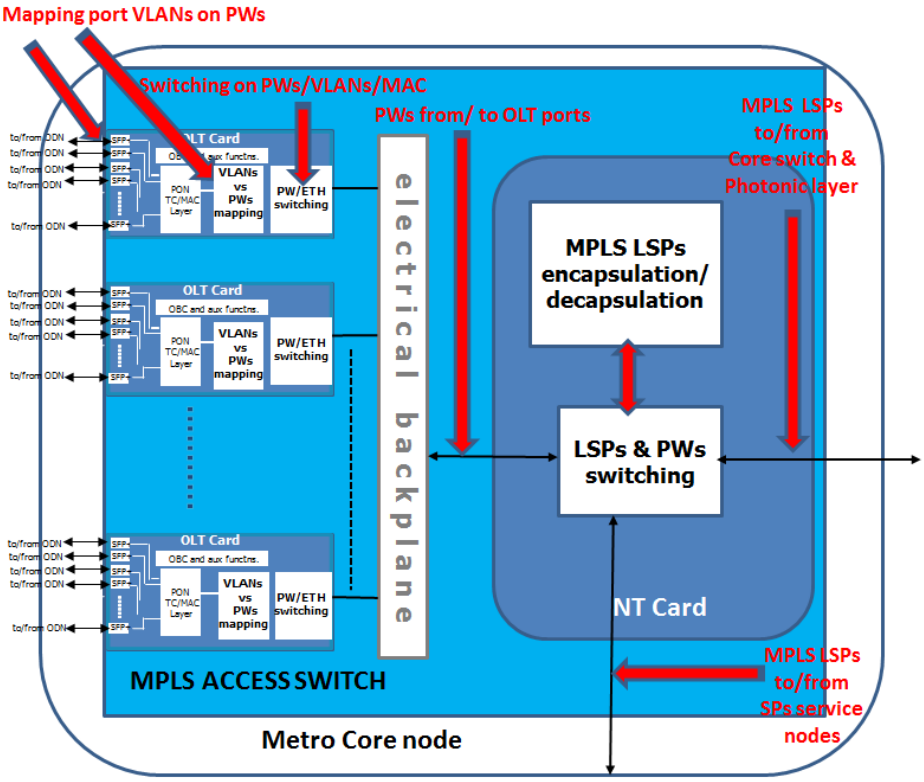


Figure 5-7 MPLS access switch detailed design in terms of functional blocks on OLT and NT cards

Considering the end user services implementation inside the access switch, Figure 5-8 illustrates the case in which the SP service edge routers (i.e. Broadband Remote Access Server BRAS, Provider Edge PE, etc.) are directly connected to the access switch, i.e. the case in which the SP customers are co-located with these edge routers. We can see that the E-LINE, E-LAN and E-TREE services (as described in D6.1) are linked to the corresponding PWs and the VSI (Virtual Service Instance) is used to perform PW switching. In particular, a hierarchical PW switching is available either on the OLT card (if switching involves customers attached to different ODNs connected the same OLT card) or on the NT card (if switching involves customers attached to ODNs connected to different OLT cards).

Operation, Administration and Maintenance (OAM) over the DISCUS network is of paramount importance in order to allow fast protection mechanisms. In recent years, IETF standardization on MPLS, and its cooperation with ITU-T on MPLS-TP requirements, led to OAM tools both in the MPLS and in the MPLS-TP domains which work at data plane level and support proper protection mechanisms for both of them.

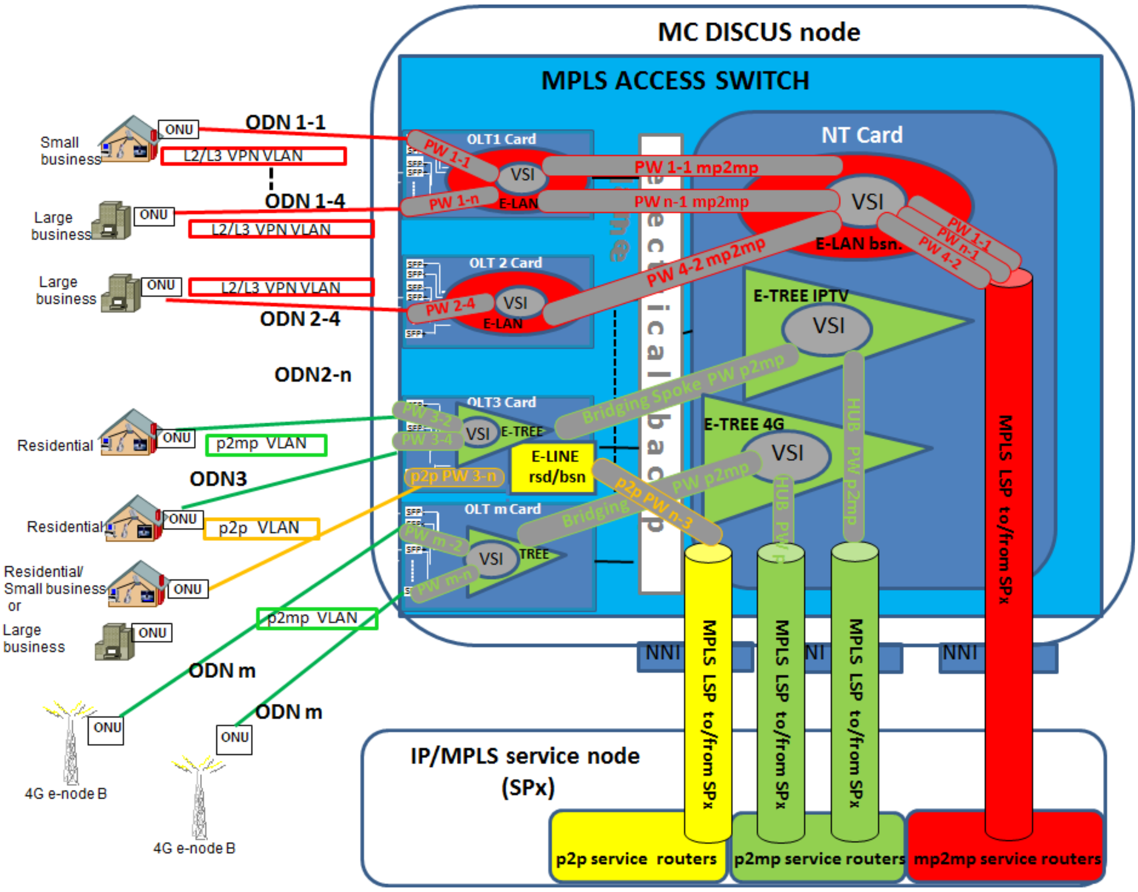


Figure 5-8: End user oriented network service support on access switch: 1) Ethernet VLANs encapsulation over PWs; 2) PWs switching for E_LAN and E-TREE services mediated by VSI; 3) transport over MPLS LSPs to SP edge service routers

In the context of the SDN approach developed in the DISCUS project, the network provisioning should include some OAM configuration on PWs and LSPs but, in order to have fast failure detection, the SDN control plane should be supported by OAM data plane protocols. In particular, considering the DISCUS service model, the OAM & protection implementations could be developed as described in the following:

Regarding *OAM monitoring*, the following functionalities must be taken into account.

- *End-to-end OAM on PW* from the OLT access side to the SP service node: this OAM can be properly managed with VCCV (Virtual Circuit Connectivity Verification), according to MPLS IETF standard *RFC 5085*. Since it is an inter-domain PW OAM, coordination between NP and SP domains is needed, supported by the DISCUS and the SP SDN control planes;
- *End-to-end OAM on LSP* and *OAM on sub-LSP in DISCUS domain:* the final evolution towards a generic MPLS LSP can lead to a common OAM (developed starting from the 2 possible standardized implementations described below) for the end-to-end LSP, with a Sub-Path Maintenance Elements (SPMEs) Tandem Connection Monitoring (TCM) for LSP OAM in the DISCUS domain. The two OAM mechanisms could be the following ones:
    - considering that the SDN approach leads to explicitly routed MPLS LSPs, the more obvious OAM choice would be an OAM inspired by MPLS OAM ITU-T standard

Y.1711 and MPLS-TP ITU-T standard *G8113.1/2* (based on Continuity Check-CC, Connectivity Verification-CV, Fast Failure Detection – FFD, etc.); in this case SDN control planes in DISCUS and SP network should manage the different OAM labels (Alert Label 14 for MPLS and G-ACH Label 13 for MPLS-TP) presently established by *RFC 5586* & *RFC 6423*, *RFC 5654* and *RFC 5860*;

- another OAM approach could be based on MPLS-BFD (Bidirectional Forwarding Detection) signalling, that has been developed for MPLS and MPLS-TP (see *RFC 4379* &*RFC 5884* as well as *RFC6428*). Also in this case the DISCUS and SP SDN control planes should coordinate network updates into their databases, after failure detection at data plane level, in order to properly support protection.

Regarding *Protection*, D6.3 has foreseen PW and LSP redundancy in order to support network protection on a back-up OLT and a back-up MC node. PW and LSP redundancy are useful for end-to-end protection, from the ODN side to the SP active or stand-by router. This means that an inter-domain coordination between DISCUS and SP networks must be implemented at SDN level. For protection from failures occurring inside the DISCUS domain, a sub-LSP OAM signalling must be exploited, where we can see that the active PW is encapsulated both on the active LSP and on the stand-by sub-LSP. In this way, a failure occurring inside the NP domain does not involve the SP domain, i.e. it doesn't involve the back-up PW and the back-up end-to-end LSP, still maintaining available the connection to the SP active service edge router.

In details, the required protection functionalities are described in the following.

- *PW redundancy* means that a back-up PW is used, for a certain SP service VLAN, from a back-up OLT through a back-up MC node to a back-up service edge router in the SP domain. The MPLS PW OAM can properly support it, with the IETF standard R*FC 6718*, also augmented with BFD (*RFC 5880*) for faster time convergence (*RFC5885*). As usual, a coordination between NP & SP SDNs is needed.
- *LSP protection with back-up LSP* can exploit one of the two possible OAM solutions described above, in order to have a common protection behaviour on the generic end-to-end MPLS LSP. In the first case, the IETF *Y.1720* and ITU-T *G.8131* standards are available. In the second case, a 1:1 LSP protection mechanism based on MPLS-BFD OAM (like the one used for MPLS-TP) can be considered, with a coordination through SDN with the SP that, at present, can use the Loop Free Alternate Fast Re-Route (LFA-FRR) protection mechanism (*RFC 5286*). Sub-LSP protection inside the DISCUS network is available with the support of the OAM sub-path connection monitoring (SPME TCM).

5.3 CONTROL PLANE

The DISCUS SDN control plane is composed of three main logical component (see Figure 5-9): the access network controller, in charge of controlling the access network elements; the core network controller, in charge of controlling the elements carrying out core transmission; the network orchestrator, in charge of taking requests from the SP and translating them into high-level commands for the access and core network controllers. A similar view, but with direct relation to the DISCUS MC node architecture is shown in Figure 5-10.

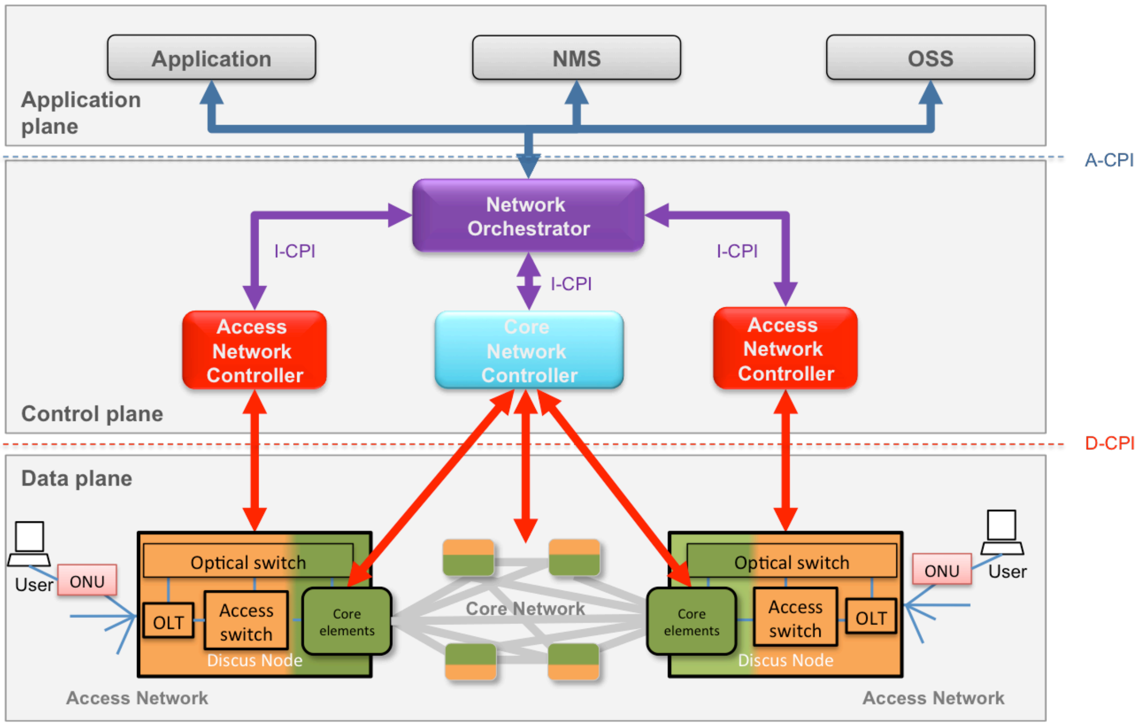


Figure 5-9 DISCUS control plane design following the ONF architectural views

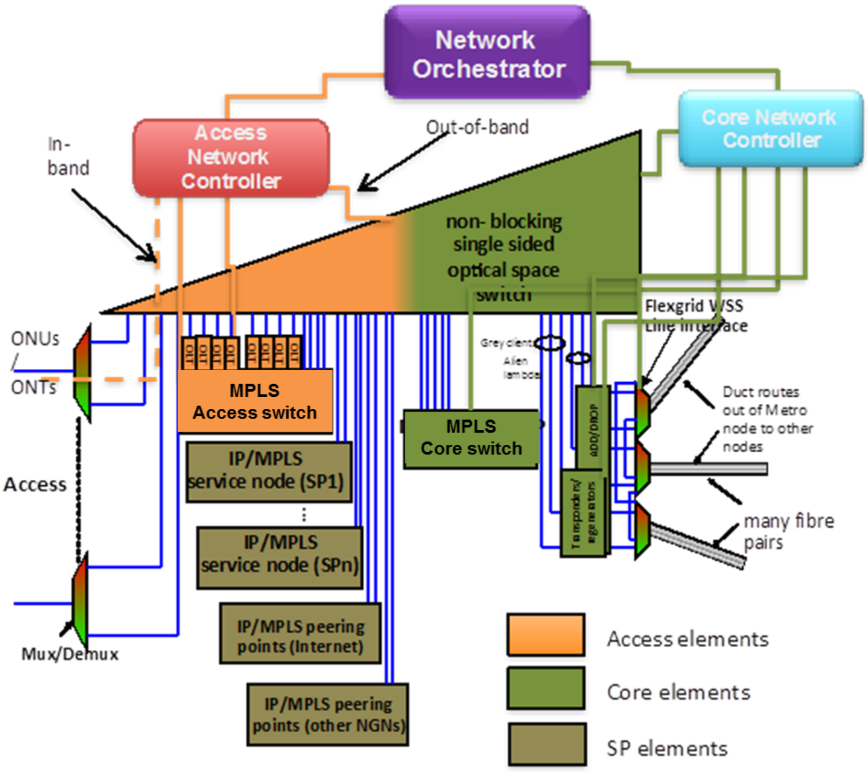


Figure 5-10 DISCUS control plane architecture with the MC node

Following this hierarchical architecture, any service request is sent by an SP to the orchestrator, which calculates a high-level path in the network and then converts the service request iteratively into sub requests towards the source and destination access network controllers and the core network controller. While highly modular and pragmatic, the main drawback is the lack of scalability due to the fact that all service requests are centrally handled by the network orchestrator, even those that do not require orchestration among different controllers.

Although the DISCUS control plane software implementation (see D6.5) has addressed specifically this fully centralized scenario, we have envisaged the possibility that the access network controller could handle part of the requests without involving the orchestrator. These are the requests where both ends of the connections lie within reach of the same MC node, thus do not require core transmission services. This concept is shown in Figure 5-11 and shows a direct link from the application plane to the access network controllers, which handles most of the requests from SPs, and decides whether the service can be handled locally or requires involvement of the network orchestrator. For example if the service involves interaction with another MC node, the access controller sends an appropriate request to the orchestrator in order to coordinate the interaction with the other controllers.

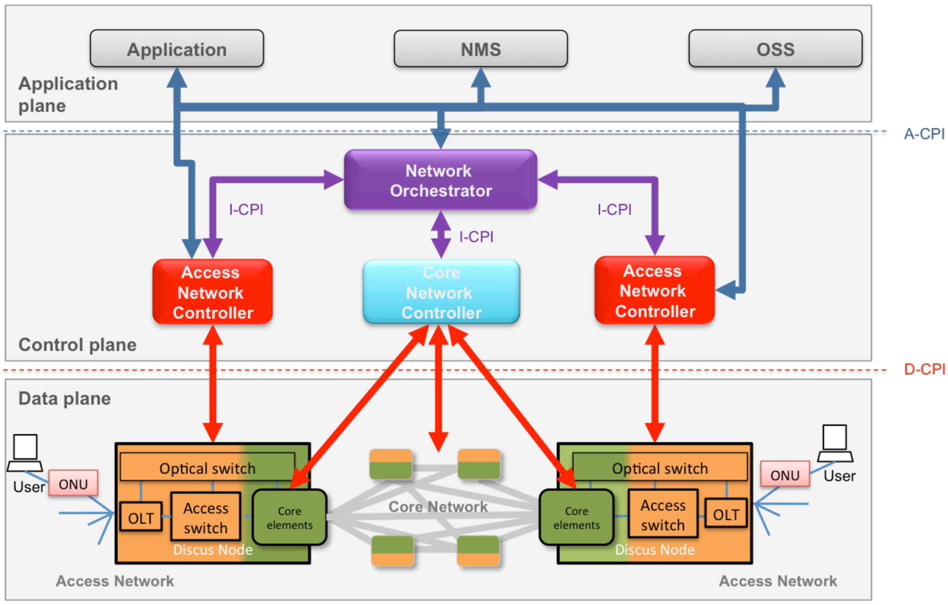


Figure 5-11 Variation on the DISCUS control plane design, where the SP can forward requests to the access controller.

5.3.1 Network orchestrator

The network orchestrator is defined as a parent controller or a centralized "controller of controllers", which handles the automation of end-to-end connectivity provisioning, working at a higher, abstracted level and covering inter-domain aspects between the access and the metro/core network. The network orchestrator has the following functionalities:

- **Communicate with the Applications, NMS or OSS for service requests.** Applications, Network Management System (NMS) or Operation Support System (OSS) can request provisioning of services. The request may contain the information about the service and the parameter required for the connection.

- **Translate the abstract link parameters into controllers' interface.** The service parameters must be translated to the A-CPI controllers' parameters.
- **Obtain abstracted network view from the controllers.** The network orchestrator interfaces with the controllers to get topological information about the resources in each controller's domain. This information must be technologically abstracted, so the physical domain details are dealt by the controller not by the orchestrator.
- **End-to-end (E2E) path computation.** The network orchestrator requires the support of a mechanism to obtain an E2E path computation. The orchestrator can either compute the path entirely by itself, based on its abstracted information, or else rely on the controllers to compute parts of the path.
- **Multi-technology configuration.** Each controller may have different interfaces, which requires the orchestrator to have a method to support multiple technologies or interfaces.
- **Determine service establishment.** The network orchestrator requires notifying if the service is created properly. This function relies on the feedback from the different controllers of each region.
- **Failure identification.** The orchestrator must have an interface to receive alarms from the network controllers.

Since the network controller does not require a D-CPI interface, its implementation is not tied to platforms with OpenFlow or GMPLS control planes. However basing its implementation on an SDN platform (e.g., RYU, Floodlight or OpenDaylight) allows a seamless integration with the network access and core controllers.

The abstract architecture of the orchestrator is shown in Figure 5-12. The interface to the SP is implemented on a JSON-based REST/API A-CPI interface, while OSS and NMS can use a more feature-rich I-CPI interface. Besides the controller unit, that coordinates the interaction among the multiple blocks, there are two main modules: the topology discovery and abstraction module, which is in charge of receiving topology information from the access and core network controller and turn it into an abstract connected graph that hides the physical details of the links; the path computation module, which is in charge of using the abstracted topological information to find a path between two end-points. E2E paths can occur between two MC nodes, in which case topological information about the core is also utilized, or else within the same MC node.

Finally, there is an I-CPI interface for communicating with the access and core network controllers, implemented as JSON-based REST/APIs. The Network Configuration Protocol (NetConf) and the Path Computation Element Protocol (PCEP) interfaces will be considered for gathering topology discover information.

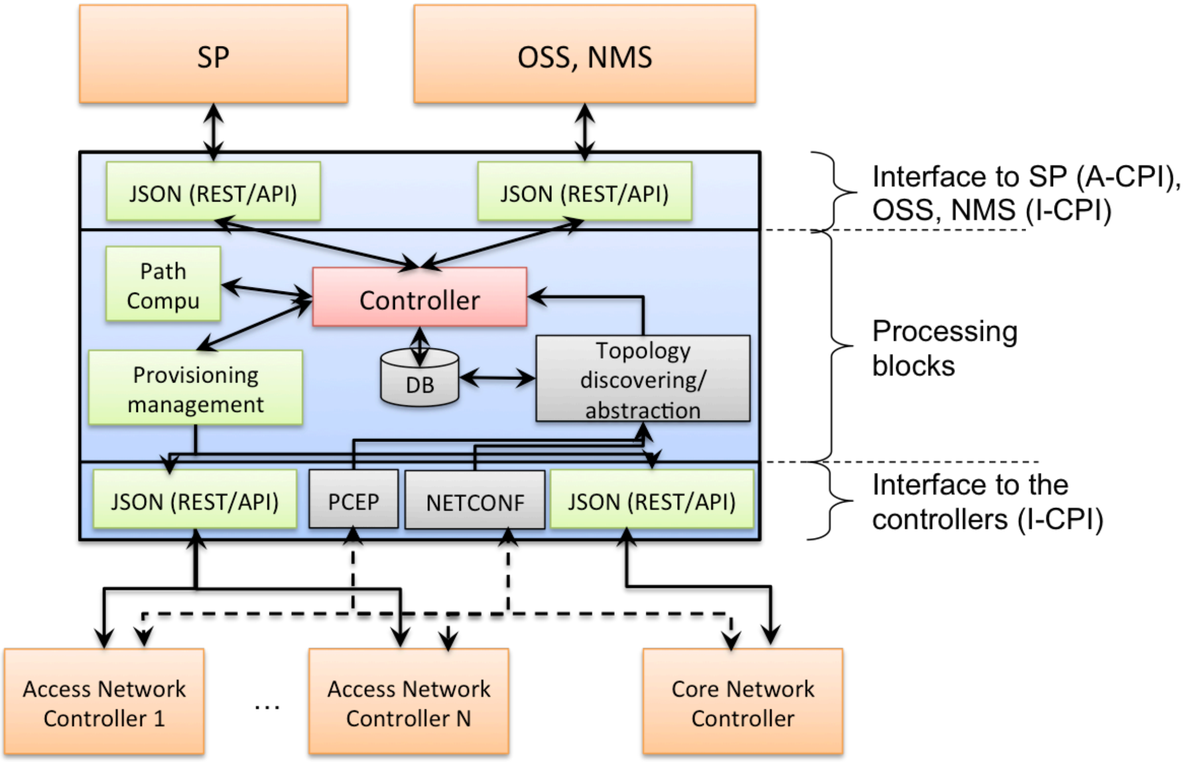


Figure 5-12 Network Orchestrator architecture

5.3.2 Access network controller

The access controller is required to operate the following actions upon request from the network orchestrator or the SP:

- **Communicate with the SP for service requests[1].** Receive provisioning requests, use an adequate addressing/labelling mechanism to identify end points (end users, SPs,…).
- **Communicate with the orchestrator for requesting core link capacity.** Where the link requests involve other MC nodes, the origin MC node requests the orchestrator for link capacity.
- **Determine whether there is enough capacity to handle a request.** This implies the assessment of bandwidth availability to connect the selected end user with the selected output port of the access switch. The node controller will assess available capacity at the access switch and ports, at current OLT, other OLTs, or spare point-to-point wavelengths and, where required, at the optical switch. This includes the case where both ends of the link request lie within the same MC node: for example when providing a dedicated link between two end users in the same MC node; or linking a user to a service provider that is located at the same MC node (either by directly connecting to the access switch or else by offering its service from one of the MC PONs).
- **Export abstracted network view to the controllers.** The access controller has to send abstracted topological information with the resources in its domain. To do

---

[1] This is only required when the architecture variation described in Figure 5-11 is considered

so, the physical domain details have to be mapped in the abstracted information required by the orchestrator.

- **Translate the abstract link parameters into appropriate (OpenFlow) commands for the southbound interface:**
    - For access switch: flow entry, QoS parameters, protocol tags, flow deletion, flow modification.
    - For OLT: GPON Encapsulation Method (GEM) ports and VLAN mapping/translation, DBA configuration (including QoS parameters), wavelength control, ONU configuration, Add/remove ONU/ONT.
    - For optical switch: port connection/disconnection, power measurement, power alarm.
    - For ONU/ONT: Traffic Container (T-CONT)/GEM ports and C-VLAN mapping/translation, move to different OLT (backup in case of OLT failure or fibre cut in protected feeder fibre scenario), use point-to-point channel on selected wavelength. Typically this can be accomplished by a conversion of OpenFlow commands to the ONU Management and Control Interface (OMCI) in PONs.
- **Operate QoS of individual or aggregate flows.** Connection Admission Control (CAC) mechanisms, capacity reservation, rate limiting.
- **Failure identification.** Detect alarms triggered by external failure management systems.
- **Feedback about the connectivity services.** The access network controller has to notify if the service is created properly or if there is any problem with the connection.

The differentiation between the network orchestrator and the access and core controllers is only logical, meaning that from a physical point of view all software components might be co-located (i.e., in the same data centre, servers, machine, etc.) or reside somewhere in the cloud. An access network controller is associated to every metro/core node, where it controls the optical switch, access switch, and OLTs/ONUs. An Ubuntu Linux server is used to run the SDN node controller in the DISCUS control plane implementation, running RYU as controller. RYU was selected as it provides software components with well-defined APIs that make it easy for developers to create new network management and control applications and supports several protocols for managing network devices, such as OpenFlow (1.0, 1.2, 1.3, and 1.4), NetConf, OF-config, and etc.

Figure 5-13 shows a schematic of the node controller architecture and its interaction with the network orchestrator. A JSON (REST/API) interface is used to communicate with the orchestrator, which, where required, calculates end-to-end paths and then requests them to the destination node controllers. An additional JSON interface allows communication with the SP.

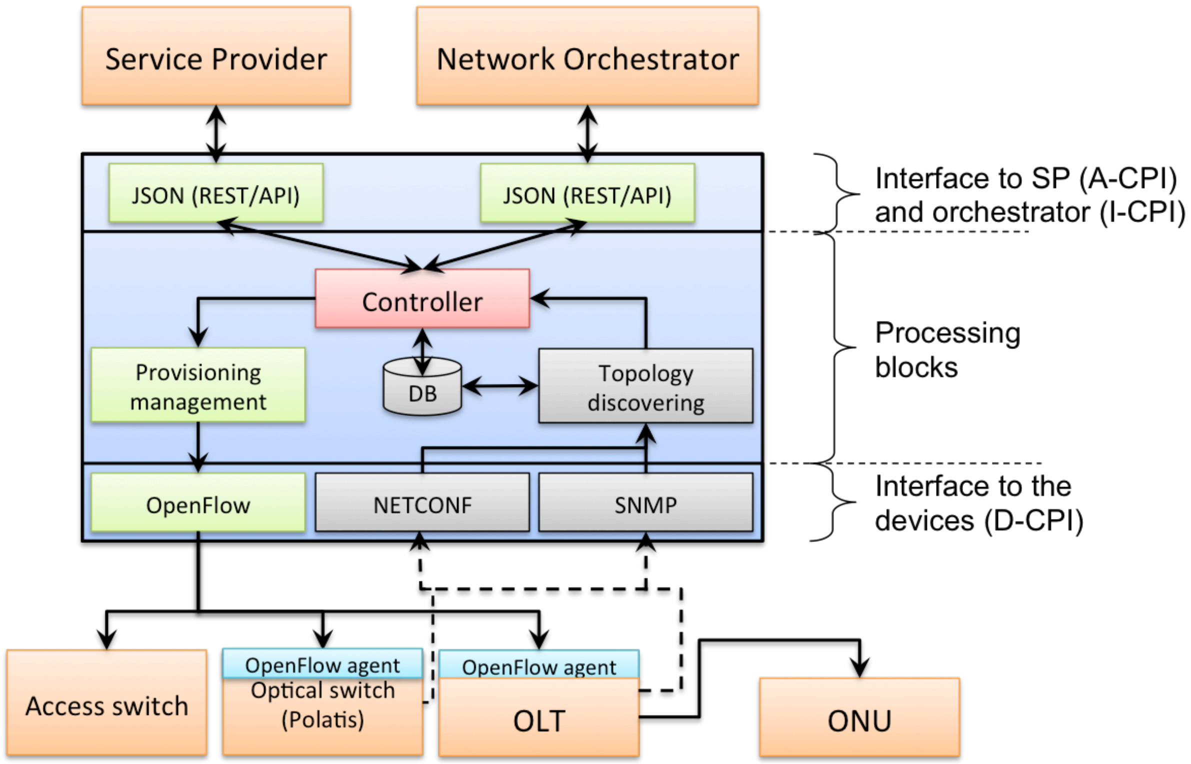


Figure 5-13 Access network controller architecture

After receiving a request from the orchestrator, the JSON (REST/API) interface passes the information to the main controller processing block, which checks the database for available capacity and ports. Topology information, together with bandwidth reservation information is stored in the database. If the request can be satisfied, the controller sends a confirmation to the SP/orchestrator and instructs the provisioning manager to carry out the appropriate actions to create the connection on the access side. The provisioning management block will translate the incoming actions into messages for the appropriate protocol that can be handled by the physical devices.

The grey blocks include protocols and modules used to maintain and manage a map of the network topology.

5.3.3 Core network controller

The core controller is in charge of receiving commands from the network orchestrator and transforming them in the D-CPI for the metro/core network. The envisaged technologies for the underlying network are Wavelength Switched Optical Network / Spectrum Switched Optical Network (WSON/SSON) networks which are based on the GMPLS distributed control plane. The core network controller has the following functionalities:

- **Communicate with the network orchestrator and NMS for service requests.** The network orchestrator can request for service provisioning requests. However, the core controller can expose its interface to other systems like the NMS. The higher interface will be based on connectivity services on the metro/core network.
- **Translate the connectivity service parameters into D-CPI.** The connectivity service parameters must be translated to the D-CPI parameters. The core network typically uses GMPLS technologies.

- **Export abstracted network view to the controllers.** The core controller has to send abstracted topological information with the resources in its domain. To do so, the physical domain details have to be mapped in the abstracted information required by the orchestrator.
- **Carry out domain path computation.** The core controller has to obtain a path from the abstracted provisioning request from the network orchestrator. The controller receives a request based on the abstracted information that the controller has, so it has to translate this connectivity service request into a feasible path based on its implementation.
- **Feedback about the connectivity services.** The core network controller has to notify if the service is created properly or if there is any problem with the connection. Moreover, the core controller must have an interface to receive alarms from the network controllers.

The preferred option for the implementation of the core controller is the Application-Based Network Operations (ABNO) [30] architecture. ABNO is composed by several modules but the most important ones to cope with the functionalities for DISCUS is presented in Figure 5-14. The ABNO Controller is the main component of the architecture and is responsible of orchestrating the workflows, and invoking the necessary components in the right order. ABNO stores a repository of workflows with operations in the network (MPLS provisioning, L3VPNs, etc.). The Path Computation Element (PCE) is the unit that handles the path computation across the network graph. If the PCE is active, it can directly operate in the nodes to create LSPs. The Topology Module (TM) has multiple databases: a view of each layer, an inter-layer relation and an inventory DB with the configuration parameters of each of the resources. Finally, the Provisioning Manager (PM) is the unit in charge of configuring the network elements. It can do this in two ways: by configuring the resources in each node (CLI, OF or NetConf) or by triggering a set of actions to the control plane via PCEP.

Based on the previous network architectures (GMPLS and OpenFlow) we consider that the DISCUS node requires to have NetConf/PCEP or OpenFlow to support the requests from the core network controller in the metro/core scenarios.

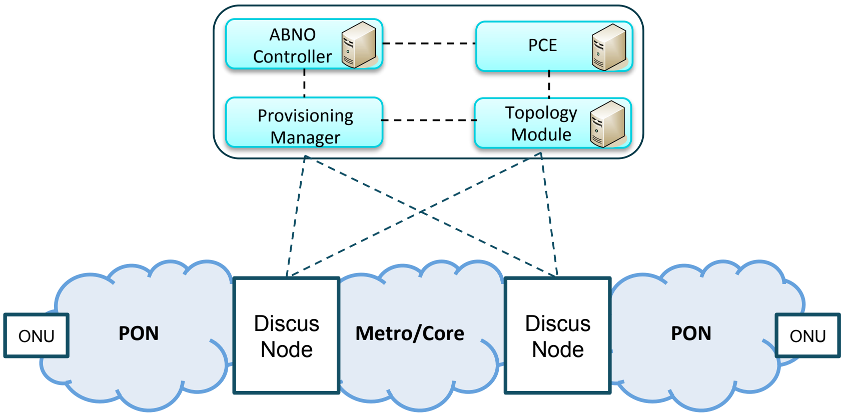


Figure 5-14 ABNO-based Control Plane Architecture for DISCUS

6 THE FLAT OPTICAL CORE NETWORK

The purpose of this section is to provide an outline of the DISCUS core architecture summarizing the entire design process from the initial requirements definition to the last dimensioning outcomes.

6.1 Core architecture drivers

The DISCUS core architecture drivers are based on ITU-T standard architectural requirements, scalability, cost and energy efficiency, and seamless evolution criteria. The whole set of DISCUS core network drivers can be summarized as follows.

- The DISCUS core architecture is based on the concepts of ITU Recommendation Y.2011 on the function separation between the service stratum and the transport stratum. Specifically, the DISCUS core network will provide:
    i) circuit transport services for the IP layer considered in its present architecture and possible evolutions in a 5 year time frame;
    ii) connections with other networks or service providers wherever needed;
- Seamless architectural evolution:
    iii) DISCUS core architecture will be defined to seamlessly evolve in parallel with IP networking evolution (e.g. change of peering points number and traffic patterns)
- Traffic scalability and cost and energy efficiency:
    iv) DISCUS core architecture will exploit innovative photonic technologies as much as possible to ensure scalability, cost and energy efficiency;

The first driver is directly derived from ITU-T Recommendations Y.2011 and Y.2012, however, the kind of transport services provided by the core network may range from layer 1 to layer 3 with different technologies options. In optical networking community it is a common opinion that layer 3 transport, i.e. the transport and switching of IP packets by means of routers, is neither cost nor energy efficient based on present IP routers characteristics. On the contrary, circuit switched ROADM/DWDM technology represents the technology of choice for todays and future transport networks, and therefore it is selected as the reference technology of the DISCUS core network as well. The main features of this technology are concisely described in the following paragraph together with their advantages for DISCUS core network.

6.2 Photonic layer and transmission technologies

The DISCUS core network is composed by a single photonic layer based on ROADM switching nodes and DWDM transmission systems. In the following the main characteristics of such technologies are outlined and a general approach to transparency islands design is proposed.

Uncompensated DWDM systems based on coherent optical channels spaced close to the Nyquist limit are already available and will become soon the state of the art in transmission technology. Therefore they represent the reference transmission technology for DISCUS core network. Their main characteristics are:

- baud rate up to 32 Gbaud;
- configurable modulation format: DP-BPSK, DP-QPSK, and DP-16QAM corresponding to 40, 100 and 200 Gbit/s per carrier (DP-8QAM corresponding to 150 Gbit/s may be considered as well);
- DSP and digital to Analog Converters in the transmitter enabling electrical spectral shaping and very tight channel spacing;
- soft decision FEC with coding gain higher than 10 dB.

A non-negligible advantage of such systems is that their performance can be accurately predicted not only by time consuming numerical simulations but also by more practical semi analytical model.

A well-known characteristic of coherent optical transmission is the trade-off between system reach and spectral efficiency: the longer the reach the lower the spectral efficiency that can be achieved. Moreover, a transparent transmission distance of more than 2 thousand kilometres can be obtained with PM-QPSK modulation format on G.652 fibres. In case of shorter transmission distance, higher spectral efficiency modulation formats can be used leading to a better optical spectrum exploitation.

Based on this characteristic, the concept of transparency islands as envisaged in DISCUS original proposal can be revisited: the whole core network can be a single transparency island where modulation format is adapted to the traffic demands reach requirements. This concept is shown in Figure 6-1 and will be the preferred option for DISCUS photonic layer.

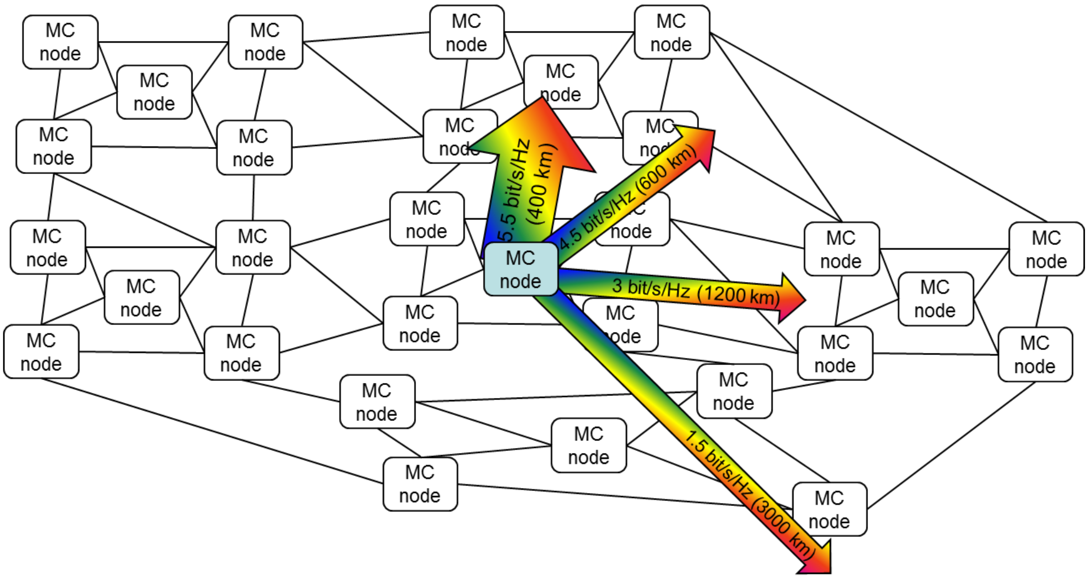


Figure 6-1 Fully transparent photonic layer based on modulation format-adaptive transponders

The photonic layer is fully flat network and all photonic connections between any couple of nodes are transparently feasible (in case some traffic paths are longer than the maximum achievable reach, appropriate regenerators allocation strategies will be adopted).

Capacity and efficiency of this kind of photonic layer can be improved if flexible DWDM grid is used. The flexible grid concept has been standardised in the last version of ITU-T Recommendation G.694.1. According to this standard, the grid is organized in 12.5 GHz slots that can be grouped to form a wider bandwidth optical channel whose centre frequency can vary in steps of 6.25 GHz.

A simple example of the improvements that can be achieved using flexible grid instead of the normal 50 GHz DWDM channel spacing is the increase in channel number. Considering 32 Gbaud optical channels with a properly shaped spectrum, their spacing can be decreased from 50 to 37.5 GHz and therefore the total channel number in C band rises from typically 88 to perhaps 120. The total link capacity increases accordingly.

In a more sophisticated approach, bandwidth variable transponders may be used to generate optical channels and super channels (i.e., aggregation of optical channels that are switched together in the ROADMs) to fully exploit flexible grid potentials.

Appropriate strategies to exploit flexible grid and bandwidth variable transponder in DISCUS core network have been investigated in relevant deliverables.

6.3 DISCUS core network as an evolution of European backbone networks

At the time of project proposal, the DISCUS core network was envisaged as a photonic backbone segmented in transparency islands, i.e. network domains where all connections are provisioned transparently through DWDM line systems and ROADMs. Transparency islands are interconnected with each other in selected boundary nodes where optical channels are regenerated. This architecture is typically adopted in large backbone networks where a non-negligible number of circuit paths is longer than the maximum transparent transmission distance of the selected transmission technology (referred to as “reach” in the following). Transparency islands represent a possible way to cope with this problem.

While progressing in the definition of DISCUS core network architecture and reference optical transmission technologies, it has emerged that:

1. today’s coherent DWDM systems provide a plurality of modulation formats characterized by given spectral efficiencies and OSNR sensitivities (that in turn translate into a specific reach for every modulation format and fibre type);
2. the reach of DP-BPSK modulation format is of the order of 2400 km for systems operating on G.652 fibres, while DP-QPSK and DP-16QAM have a reach of the order of 1200 and 500 km respectively (see deliverable D7.2);
3. even the larger European countries’ national backbones have diameters of 2200 km and therefore they can be regarded as single transparency islands.

The last statement is supported by studies performed by ICT STRONGEST project.

ICT STRONGEST has developed very realistic backbone models based on real network infrastructure, tailored on the largest European countries: Germany, Great Britain, Italy and Spain. The main characteristics of such reference networks are shown in Table 6-1, together with the main geographic and demographic data of each country.

Table 6-1 Main characteristics of optical backbones of Deutsche Telekom (DTAG), British Telecom (BT), Telecom Italia (TI) and Telefonica (TID). From ICT STRONGEST deliverable D21

	TID	TI	BT	DTAG
Number of network sites	150	292	1113	987 (1975)[1]
Number of fibre links	319	513	1955	3911
Nation area	505,000 km^2	301,000 km^2	219,000 km^2	357,000 km^2
Nation population	47 million	60 million	61 million	82 million
Average area per site	3,370 km^2	1,031 km^2	197 km^2	362 km^2

It is evident that the number of nodes of these networks is larger than the one foreseen in DISCUS (of the order of 100 for a country like Great Britain). Nevertheless, from the optical path length distribution of these backbones shown in Figure 6-2 we can derive a consistent estimation of the DISCUS core network diameter for large countries (the network diameter is defined as the maximum of the set of shortest path lengths between all couples of network nodes).

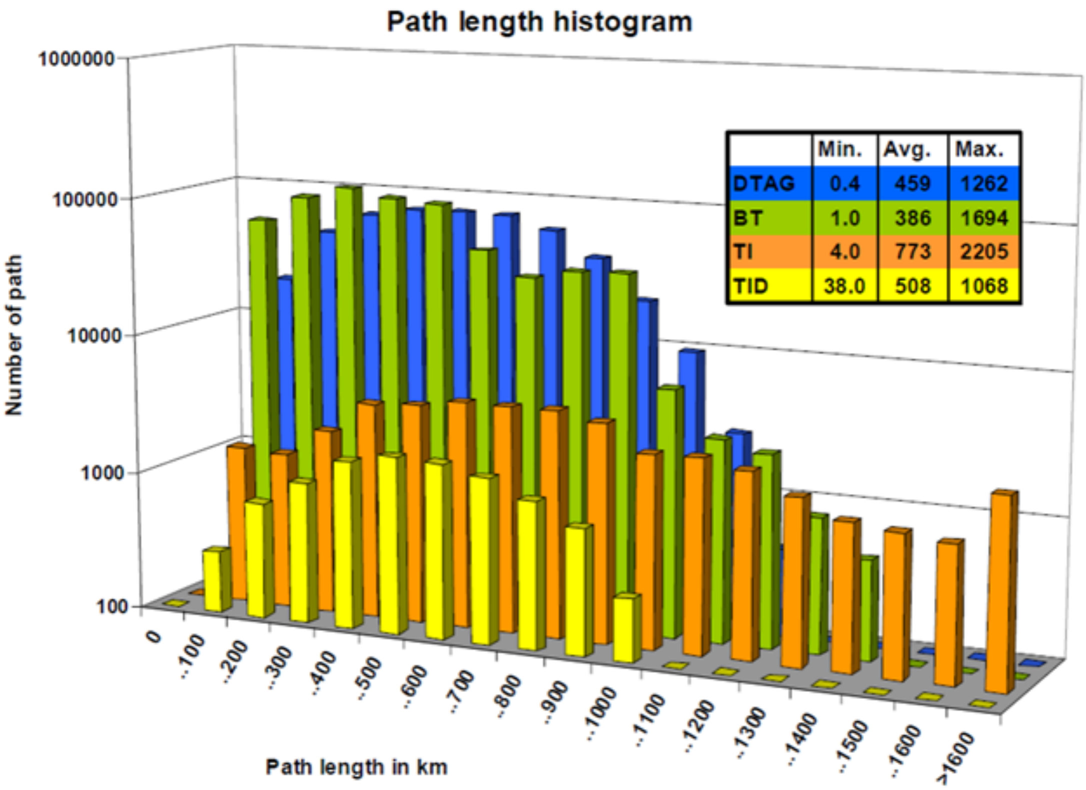


Figure 6-2 Histogram of optical backbones path lengths of Deutsche Telekom (DTAG), British Telecom (BT), Telecom Italia (TI) and Telefonica (TID). From ICT STRONGEST deliverable D21

We see that the longer network diameter is the one of Telecom Italia backbone (2205 km) followed by the one of British Telecom (1694). Spanish and German backbones diameters are in the range 1000 – 1300 km. These relatively large network diameters of Italian and British backbones are probably due to the peculiar geography of the two countries whose shape is rather long and narrow compared to Germany and Spain.

These network diameters do not coincide necessarily with the maximum length of light paths, that depends on the traffic pattern, but they represent an upper bound.

From these data one can conclude that the DISCUS core network can be designed as a single transparency island even in large European countries.

The main benefits of this approach compared to multiple transparency islands are:

- CAPEX, OPEX, and energy savings due to optoelectronic regenerators complete elimination;
- Elimination of routing constraints for traffic crossing transparency island borders through predefined gateway nodes.

6.4 Transparent network with sparse Raman amplified links

In this subsection, the new concept of transparent network with sparse Raman amplified links is presented as a viable improvement for the DISCUS core network.

Raman amplification is a well-established technology suitable for increasing system reach in a much cheaper way compared to regeneration.

The main characteristics of Raman amplification are:

- the transmission fibre is used as the active medium;
- pump power is injected at the receiver side (counter-propagating) or at the transmitter side (co-propagating) of the transmission fibre;
- like EDFAs, a Raman amplifier works on the whole DWDM aggregate and its cost is of the order of an EDFA;
- Raman amplification is typically used in combination with EDFAs with a remarkable reduction of the equivalent noise figure of EDFAs and therefore of the link OSNR.

In terrestrial systems, counter propagating Raman amplifiers with pump power of the order of 500 mW, typically give a 3 dB reduction of the equivalent noise figure of the EDFAs and, if used in all links, they allow doubling the transparent transmission reach with respect to a transmission technology based solely on EDFAs.

In DISCUS core network, it is unlikely that transmission reach doubling is needed on all lightpaths (see deliverable D7.2 results), and therefore an architecture with a limited number of sparse Raman amplified links is proposed as shown in Figure 6-3.

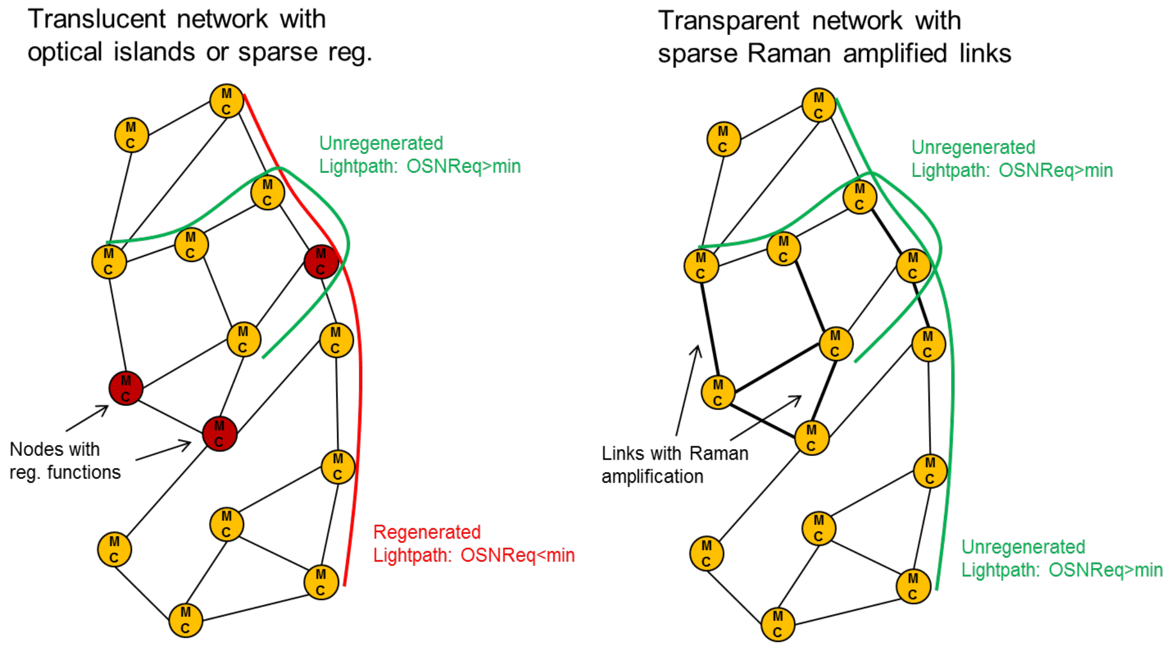


Figure 6-3 Translucent network with sparse regeneration nodes (on the left), and transparent network with sparse Raman amplified links (on the right). In the latter network regenerators are replaced by Raman amplified links thus obtaining a fully transparent network

The development of this network concept require two basic tools: a transmission degradation model which includes Raman amplification and a network optimization strategy to minimize the number of Raman amplified links in the network.

As far as it regards the transmission degradation model, the one already described in deliverable D7.2 and suitable for EDFAs only, has been updated with Raman amplification formulas.

The problem of optimizing the transparent network with Raman amplified links is briefly outlined here.

The Raman amplified links can be allocated heuristically considering that typically all the longest lightpaths pass through a limited number of common links located in the central part of the network. Rigorous design criteria can be envisaged as well as described below.

The problem of minimizing the number of Raman amplified links can be stated as follows: minimise the number of Raman amplified links that makes the network transparent for a given modulation format on all shortest paths (i.e. the OSNReq of all shortest paths is higher than OSNReq, min characteristic of that modulation format). The optimization procedure can be outlined as follows:

1. OSNReq of all shortest lightpaths is calculated using the formulas of deliverable D7.2 (updated to include Raman amplification);
2. The set of shortest lightpaths whose OSNReq is lower than a given modulation format threshold OSNReq,min is considered (non-transparent lightpaths);
3. Raman amplifiers are progressively introduced in the links that are shared among the maximum number of non-transparent lightpaths unless their OSNReq becomes higher than OSNReq,min;

4. If some non-transparent lightpaths remains after the previous step, further Raman amplified links are heuristically introduced in the network.

This procedure can be repeated for the second shortest paths to guarantee protection and possibly to the third one for enhanced resilience.

The procedure can be repeated also for other modulation formats (i.e. setting other values of OSNReq,min).

6.5 Architectural updates based on core network dimensioning

A first update of the core architecture has become necessary looking at the dimensioning results of the UK reference core network with 73 nodes. It appears that in the most challenging traffic scenario, an optical bandwidth broader than the C band is required (see deliverable D7.7). Therefore we plan adopting wideband Raman amplification technology and ROADM nodes with WSS components supporting 100 nm bandwidth.

Another central result coming from early dimensioning studies is that, even using wideband components, the number of ports of 1x20 WSS is not sufficient to accommodate all add-drops and lines in many of the network nodes. Therefore in those nodes we will adopt the stacked OXC architecture already presented in literature and shown in Figure 6-4.

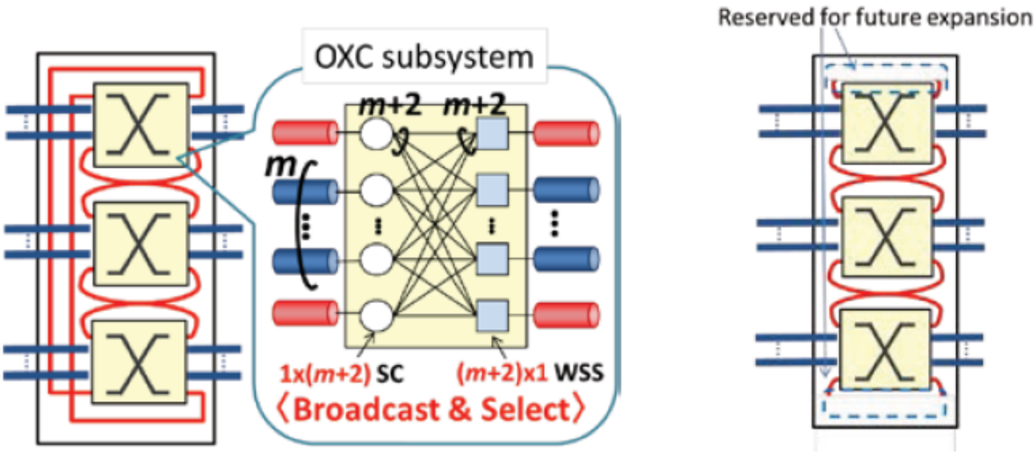


Figure 6-4 OXC stacked architecture

6.6 Final core architecture vision

This section shows the final architectural vision of the DISCUS core network and provides some remarks on the core traffic load and the related dimensioning and technological issues.

The DISCUS core architecture has been already updated based on the UK reference core network dimensioning results.

The updates address the photonic technologies, and can be summarized as follows.

- The offered traffic estimation is as large as 3003 Tbit/s in the highest traffic scenario and this imposes the adoption of challenging transport technologies like stacked Optical Cross Connect (OXC), and wideband Raman transmission systems.

This poses the problem of the development of an innovative photonic technology which, although technically feasible, will require non negligible development time and investments.

To address the stacked OXC issue we have repeated the UK core network dimensioning as shown in the following subsection.

6.6.1 New dimensioning based on minimum congestion routing

In order to investigate if a more appropriate traffic routing would lead to a reduced number of stacked OXC, we have repeated the whole network dimensioning procedure described in Deliverable D7.7 adopting a different Routing and Spectrum Assignment (RSA) strategy.

As a first step, traffic routing has been performed using a Minimum Congestion algorithm embedded in the library of the Net2Plan dimensioning tool (www.net2plan.com), rather than routing traffic on the mere shortest path as we did in D7.7. Given a set of nodes and links, with their capacities, an offered traffic vector, and a set of admissible paths for each demand, this simulated annealing meta-heuristic algorithm finds the routing solution that minimizes the network congestion.

The remainder of the dimensioning procedure has followed the same steps as described in D7.7.

The results of this new dimensioning attempt compared to the one shown in D7.7 can be summarized as follows:

- As expected the traffic is more distributed and link peak utilization is considerably reduced.
- As a consequence of the different routing strategy, the average light path length is slightly longer and a non-negligible number of light paths is longer than 1000 km that implies the adoption of DP-QPSK modulation format in order to guarantee optical transparency;
- After applying the spectrum assignment algorithm of D7.7 the maximum number of fibre pairs decreases from 12 to 8 (before considering the resilience requirements);
- Unfortunately, after node dimensioning the maximum number of stacked OXC does not change.

This results shows that, applying a different routing strategy is not beneficial for the number of stacked OXC.

6.6.2 Remarks on core network traffic load

Based on the results of the previous subsection, we can conclude that, while minor improvements in the core network dimensioning are still possible, the major issue arising from the huge core network traffic load in the extreme traffic scenario cannot be solved but using challenging photonic technologies like wide band transmission systems and stacked OXC.

However, we should also consider that the traffic predictions upon which our dimensioning is based have been derived under some specific assumptions:

- service platforms such as video cache and Data Centre (DC) servers are located in only 30% over 73 MC nodes of the UK reference network;
- for each MC node with embedded service platforms, traffic is conveyed equally to all servers through the core network.

These two assumptions together force the DISCUS core network to provide simultaneously two distinct functions:

- the one of today's aggregation networks that groom user's traffic in metro nodes;
- and the one of today's transport backbone providing long distance connections for the Internet and for inter-DC traffic.

Especially the first of these two functions is the origin of the heavy traffic load: the aggregation function which today is provided by a number of metro and regional networks in a country (each serving a fraction of the total number of users) is now devolved to a single large network serving the totality of users.

This drawback could be significantly mitigated if we decided to distribute service platforms in all MC nodes and to move into those service platforms most of the contents and functions actually exploited by the users connected to that specific MC node. This approach is actually in line with the latest trend in data centre allocation strategy envisaged in the next few years. This remark represents the major final recommendation that originates from the core network dimensioning.

7 END TO END DESIGN CONSIDERATIONS

The DISCUS project was an end to end network design project; however in order to take advantage of the individual expertise of its partners and for obvious organisational reasons, it was divided up into work packages that focus on parts of the whole network. There will therefore be a natural tendency for experts in a particular area to focus on the design details and technological issues of that part of the architecture. To overcome this natural tendency in the design process, the architectural framework of WP2 was designed to provide the guidance to the respective designers, controlling the trade-off choices in the different parts of the network, in order to come up with an overall more optimised and agreed solution for the end to end design.

The ideal was to have an optimisation model that could trade off all the design tensions and determine the optimal choices for the final solution but of course the optimisation problem is far too large and complex to be solvable and we therefore needed to follow design principles supported where possible by the modelling activities to make design choices. The end to end design naturally has conflicting tensions, an example, and one of the more difficult to resolve, is the reach of the LR-PON access network. We have shown through the modelling of the core network that the flat optical core is lower cost once a threshold customer sustained bandwidth is passed and the benefits increase as bandwidths continue to grow. This result is however dependent on the number of nodes in the core network with a general tendency for the benefits to increase as the number of core nodes is reduced. However reducing the number of core nodes increases the reach requirement on the LR-PON network. This not only stretches the technical challenges of the LR-PON design but also increases the round trip time (RTT) of the access network from customer to the first traffic processing node (the MC-node for our architecture). This RTT increase in turn has problems for certain wireless systems such as wireless front hauling, which has the potential for reducing antenna site costs for these mobile networks. However simply reducing the maximum reach of the LR-PON would jeopardise the economic benefits of the flat optical core network pushing up the costs for the whole network and all users.

We have shown that this can be overcome by placing radio technology in the remote nodes where the optical amplifiers for the LR-PON are placed. This of course adds cost for the radio systems but does keep the benefits of the flat core for all other services and customers. The very long LR-PON is best for minimising the end to end cost of the fixed network but can produce problems for some wireless network solutions. However even though the long LR-PON is not ideal for the wireless solution, that system can still benefit from the infrastructure put in place for the LR-PON solution. What should not happen is that the wireless network requirements determine the end to end design to the detriment of all other services and users. Unfortunately there was not sufficient resource or time to fully model the competing requirements of all the opposing systems to determine the overall optimal design that minimises costs for all systems and users, this could however be part of future projects.

There is still work to be done in modelling end to end solutions: it is too big a problem for a complete optimisation model and needs to be divided into a mix of analytic, heuristic and optimisation modelling. One issue we have found while building optimisation models is the problem of determining intermediate constraint parameters, because the overall constraint of minimal cost is too complex to implement. This has led to the use of intermediate parameters that, although logical at the time, may lead to non-optimal solutions at a later stage when further constraints need to be introduced. One such area of complexity is the selection and placement of the MC-node sites and then the assignment of the LE sites to MC-node pairs for their primary and secondary connections. Initially we assigned MC sites to minimise total numbers required while meeting the LR-PON reach constraints. However this leads to a wide variation of MC-node sizes which can have cost implications when very small nodes are used and resilience issues when very large nodes are used. This led to further constraints being imposed on the sizes of MC-nodes and required new locations and numbers to be determined.

Again further into the project we decided that the backhaul network that connects the LE sites back to their respective MC-nodes would be better in an open ring or chain configuration. In this case we kept the MC-nodes as previously located and attempted to produce optimised chains for that set of nodes. But it would now appear that what is really needed is an optimisation of node placement and LE chains assignment that takes into account, as part of the design process, the chain architecture. Unfortunately we are now at the end of the project and this extension of the optimisation work will have to be carried out in future projects.

There a numbers of such loose ends that are inevitable from such a wide ranging project as DISCUS. We are now at the end of the project and the suite of modelling tools and network designs could now be applied to interrogate solution options to a depth not available before. It is also only after the questioning is applied to the network designs, using the tools developed within the project, that further questions and analyses will arise. Again this work will need to be picked up within future projects

8 SUMMARY/CONCLUSIONS

In section 2 of this deliverable we described the design philosophy for the DISCUS architecture aimed at solving the three major challenges facing future communications networks, namely:

- To remain economically viable while user bandwidth grows by 1000 times or greater over the next decade
- To reduce power consumption by at last 95% compared to growing today's networks.
- To avoid the digital divide by redistribution and reduction of costs to enable FTTH solutions for sparse rural areas.

This deliverable describes the solution design which has become the DISCUS architecture and that we believe has the most promise for a future network that addresses the above problems and remains viable for user bandwidth growth to levels 1000 times greater than when the project started in 2012. The original architecture proposed was a long reach access network to by-pass the majority of LE/COs and the elimination of the separate backhaul network. The long reach access networks then terminate on a small number of core nodes that we call metro-core nodes (MC-nodes) that are sufficiently small in number to enable interconnect with direct transparent optical light path with no hierarchical layers within the core network. We called this core network an “optical island”.

Much of the focus of the project has therefore been on the design of the long reach access network, the design of the MC-nodes and the design of the flat optical core network and these have been described in the technical sections of this deliverable.

For the long reach access network the LR-PON was the design choice as it provides transparent optical paths between the MC-nodes and the customer premises: the only components in the path are optical amplifiers which we locate at the old LE sites. For those wireless systems that need to terminate protocols over much shorter distances, for latency reasons, we also enable some processing electronics at those nodes where required but this should be kept to a minimum and the costs of the electronic processing must be borne by those network services requiring the equipment and not the remainder of the network that does not require it.

We have shown both theoretically and at the final demonstration that two solutions and two amplifier technologies for the LR-PON design can be used depending on the geographical serving area and the services required to be delivered. These are the standard “lollipop” LR-PON solution with a long feeder length between MC-node and LE site (up to 90km) and a relatively short ODM splitter network with 512 way split and ~10km reach from the LE site to the customer premises. The amplifier technology can be EDFA exploiting the C-band and also SOA which can open other operating windows for use for additional network services including front-haul systems for wireless networks that require that technology. We also have an amplified chain solution which can further increase the reach of the LR-PON for the sparser rural areas of countries. This also could exploit EDFA or SOA technology.

We have shown an upgrade to the LR-PON which increases the downstream line rate to 40Gb/s using a three level, duo-binary modulation scheme. It uses a bit interleaved protocol which helps to reduce the amount of electronics needing to operate ONUs at 40Gb/s to a minimum and hence reduces power consumption and cost of the ONU termination.

We have also demonstrated 100Gb/s DP-QPSK modulated, point to point wavelengths, operating in parallel with the 10Gb/s OOK, LR-PON protocols over the same fibre infrastructure. Such wavelength channels can deliver core bandwidth capacities to the access edge and provide very high speed link circuits for larger business customers wherever they are located.

The MC-node design has been refined over the duration of the project. However from the outset we incorporated an optical switching layer that enable transparent interconnect between fibre channels, wavelength channels and the electronic packet processing equipment for both access and core networks while also enabling direct light path connection between core and access networks. The technology of choice was beam steering switch which are low loss, low cost per port and can scale to very large sizes. The favoured architecture for the optical switch is a single sided Clos network (which can be partitioned if required to further save optical ports of full interconnect between all MC-node functions are not required, e.g. limited connections between core and access networks). The optical switching layer also enables new protocols and switching/routing technologies, even experimental technologies, to be tried out in a real network environment without risking service disruption in the main network. If new systems prove viable and valuable then legacy systems could be gracefully displaced enabling complete change out, over time, of even Ethernet and/or TCP/IP.

The packet processing switches and routers proposed is based on MPLS-TP for both the access switch and core switches with additional switch/router capability provided for service provider connection. These latter switches could be either separate pieces of hardware paid for by the individual SPs or preferably, for a VNF and SDN future, they could be functional partitions of a common fabric using VNF to provide tailored services and capability to individual SPs. The whole design of the MC-node lends itself well to a virtualised and software defined future network: the optical switch enables software configuration at the physical layer while partitioning and virtualisation of the packet processing hardware enables SDN at the higher layers.

The core network design has focussed on the flat optical core: modelling work has shown this to be the lowest cost (and lowest power consumption) once a threshold customer bandwidth is reached, after which the benefits of the flat core continue to grow. The general objective of the DISCUS architecture was to have transparent light paths throughout the optical island if possible but it was recognised that in some geographies there may be particularly long light paths between some node pairs, particularly under fault (protection switched) conditions where the occasional regenerators may be needed. However the proposition of using sparse Raman amplification reduces the need for the sparse regenerators and we have shown that for European countries there would be no need for any regenerators and that all countries can be served by a single transparent optical island. To interconnect the in-country optical islands a selected subset of the in-country MC-nodes would be interconnected via a large span optical island that would form the Pan-European network. At those in-country nodes forming the pan–European network there would be packet processing and regenerators to enable very long haul links where required. The detailed design of this Pan-European network was beyond the scope and resource of the DISCUS project but could be carried out in future projects.

Finally it must be stressed that DISCUS is an end to end architecture project and that end to end consideration must steer the whole design, the design of the parts and the technology options studied within the project. Modelling and optimisation activities carried out within the project and imported from other and previous projects were a critical part of the overall design process providing the mechanism for comparing, eliminating and selecting the various options that could be parts of the overall DISCUS architecture. The models developed within the project are now reaching a stage of maturity but as we are at the end of the project full use and exploitation of this modelling capability and indeed further refinement and development will need to be carried out in future projects.

DISCUS has however shown that the simplified network with long reach access and flat core does indeed have the promise of being the lowest cost and lowest energy consumption network that could solve the future problems that were identified at the start of the project.

9 References

[1] Zukowski, D. B. Payne, M. Ruffini. Modelling accurate planning of PON networks to reduce initial investment in rural areas, ONDM 2014.

[2] S. McGettrick, F. Slyne, N. Kitsuwan, D.B. Payne, M. Ruffini. Experimental End-to-End Demonstration of Shared N:1 Dual Homed Protection in Long Reach PON and SDN-Controlled Core. Paper Tu2E.5, OFC, March 2015

[3] V. Houtsma, "Experimental update on PONs with duobinary detection", presentation in IEEE 802.3 Plenary Meeting, Dallas, TX, 9-12 November, 2015.

[4] Xin Yin, Fabrice Blache, Bart Moeneclaey, Joris Van Kerrebrouck, Romain Brenot, Gertjan Coudyzer, Mohand Achouche, Xing-Zhi Qiu and Johan Bauwelinck, "40-Gb/s TDM-PON Downstream with Low-Cost EML Transmitter and 3-Level Detection APD Receiver", accepted by OFC'16 for oral presentation.

[5] DISCUS deliverable D5.6, "Report on 40Gb/s downstream duobinary transmitter and 10/40Gb/s APD-TIA test version module".

[6] 3GPP TR 36.819, "Coordinated multi-point operation for LTE physical layer aspects", V.11.1.0, December 2011.

[7] C. Yang, et al., "How do we design CoMP to achieve its promised potential?", IEEE Wireless Comm., vol. 20, no. 1, 2013.

[8] M. Hogan, "Mobile backhaul and synchronization for heterogeneous networks", IEEE ITSF 2012.

[9] T. Pfeiffer, "Converged heterogeneous optical metro-access networks", IEEE ECOC 2010.

[10] C. Choi, et al., "Mobile WDM backhaul access networks with physical inter-base-station links for coordinated multipoint transmission/reception systems", IEEE Globecom2011.

[11] M. Mahloo, et al., "EfficientArchitectureSupporting Coordinated Multipoint Transmission in Mobile Networks", IEEE/OSA/SPIE ACP 2015.

[12] M. Mahloo, et al., "Toward reliable hybrid WDM/TDMpassive optical networks", IEEE Comm. Mag., vol. 52, no. 2, 2014.

[13] M. Mahloo,et al., "Cost modeling of backhaul for mobile networks", IEEE ICC 2014.

[14] C. M. Machuca, et al., "Cost-efficient protection in TDM PON", IEEE Commun. Mag. vol. 50, no. 8, p.110-117 (2012).

[15] J. Chen, et al., "Cost-efficient Fault Supervision Schemes for Next Genration Optical Access Networks", Proc. ACP, ATh1H.4, Shanghai (2014).

[16] M. Cen, et al., " Fast and Simple Fault Monitoring for Long-reach Passive Optical Networks", Proc. ECOC, P.7.15, Cannes (2014).

[17] M. Cen, et al., "Efficient Monitoring for Ring-based Long-Reach Passive Optical Networks", Proc. OFC, Th4H.4, Los Angeles (2015).

[18] M. A. Esmail, et al., " Physical Layer Monitoring Techniques for TDM-PON: A Survey", IEEE Commun. Surv. Tutor. Vol. 15, p.943-958(2013).

[19] M. Cen, et al., " A Full Monitoring Scheme for Long-reach TWDM PONs", Proc. ACP, Hongkong (2015).

[20] P. J. Urban, et al., "Fiber Plant Manager: An OTDR- and OTM-based PON Monitoring System", IEEE Commun. Mag. vol.51, no.2, p.9-15(2013).

[21] M. Cen et al., " Multi-wavelength transmission-reflection analysis for fiber monitoring," OPT. EXPRESS vol. 22, pp. 31248-31262(2014)

[22] Th. Pfeiffer, "Next Generation Mobile Fronthaul and Midhaul Architectures [Invited]", J. of Optical Comm. Networking, Special Issue on OFC 2015, vol. 7, issu.11, page B38 ff., Nov. 2015.

[23] Th. Pfeiffer, "Next Generation Mobile Fronthaul Architectures", OFC, Los Angeles 2015, paper M2J.7.

[24] K. Roberts, M. O'Sullivan, K.-T. Wu, H. Sun, A. Awadalla, D.J. Krause, and C. Laperle, "Performance of dual-polarization QPSK for optical transport systems," J. Lightwave Technol., 27, 3546-3559 (2009).

[25] A. Viterbi et al., "Nonlinear estimation of PSK-modulated carrier phase with application to burst digital transmission," Information Theory, IEEE Transactions on, vol. 29, pp. 543-551, 1983.

[26] Beam Steering Optical Switch, US Patent 7,389,016

[27] Clos, C.," A Study of Non-Blocking Switching Networks", BSTJ 32-2, p406, 1953

[28] D.G. Foursa, H.G. Batshon, H. Zhang, M. Mazurczyk, J.-X Cai, O. Sinkin, A. Pilipetskii, G. Mohs, N. S. Bergano, "44.1 Tb/s transmission over 9,100 km using coded modulation based on 16QAM signals at 4.9 bits/s/Hz spectral efficiency," 39th European Conference and Exhibition on Optical Communication (ECOC 2013), pp.1,3, 22-26 Sept. 2013

[29] IDEALIST: http://www.ict-idealist.eu/

[30] D. King, A. Farrell, A PCE-based Architecture for Application-based Network Operations. IETF draft: https://datatracker.ietf.org/doc/draft-farrkingel-pce-abno-architecture/

[31] H. Hasegawa, "Large Scale Optical Cross-connect: architecture, performance analysis, and feasibility demonstration," in Optical Fiber Communication Conference 2015, OSA Technical Digest, paper W3J.1

[32] Puc, A.; Grosso, G.; Gavrilovic, P.; Fevrier, H.; Kaminski, A.; Burtsev, S.; Chang, D.; Foster, M.; Pelouch, W.; Perrier, P., "Ultra-wideband 10.7 Gb/s NRZ terrestrial transmission beyond 3000 km using all-Raman amplifiers," 31st European Conference on Optical Communication, 2005, ECOC 2005., pp.17,18 vol.1, 25-29 Sept. 2005

[33] Do-il Chang, Wayne Pelouch, Philippe Perrier, Herve Fevrier, Sergey Ten, Christopher Towery, and Sergejs Makovejs, "150 x 120 Gb/s unrepeatered transmission over 409.6 km of large effective area fiber with commercial Raman DWDM system," Opt. Express 22, 31057-31062 (2014)

[34] IDEALIST project, http://www.ict-idealist.eu/

[35] Rambach F., Konrad B., Dembeck L., Gebhard U., Gunkel M., Quagliotti M., Serra L., Lopez V., "A Multilayer Cost Model for Metro/Core Networks" in Journal of Optical Communication Networks, Vol. 5, No. 3, March 2013

[36] DISCUS Deliverable D6.5, "Final report on the specification of the Metro Core node architecture", July 31st 2015

[37] DISCUS Deliverable D7.7, "Consolidated/integrated optical core design", July 31st 2015

[38] Van Heddeghem W., Idzikowski F., Vereecken W., Colle D., Pickavet M., Demeester P., "Power consumption modeling in optical multilayer networks", in Photonic Networks, January 2012

Abbreviations

ABNO	Application-Based Network Operations
A-CPI	Application-Controller Plane Interface
ADP	Avalanche photo detector
ADSL	Asymmetric digital subscriber line
AMCC	Auxiliary management and control channel
API	Application Programming Interface
ASON	Automatically Switched Optical Network
AWG	Array waveguide grating
BAU	Business as usual
BBU	Baseband unit
CIR	Committed information rate
CLI	Command Line Interface
CO	Central office
CoMP	Coordinated Multi point
CoS	Class of Service
CPE	Customer premises equipment
CPRI	Common public radio interface
D-CPI	Data-Controller Plane Interface
DP	Distribution point
DP-QPSK	Dual polarisation quadrature shift keying
DPSK	Differential Phase-Shift Keying
EDFA	Erbium Doped Fiber Amplifier
FSAN	Full service access network

FTTH	Fibre to the home
FTTP	Fibre to the premises
LBMRx	Linear burst-mode receiver
LTE	Long-term evolution
GMPLS	Generalised Multi-Protocol Label Switching
GPON	Gigabit PON
ICU	IDEALIST Cost Unit
I-CPI	Intermediate-Controller Plane Interface
IETF	Internet Engineering Task Force
I-NNI	Internal Network to Network Interface
IP	Internet Protocol
IPTV	IP Television
IS-IS	Intermediate System to Intermediate System
JSON	JavaScript Object Notation
JVM	Java Virtual Machine
L2	Layer-2
L3	Layer-3
LDP	Label Distribution Protocol
LE	Local exchange
LR-PON	Long-Reach PON
LSP	Label Switched Path
MC	Metro-Core
MPLS	Multi-Protocol Label Switching
MPLS-TP	MPLS-Transport Profile
NetConf	Network Configuration Protocol
NMS	Network Management System
NP	Network Provider
ODN	Optical distribution network
OEO	Optical-electronic-optical
OF	OpenFlow
OLT	Optical Line Terminal
ONF	Open Networking Foundation
ONU	Optical Network Unit

ONT	Optical Network Terminal
OSI	Open system interconnect
OSPF-TE	Open Shortest Path First-Traffic Engineering
OSNR	Optical signal to noise ratio
OSS	Operation Support System
OTDR	Optical time domain reflectometry
OXC	Optical Cross Connect
PCE	Path Computation Element
PCEP	Path Computation Element Protocol
PIR	Peak information rate
PON	Passive Optical Network
PM	Provisioning Manager
PW	Pseudo-Wire
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RAN	Radio access network
REST	Representational State Transfer
RL	Return loss
RN	Remote node
RRH	Remote radio head
RSVP-TE	Resource Reservation Protocol-Traffic Engineering
SBS	Stimulated Brillouin scattering
SDN	Software Defined Network
SLD	Super luminescent diode
SOA	Semiconductor optical amplifier
SP	Service Provider
SSON	Spectrum Switched Optical Network
TE	Traffic Engineering
TM	Topology Module
TPC	Transmission Control Protocol
TWDM	Time-wavelength division multiplexing
WB	Wide Band
VLAN	Virtual Local Area Network

VoD	Video on Demand
VPN	Virtual Private Network
WDM	Wavelength division multiplexing
WSON	Wavelength Switched Optical Network
WSS	Wavelength selective switching

Version	Date submitted	Comments
V1.0	24/02/2016	First version sent to the EU.