D2.2

First WP2 Progress Report

Dissemination Level: PU

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Abstract:

This deliverable is a progress report on WP2 activities regarding the following tasks:

Task T2.1: "Network architecture specification" describes a summary of the current all-optical DISCUS architectures that use optical networking to span and eliminate electronic layers between access, metro, and core.

Task T2.2: "Techno-economic studies", describes the techno-economic model and software for optimizing the access network. We describe techno-economic comparison between various solutions including LR-PONs, GPONs, FTTC, XRGPON, and Pt-Pt. The Metro-core node model will be added later, and further details will be provided in a later deliverables.

Task T2.3: "End-to-end network architecture optimization" provides geo-type reference network data for later techno-economic studies of Task 2.2 and for joining the various optimization methods developed in WP4 and WP7 into an overall end-to-end optimization process. Using non-operator-specific data, we have modelled reference topologies at different levels of detail, from CO sites to metro/core, and from local exchange to buildings for specific areas in potential reference countries (Italy, Spain, UK), starting with the Italian reference network.

Task T2.4: "Resilience, reliability, and supervision", Task 2.4 conducts architectural design and modeling focusing on aspects of resilience, reliability and supervision in the access segment (interacting with WP4, mainly Task 4.3 optical layer supervision and management). We describe here progress with reliability assessment, resilience schemes, and supervision techniques.

Task T2.5: "Power consumption modeling" provides current progress regarding end-to-end DISCUS architecture power consumption. In the core network, we describe a technique to redistribute power consumption, and in the access network we describe a statistical model for power consumption estimation of high speed connectivity. Several PON technologies are considered: GPON/EPON, 10G PON, XLG-PON, TWDM-PON, OFDM-PON and Co-UDWDM-PON. Further progress with power consumption shall be presented in Deliverable D7.1 focused on power consumption.

Task T2.6: "Traffic and service modeling" we describe progress with traffic and service modeling using range of service scenarios, including dimensioning of access, metro-node and core network, e.g. potential link capacities, node ingress and egress traffic, inter-node traffic granularity, and the wavelength and fibre counts required. We describe use of these in a range of scenarios that stress the network architectures.

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1 Introduction

This deliverable is a first progress report for tasks performed in WP2 work. The following work is described:

Chapter 2 describes a summary of the progress with Task 2.1 regarding network architecture specification. We briefly describe the overall DISCUS network architecture objectives, the architecture including the end-to-end network, i.e. encompassing the Access, Metro, and Core networks. Regarding LR-PON architectures, we compare three types of architectures, and various resilient options including basic, enhanced, and fuller protection. We describe the latest progress with optimising the LR-PON for rural and remote regions. Regarding the Metro-Core node we summarise the various architecture options. Regarding core network, we briefly describe the flat optical core with the optical islands concepts. A detailed report of all these concepts and progress has been made in Deliverable D2.1.

Chapter 3 describes latest progress with Task 2.2 regarding the techno-economic model and software. Full details will be provided in later deliverables. Task 2.1 covers entire end-to-end network, encompassing the access network, metro-core node, and core network. The techno-economic model is currently optimized for access network, and does not yet include the metro-core node model, which will be added later. We have performed a techno-economic comparison between the various optical access network solutions including long-reach PONs (LR-PONs), Gigabit/s PONs (GPONs) with 21cn backhaul, Fibre-To-The-Cabinet (FTTC), GPON with Reach Extender (XRGPON), and Point-to-Point (Pt-Pt).

Chapter 4 describes latest progress in Task 2.3 regarding the DISCUS end-to-end network optimisation. Creating realistic reference topologies are critical for techno-economic evaluations of various architectures in Task 2.2. Without such networks the influence of topological connectivity (e.g. for resilience issues) and technological restrictions (e.g. a maximal LR-PON distance of ~100) could not be properly analysed. We have generated the necessary geo-type reference network data to perform techno-economic studies of Task 2.2 joining various optimization methods developed in WP4 and WP7 into an overall end-to-end optimization process. The specification of the approach for the network modeling and analyses, optimization models and techniques and Task 2.3, are used in Task 2.1 and Task 2.3 to ensure fair comparison between architectural options. We provide networks for different geo-types (nation-wide, urban, suburban, and rural) and different countries (Italy, Spain, UK) a proper specification of the data interface, such that each partner is enabled to use this data with basic I/O functionality and execute similar studies on its own or for other operators. Progress in this first phase of the project has been mainly related to modelling reference topologies at different levels of detail, from CO sites to metro/core, and from local exchange to buildings. Progress specifically has been investigation and derivation of publically available geo-data from public sources for specific areas in potential reference countries, starting with the Italian reference network, the development of data-models to store geo-referenced data, e.g. data from Open Street Maps (OSM) (nodes with coordinates, trails/streets with their geographical representation, buildings), identification of requirements about the data to extract, development of data-models to store geo-referenced data, e.g. data from OSM (nodes with coordinates, trails/streets with their geographical representation, buildings), implementation of tools that allow to process, simplify, and store geo-referenced data, implementation of a process that is able to combine geo-data with a set of arbitrary coordinates for specific locations to compute a realistic network topology. The aim is to create non-operator specific but realistic reference topologies. Operator-specific and non-public data sources (e.g. population statistics and street or building data) are combined so that network operators within DISCUS consortium do not have to disclose their complete nation-wide network infrastructure (e.g. customers, today's cabinet, and central office structure, existing fiber topologies). Eventually it should be possible to demonstrate functionality and usefulness of the developed approach by computing a nationwide reference network for Italy combining data from Telecom Italia and from Open Street maps.

Chapter 5 describes latest progress with Task 2.4. Task 2.4 conducts architectural design and modeling focusing on aspects of resilience, reliability and supervision. Task 2.4 targets the access segment (interacting with WP4, mainly task 4.3 optical layer supervision and management), whereas Task 7.5 considers the core network.

The progress with reliability performance that will be further used for the schemes developed in other activities to assess the corresponding reliability performance. The methodologies includes reduction of impact of failure, and connection availability, in various WDM/TDM PON hybrid PON architectures implementation scenarios in the context of Deutsche Telekom (DT) network. The impact of sleep-mode operation on energy saving and reliability is also studied.

The progress with resilience schemes include design of resilient fibre layout, because the cost of fiber infrastructure is the dominating part of the capital expenditures (CAPEX) and should be minimized by a proper fiber layout. Investigation of hybrid protection technique, where different user types, e.g. residential/business users and mobile backhauling, may have different requirements for resiliency, and optimised layouts and traffic off-loading techniques in order to minimise routing and protection switching capacity required within the metro-nodes. The progress with resilience also includes a more efficient N:M OLT backup schemes by introducing an optical fibre switch between the feeder fibres and the OLTs, instead of conventional 1+1 protection schemes that lead to doubling the total number of OLTs in the network.

The progress with LR-PON supervision techniques includes identifying various generic PON supervision tools, including Optical Time Domain Reflectometers (OTDR), External OTDRs, Active and Passive demarcation points, and Dark fiber supervision.

Chapter 6 describes initial progress with the power consumption modeling in Task 2.5. Task 2.5 considers end-to-end DISCUS architecture, and describes work performed in task 2.5 together with Task 7.1. A more detailed description of the power consumption studies is presented in Deliverable D7.1 focused on power consumption. Here, we describe progress with the power consumption modeling of the core network. As the network expands, increasing practical problems can be encountered with supplying large amounts of energy to large network nodes. We describe a power-aware network that helps equalize power consumption of network nodes. We describe an approach for redistributing power consumption in network implementations in which each node location is constrained by a limited electricity power supply, for example areas with large population where we want to avoid power shortages. We provide results for "static" and "dynamic" power consumption models based on the power consumption of the equipment required to implement a particular architectural solution and traffic load. The "dynamic" power consumption model takes into consideration traffic level dependent power-down or power reduction strategies to take advantage of short-term variations in traffic load. We show that non-uniform traffic can results in 76% reduction in power consumption requirement for majority of the outer core nodes. Localization of traffic deeper in the network allows provisioning of additional resources to increase network capacity to be efficiently and cost-effectively implemented. We show that sparse wavelength conversion placement in the inner core nodes can increases network capacity by 27% compared with uniform traffic. Application of this strategy allows power consumption in various nodes of the optical networks to be adjusted.

We also study the power consumption of the access network we describe progress of statistical model for power consumption estimation of high speed connectivity, for properly dimensioning service provider equipment with traffic load in order to guarantee certain QoS. The access network power consumption at the CO is calculated for several PON technologies including GPON/EPON, 10G PON, XLG-PON, TWDM-PON, OFDM-PON and CO-UDWDM-PON).

Chapter 7 describes the latest progress with traffic and service modeling. It is proposed that study of future traffic demands should be service oriented, i.e. a range of service scenarios rather than simple bandwidth extrapolation should be used to drive traffic growth. We study dimensioning of access, metro-node and core network, e.g. potential link capacities, node ingress and egress traffic, inter-node traffic granularity, and the wavelength and fibre counts required. We then use these in a range of scenarios that stress the network architectures. Together with Tasks 2.1 and 2.2, the tradeoffs of higher speed transmission, higher density WDM and spatial multiplexing using higher fibre count cables are studied. A mix of dynamic/stochastic and average plus peak rate multipliers approaches are used to modelling network traffic patterns and growth scenarios in order to study requirements and performance of network architectures built to deliver future load/traffic demand patterns driven by FTTP access networks.

Finally, chapter 8 provides the summary and conclusions.

2 Network Architecture Specification

2.1 Introduction

This chapter describes the progress in Task 2.1 regarding Network Architecture Specification for producing various options for all-optical architectures that use optical networking to span and eliminate electronic layers between access, metro, and core, resulting in a complete end-to-end approach with a common protocol. The task covers the overall DISCUS architecture considerations, and remains the primary reference for other work packages. Task 2.1 feeds periodic reference design updates to various tasks in WP2, 4, 6 and 7 regarding access, metro/core node and backbone architectures. Task 2.1 work in the first year has been to produce deliverable D2.1, and additional work will be carried out from beginning of year 2.

2.2 DISCUS Architecture Objectives

Overall objectives of the DISCUS architecture design are described in Table 2-1:

Objectives	Description
1. *Ubiquitous Broadband and Principle of Equivalence.*	• *Ubiquitous* high speed high speed broadband. • All points of presence of the optical network have equivalent capability. • Independent of geographical location. o Rural and remote locations

2. *End-To-End Optimisation.*	• The overall architecture is optimised and this steers designs of individual parts:
	  o Optimal balance between various parts.
	  o End-to-end considerations.

3. *Improved Energy Efficiency*	• Improved energy efficiency over current architectures:
	  o ~95% target power savings in the network (excluding Customer Equipment)
	1. Reducing electronics →
	  a. Produces huge cost savings
	  b. Minimises power consumption.

4. Core network bandwidth capability in Access Edge	• Bandwidth/customer should be equivalent to today's core network bandwidth capability.
5. Evolvable	• DISCUS architecture should be able to evolve from today's networks and adopt new future technologies as they emerge in the future.
6. Economically Scalable with increasing bandwidths	• Architecture should remain economically viable while: o Customer bandwidths grow by > 3 orders of magnitude. o Network services and capability available anywhere at any location. • Removing local exchange nodes and electronics from the network o Much longer reach access networks are required. • Removing cost from upper reaches of the network balances increased cost of d-side and fibre drop provisioning at the access edge.

Table 2-1: DISCUS Architecture Objectives

2.3 DISCUS Architecture

DISCUS architecture features an LR-PON plus a flat optical core. This architecture can economically deliver ubiquitous high speed broadband to all users and ensure all optical points of presence can deliver equivalent network and service capability regardless of geographical location.

Figure 2-1 shows a simple schematic of the DISCUS architecture consisting of a dual homed LR-PON bypassing existing local exchanges and terminating on the metro-core nodes. The metro-nodes are interconnected with an optical circuit switched wavelength layer creating the optical island.

The overall architecture therefore consists of three major parts:

1. LR-PON access network.
2. Metro-core node
3. Core-network optical island.

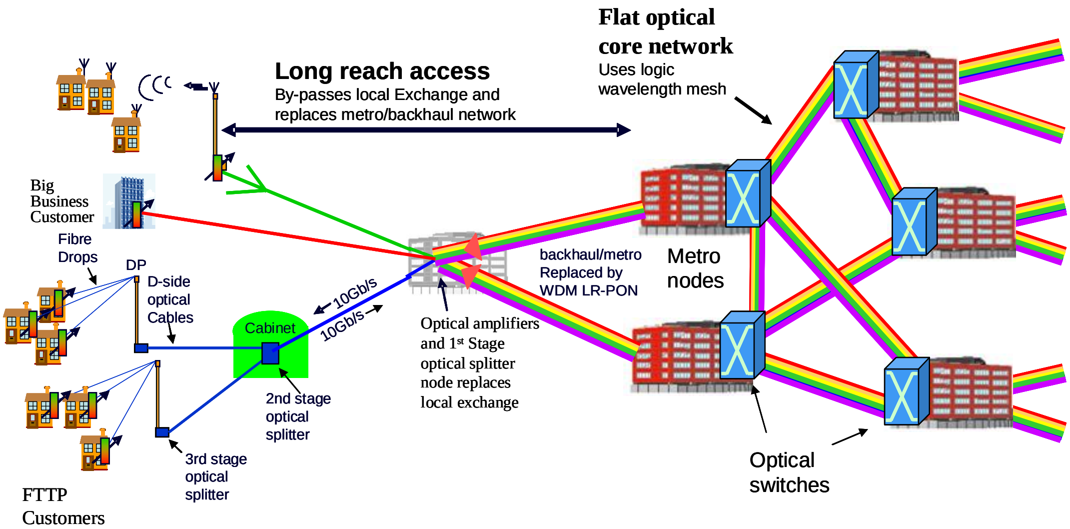

Figure 2-1: DISCUS initial architecture LR-PON plus flat core network

2.4 LR-PON optical access network

The LR-PON uses optical amplification to support greater total split, longer reach and higher bit rates than today's PON solutions. The higher split means that it is possible to have multiple split stages to further increase infrastructure sharing and minimise cost per customer.

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

DISCUS LR-PON design consists of a single wavelength upsteam and downstream. We considered three alternatives for the optical distribution network (ODN) and the backhaul sections:

1. Single fibre working ODN, two fibre working backhaul
2. Two fibre working in the ODN and backhaul
3. Single fibre in ODN and backhaul

The various configurations are shown in Figure 2-2, Figure 2-3, and Figure 2-4:

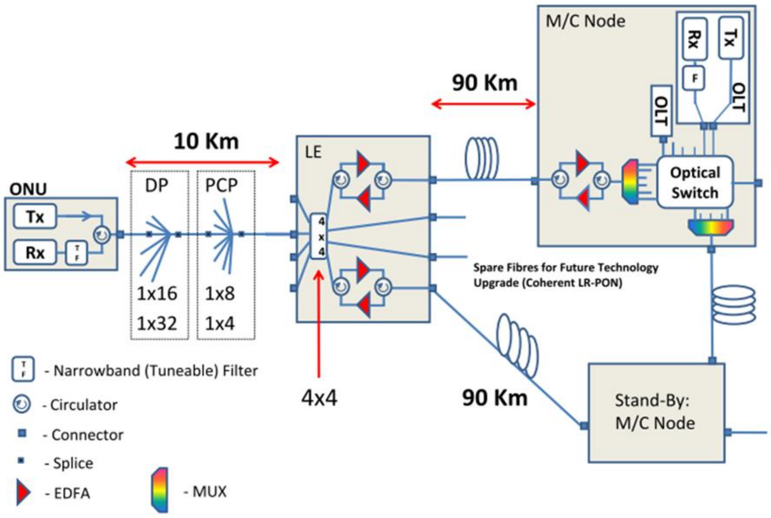

Figure 2-2: Basic LR-PON design with single fibre working in ODN and two fibre working in the Backhaul.

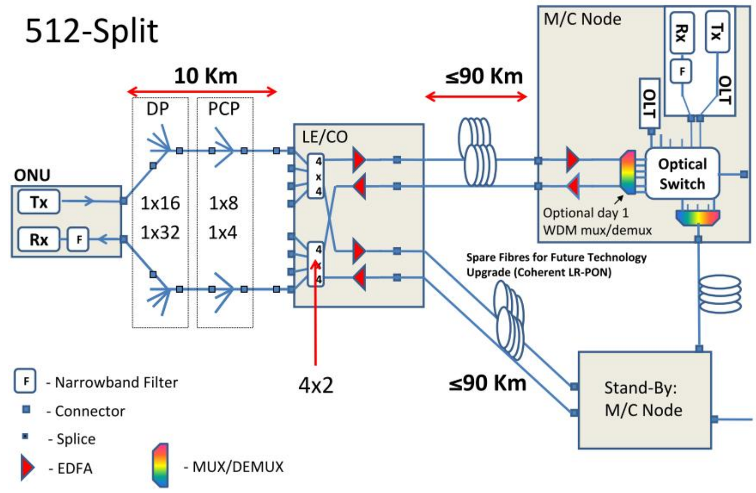

Figure 2-3: LR-PON architecture with two fibre working in both the ODN and backhaul.

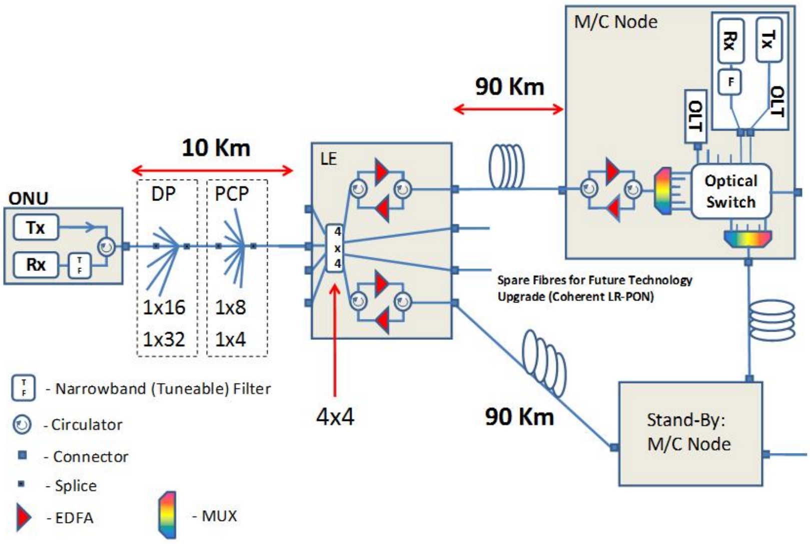

Figure 2-4: Flexible wavelength assignment LR-PON with single fibre working in both ODN and Backhaul.

The advantages/disadvantages of each of these architectures are summarized in Table 2-2: Summary of advantages and disadvantages of single fibre or two fibre working in LR-PON.

Options for single fibre and two fibre working	Advantages	Disadvantages
Single fibre in backhaul Single fibre in ODN	Minimises splitter costs and fibre cost in both backhaul and ODN. Releases two fibres in the backhaul section which can be used for future upgrades.	Increased optical loss budget which will reduce system margins and may reduce split. Extra cost of optical circulators. Reduced optical spectrum for service provisioning and system capacity by factor two.
Single fibre in backhaul Two fibre in ODN	Reduced loss in ONT. Diplexer not required in ONT, reduced cost ONT. Releases two fibres in the backhaul section which can be used for future upgrades.	Increased cost of ODN fibre and splitters (In practice the there may be no increased cost of fibre as LR-PON is very fibre lean and there will be spare fibre in the E-side and D-side cables and Drop cables). There will however be increased cost of fibre splitters (approx 1 additional splitter port per customer). Reduced optical spectrum for service provisioning and system capacity by factor two.
Two fibre in backhaul Single fibre in ODN	This would be considered to be a “standard” solution. Minimises splitter costs and potentially fibre cost in ODN. Reduced loss and cost in backhaul (no circulators).	Diplex (circulator) required in ONT, higher cost and higher loss. Reduced optical spectrum for service provisioning and system capacity by factor two.
Two fibre in backhaul Two fibre in ODN	Reduced loss and cost in backhaul and ONT (no circulators). Diplexer not required in ONT, reduced cost ONT. Full optical spectrum available upstream and downstream (doubles spectrum availability compared to other options).	Increased cost of ODN fibre and splitters.

Table 2-2: Summary of advantages and disadvantages of single fibre or two fibre working in LR-PON.

2.5.1 40 Gb/s downstream for LR-PON

The initial DISCUS architecture LR-PON is designed for 10Gb/s symmetrical. However 40 Gb/s transmission downstream is also being investigated as an upgrade option. The architecture being studied is shown in Figure 2-5 studying options with and without the SOA preamplifier at the ONU.

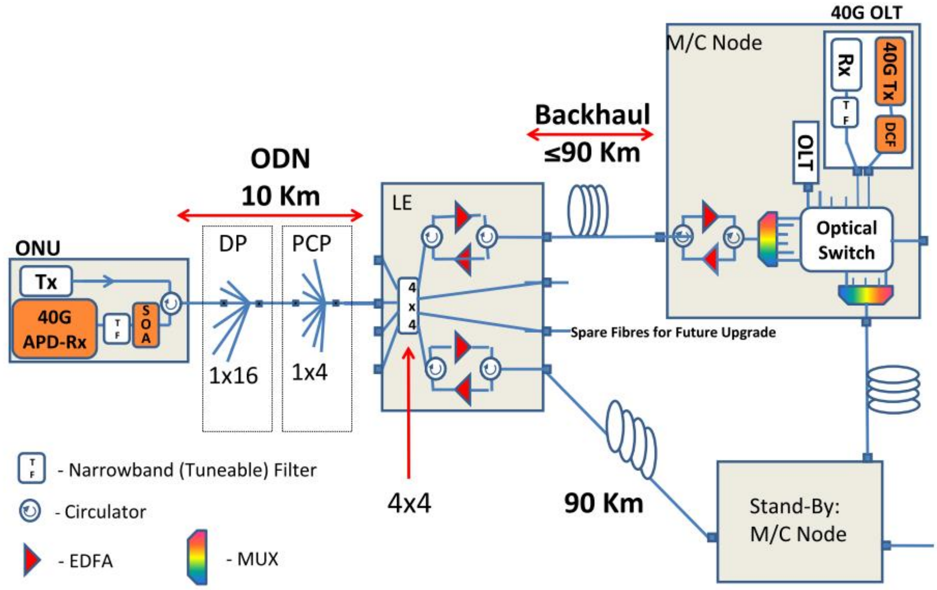

Figure 2-5: 40 Gb/s downstream LR-PON with SOA-preamplified PIN-Rx at ONU

2.5.2 LR- PON Resilience Options

We studied three protection options for the LR-PON:

1. We studied the basic protection for all customers via dual parenting of last splitter and amplifier node onto two metro-core nodes
2. Enhanced protection via two ONUs at the customer premises, the second ONU connected to last splitter and amplifier through a separate branch of the LR-PON ODN.
3. Fuller protection via two ONUs at the customer premises and the second (protection) ONU connected to a separate LR-PON (see Figure 2-6).

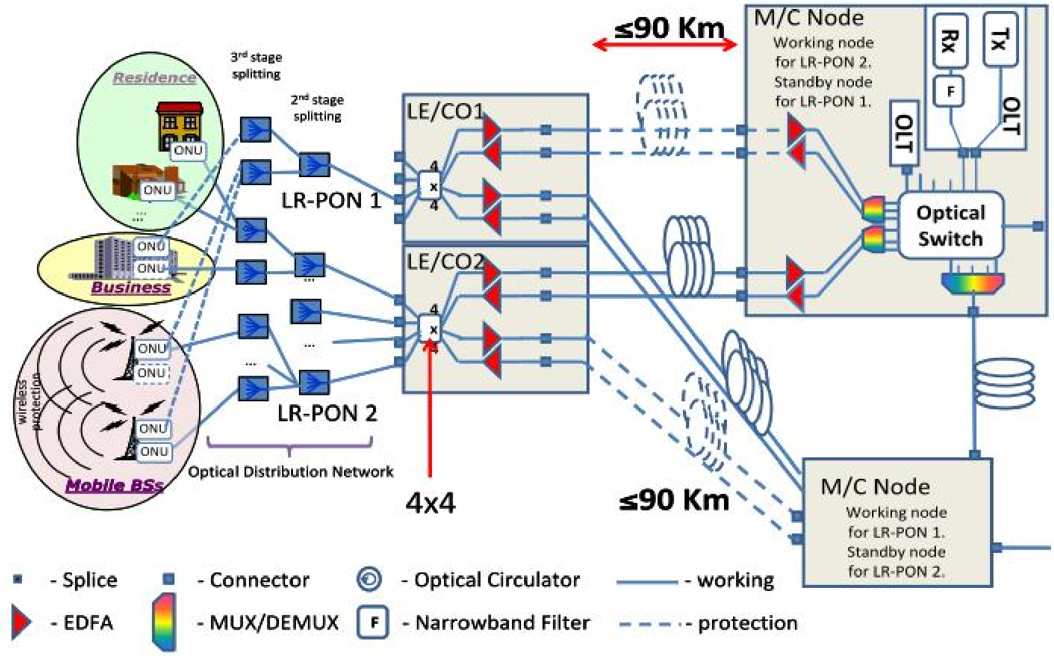

Figure 2-6: Full Protection for Business Access and Mobile Backhaul.

2.5.3 LR-PON Optical Power Budget

The limitations on optical split are the optical power budget and the OSNR. In the upstream direction the limitation is OSNR which is limited by the ASE from the optical amplifiers. The power and OSNR budget for the architecture shown in Figure 2-2 was studied, assuming that within DISCUS the linear burst-mode receiver technology developed by the Tyndall research group will be employed. The results suggest that a 512 split can be supported with OOK modulation of optical signals at 10Gb/s in both directions. See Deliverable 2.1 for more details.

2.5.4 Rural and Sparse Populations

We studied sparse rural area implementation of the LR-PON with a short backhaul, and extended access reach (see Figure 2-7).

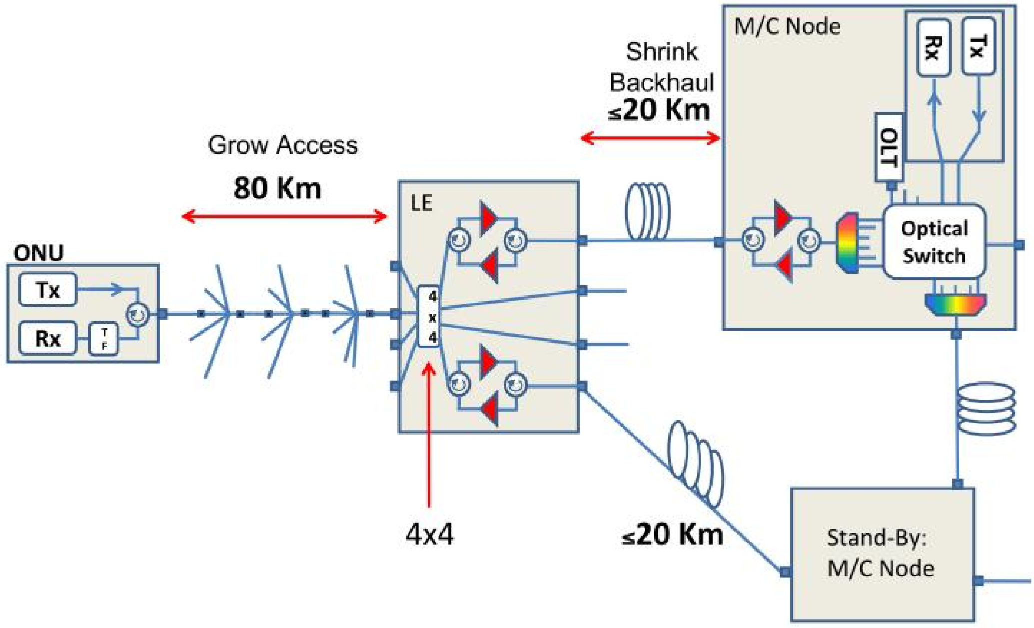

Figure 2-7: Sparse Rural Region, simple solution - grow access, shrink backhaul.

The relationship between the ODN reach and the LR-PON split for a given power budget is illustrated in Figure 2-8.

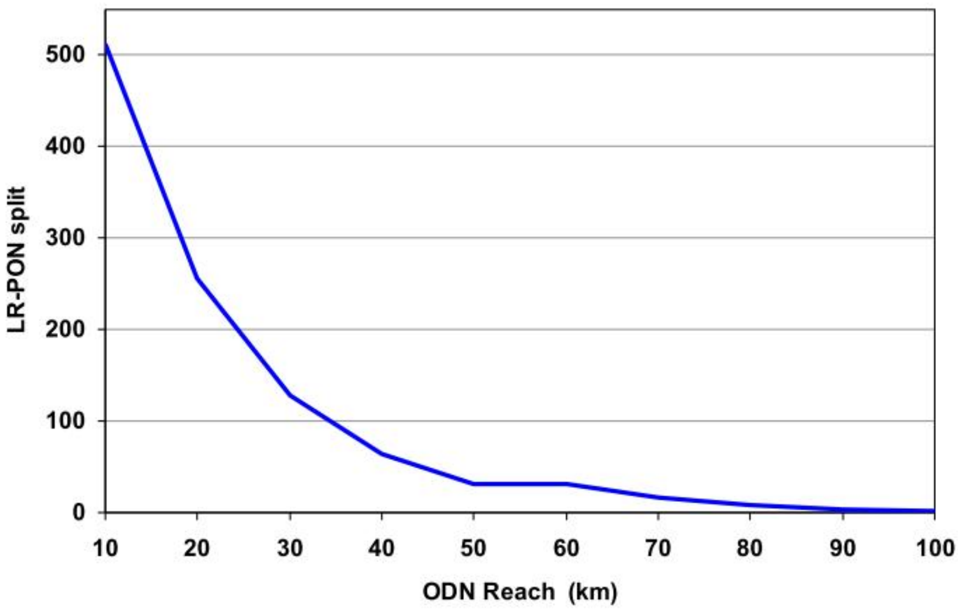

Figure 2-8: PON split reduction as ODN length increases.

An improved architecture currently being studied consisting of a chain of local exchange sites is shown in Figure 2-9.

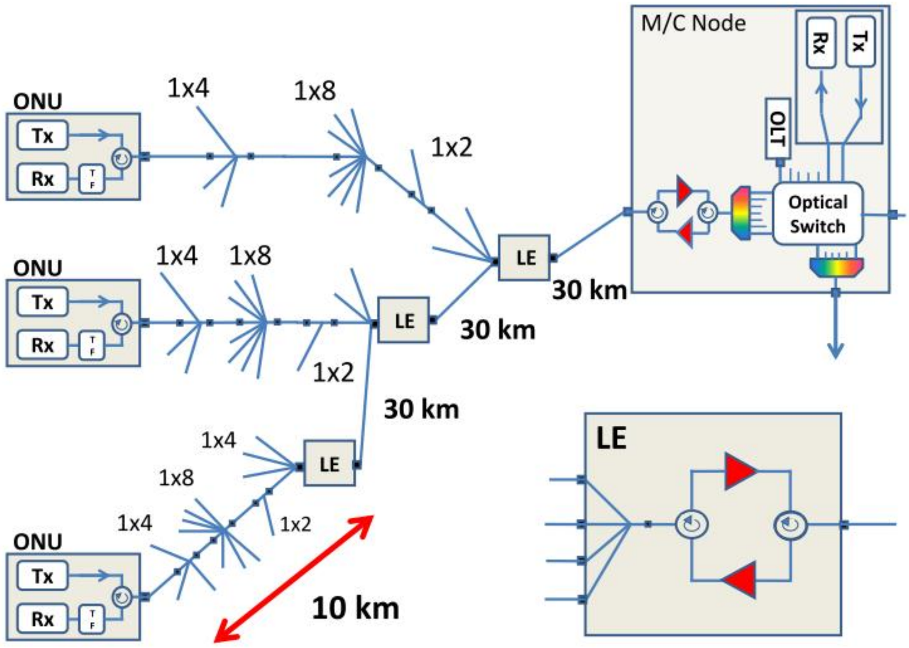

Figure 2-9: Distributed amplifier node solution for rural areas.

2.5.5 Amplifier node design issues and options

Various amplifier node designs were studied, see Deliverable D2.1 for more details.

2.5.6 Candidate modulation formats for Core bandwidth over LR-PON

Besides OOK, various transmission technologies were (a) DP-QPSK, (b) OFDM, and (c) Nyquist WDM. Multilevel modulation formats require higher OSNR, which reduces maximum achievable transmission distance due to nonlinear impairments. Nonlinearities appear to be even more dominant in OFDM due to high peak-to-average power ratio (PAPR). Several approaches to improve tolerance to nonlinearities were studied.

2.5.7 OLT design options

See Deliverable D2.1 for details.

2.5.8 Bespoke networks solution over LR-PON infrastructure

See Deliverable D2.1 for details.

2.6 Metro-Core Node

2.6.1 The metro-node core design

The metro node design in the DISCUS proposal is studied in detail in deliverable D2.1 and D6.1. We show here two alternative architectures in Figure 2-10 and Figure 2-11.

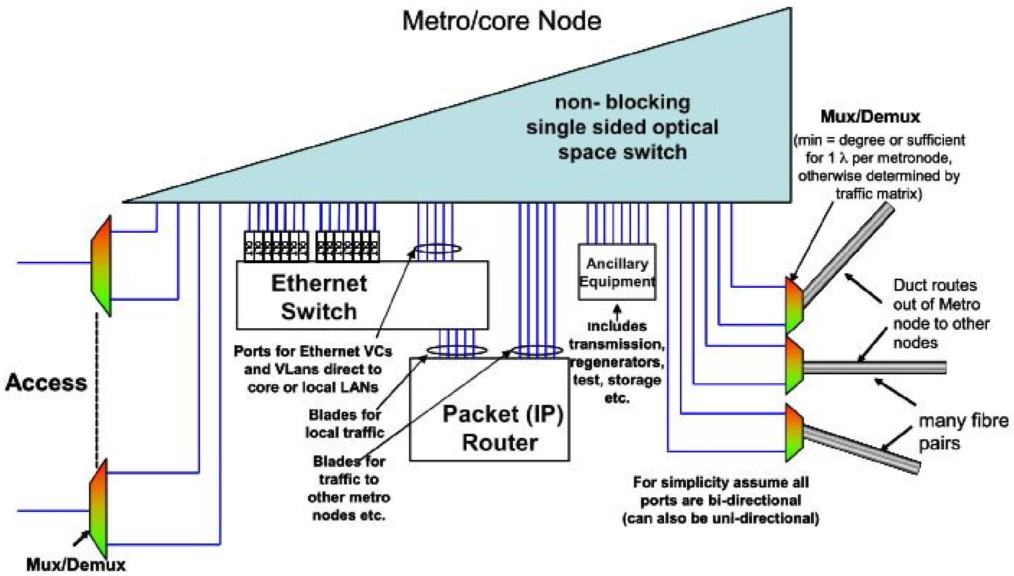

Figure 2-10: Initial proposal for metro-core node architecture.

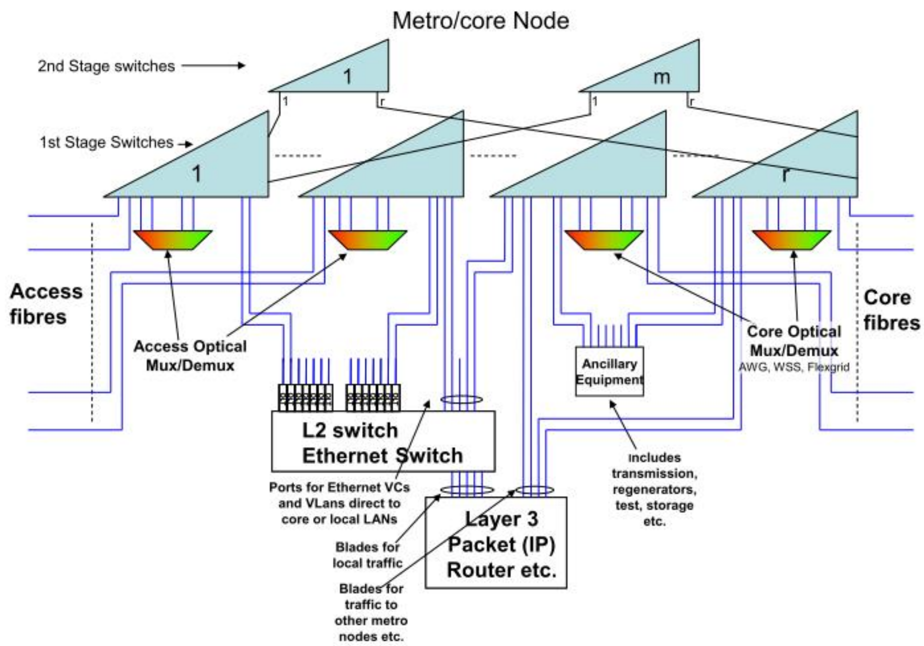

Figure 2-11: Metro node structure using single sided partitioned switch structure.

2.6.2 Core Network

In the core network, node reduction and enabling transit traffic through core nodes to bypass electronic routers and switches can be done by keeping such traffic in the optical domain, and exploiting a flat optical core whereby wavelength paths are setup across the network interconnecting the core nodes (or metro-core nodes as we refer to them in the DISCUS architecture). Traffic passing through a node stays in the optical domain and is not electronically processed. Only the traffic originating from or terminating on a metro-node needs to enter the electronic processing layers.

2.6.2.1 Flat Optical core

The advantage of the flat optical core is the reduction in OEO conversions and reduction in switching, routing, and packet processing in the metro-core nodes. 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. Wavelengths can be used to enhance access capacity for users connected to LR-PON systems.

2.6.2.2 Optical Islands

An optical island (see Figure 2-12) was defined as a set of nodes that can be fully interconnected by transparent wavelength routes. For large countries it is envisaged that multiple islands will be needed and these islands will be interconnected via a further "higher layer" optical island layer which interconnects the lower optical island through a small sub set of the metro nodes within those islands. For most European countries it is envisaged that a single optical island will suffice and the next layer up would be a trans-European optical island providing interconnections between the in-country optical islands and the international routes to the rest of the world.

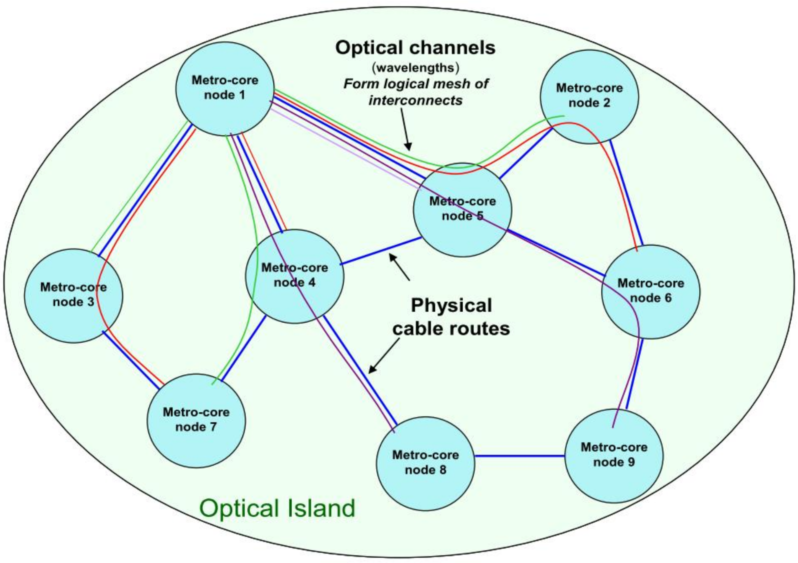

Figure 2-12: Optical Island Concept

Configurable modulation formats can be 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). However there is a trade-off between system reach and spectral efficiency. A transparent transmission distance of about 3 thousand kilometres can be obtained with PM-QPSK modulation format on G.655 fibres. In case of shorter transmission distance, higher spectral efficiency modulation formats can be used leading to better optical spectrum exploitation. This means that the photonic layer can be a single transparent network domain for most European countries. The whole core network can be a single transparency island where modulation format is adapted to the traffic demands reach requirements.

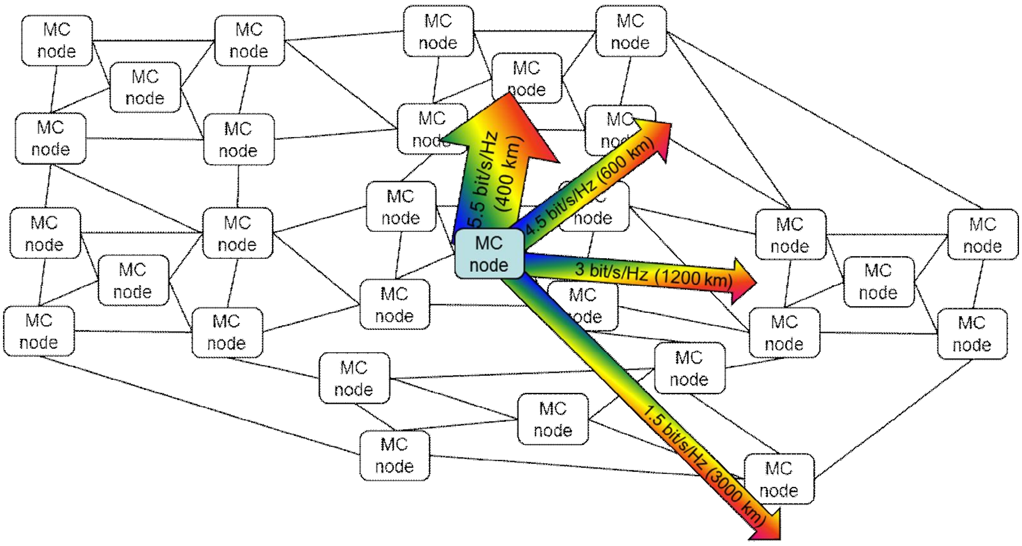

Figure 2-13: Fully transparent photonic layer based on modulation format-adaptive transponders.

However, photonic technologies provide the lower cost and energy per bit for only the larger traffic demands. A packet transport network can be used that complements the photonic layer for small to medium size traffic demands. Its architecture is shown in Figure 2-14 where the client-server relation with the photonic layer is highlighted. In DISCUS the most effective organization of the packet transport layer will be investigated based on suitable optimization criteria. Use of flexible grid and bandwidth variable transponder in DISCUS core network will be investigated in other deliverables, e.g. D7.2.

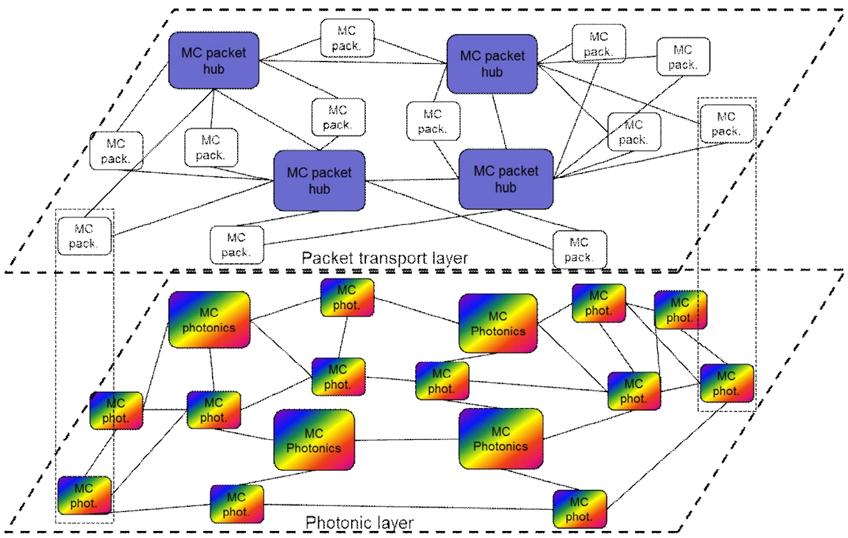

Figure 2-14: Packet transport layer and the underlying photonic layer.

3 Techno-economic Studies

3.1 Introduction

This chapter describes the progress in techno-economic studies in Task 2.2. We compared different optical access network solutions, including long-reach PONs (LR-PONs), Gigabit/s PONs with 21cn backhaul (GPONs), Fibre-To-The-Cabinet (FTTC), GPON with Reach Extender (XRGPON), and Point-to-Point (Pt-Pt) access networks.

3.2 Long-reach passive optical networks (LR-PONs)

3.2.1 All-optical technology

The LR-PON is an all-optical technology of interest because it can provide greater bandwidth using reduced number of electronic components, has increased network reliability, and lower operating costs compared with copper networks. The increased network reliability leads to lower operating and maintenance costs, as well as less power consumption.

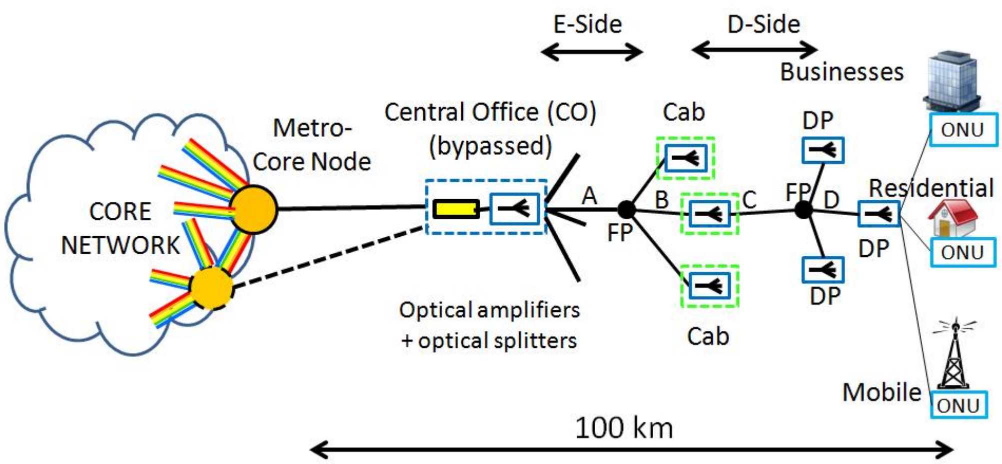

Figure 3-1: Schematic of Long-reach PON architecture. FP= flexibility points. The FPs divide the E-Side to A and B Segments, and the D-Side to C and D segments.

Figure 3-1 shows a simplified schematic of the LR-PON architecture. LR-PON achieves cost and energy savings by increasing the physical reach of the PON, bypassing the metro network systems and CO electrical equipment thus connecting the access network to the optical core. The LR-PON architecture leads to cost savings by placing the shared OLT equipment deeper in the network, at the metro node, so that expensive equipment, such as optical amplifiers and dispersion compensating equipment are shared more and used with minimal cost to the customer.

3.3 Techno-economic studies

We compared the LR-PON with competing technologies, and the network architectures modeled in this chapter are shown in Figure 3-2.

GPON [1][2][3][4][5] (ITU-T G984.1 [1]). Typical splitter sizes are shown for each stage. GPON systems typically serve 32 customers, however split sizes of up to 1:64 are realistic for the physical layer. Standard GPON architecture uses BT's 21cn backhaul network. They have a range of 20 km with 2.5 Gbit/s symmetrical bandwidths, or only 1.2 Gbit/s upstream. GPON uses different wavelengths for downstream and upstream, typically 1495 nm downstream, and 1310 nm upstream. Customer traffic is terminated at the central office (CO) by the GPON OLT, situated in a multi-service access node (MSAN). The MSAN aggregates traffic and sends it via a protected backhaul network using Ethernet transmission systems terminated at the metro-nodes.

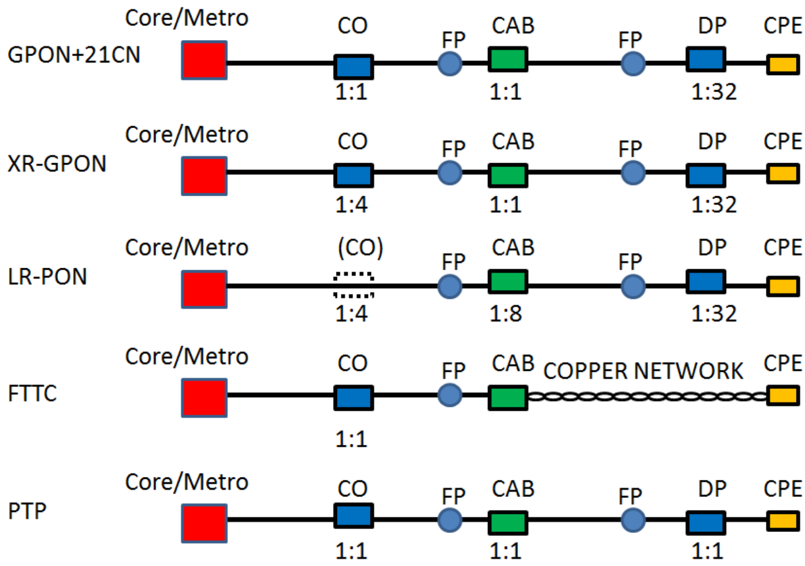

Figure 3-2: Schematic of the architectures modeled in the cost model. The splitter sizes are shown at each stage.

With future optical module technologies, split sizes of up to 1:128 may be possible. For example, XRGPONs [6][7][8][9] or amplified GPON define networks with reach of 60 km to 64-128 customers with symmetrical data rates of 10 Gbit/s. The CO splitter size is 1:4 instead of 1:1 for the GPON. Extended-reach GPON (XR-GPON) increases the reach and address the issue of remote users in rural areas.

Because FTTH is considered more expensive, network operators have carried out large-scale deployment of Fibre-To-The-Cabinet (FTTC) in their network. FTTC uses the existing copper network of the telephone network from the cabinet to the CPE. FTTH solutions are to be deployed in newly build locations. An alternative to PON solutions is to connect from the Metro Core (MC) node to the CPE directly using PTP/Pt-Pt. Although Pt-Pt is very expensive it is however a future-proof solution.

3.4 Techno-economic model and Software

We have created a techno-economic cost model and software (see Figure 3-3) for interactively studying a variety of access architectures for comparing various optical access solutions. Given certain network design parameters, the software automatically dimensions the network, calculates the quantity of equipment required, and costs the network. Using this model we can study network costs for various architectures for different CO area geo-types and take-up rates. We can thus study the feasibility of providing universal capability to all sectors of the community in widely varying geographical locations.

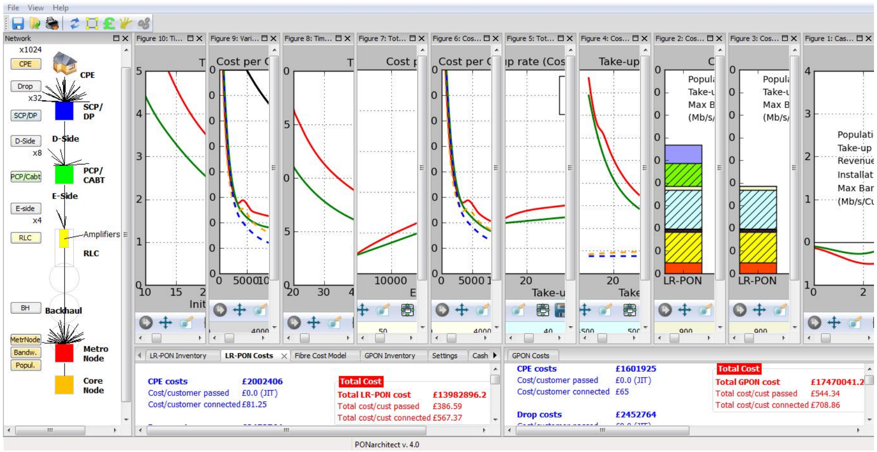

Figure 3-3: Screenshot of the cost model software created showing graphics modules.

3.4.1 Description of model

Figure 3-4 shows a flow diagram of the cost model. Depending on the particular network being modeled, the program dimensions the network accordingly, calculates splitter sizes, and quantity of equipment needed. The program then calculates total costs and costs per sub-systems in the network. The base cost data for component and sub-systems were obtained from public domain sources. Fibre, duct, and cable costs were obtained from Analysys Mason [10]. Other costs were obtained from manufacturers' websites.

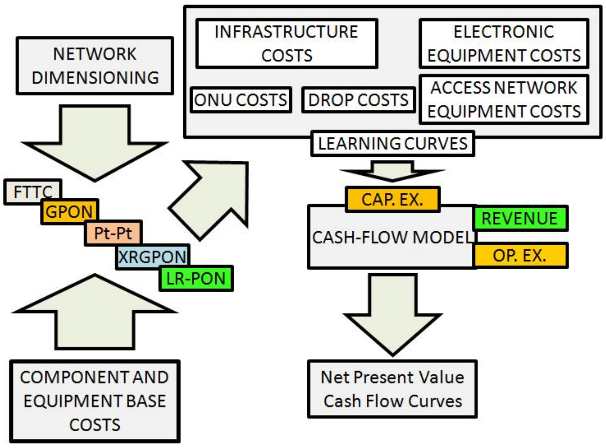

Figure 3-4: Flow diagram of the cost model.

3.5 Comparison of various technologies

Figure 3-5 below shows the cash flow curves for all the architectures for a medium sized town, in this case the Swansea UK, CO area. The graphs show cash flow curves that demonstrate typical negative cash flow in the early years, due to debt because of investment on the network in terms of infrastructure and equipment. This is subsequently followed by positive cash flow with LR-PON reaching profitability earlier than GPON, XRGPON, FTTC, and Pt-Pt. GPON and XRGPON curves are approximately similar, with XRGPON reaching profitability 2-3 years earlier. Figure 3-5 also shows that the FTTC and Pt-Pt curves are the most expensive and reach profitability in more than 20 years. Note that although FTTC appear to be expensive, however this is not the case for every situation. The cost is very sensitive to the amount of duct build required. With 0% duct build FTTC becomes comparable and even less expensive than LR-PON. Therefore the amount of duct build in the location it is implemented is important. However, in new builds and sparsely populated areas, LR-PON is the best option.

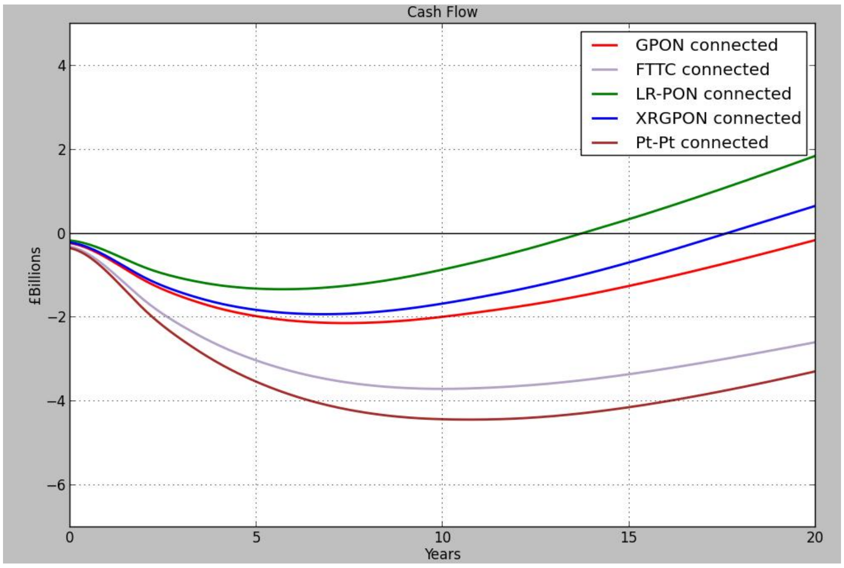

Figure 3-5: Comparison of the cash flow curves for architectures modelled (Exchange population= 24645, take-up rate=30%, revenue= £15, installation rate= 1000000, backhaul distance= 140 km, E-Side Distance=1.1 km, max sustained bandwidth= 100 Mb/s/customer).

Further results are shown in Appendix, sub-section 10.1.

3.6 Conclusions and discussions

A techno-economic model has been described that models the LR-PON, FTTC, GPON, Pt-Pt, and XRGPON architectures. The cost model dimensions the network, calculates equipment and infrastructure costs, and creates cash flow curves. For the parameters that we have studied, the results show that LR-PON has the lowest cost of the optical solutions. With no additional copper loop network to be built, FTTC would be the lowest cost solution.

The techno-economic model needs to be further optimized for very low population CO areas. Optimisation of the LR-PON model depends on local geography and customer density. The initial design of metro-node has been made. This will later be incorporated in the techno-economic model. The model includes some switch and OLT configurations that were described in D2.1. The impact of the optical switch in the DISCUS architecture could be studied.

4 End-to-End Network Architecture Optimisation

In this chapter we describe progress in Task 2.3 of the DISCUS project. This task has two main targets: (i) to generate the necessary geo-type reference network data to perform the techno-economic studies of Task 2.2. (ii) to glue together the various optimization methods developed in WP4 and WP7 into an overall end-to-end optimization process

In this first phase of the project, the activities (of atesio) have been related mainly to the first point, the modelling of reference topologies. Realistic reference topologies are critical for all techno-economic evaluations. This data is needed to make realistic comparisons of the variants of the DISCUS architecture described in deliverable D2.1 but also comparisons with other architecture such as GPON or P2P Active Ethernet in the access and today's mix of Ethernet and IP in the aggregation and core networks. Without such networks the influence of topological connectivity (e.g. for resilience issues) and technological restrictions (e.g. a maximal LR-PON distance of about 100) could not be properly analyzed.

The main goal of atesio in Task 2.3 is to provide reference networks at two different levels of detail: (i) Up from local exchange sites (LE) to metro/core nodes (MC): These reference networks should cover national networks starting on a level similar to today's central office locations (CO). The topologies should resemble national fiber topologies. They will be the basis for LR-PON studies in the backhaul network and also for studies of optical islands in the core network. (ii) Down from local exchange sites to buildings: These reference networks should cover geographically areas at the size of smaller towns of around 100 km² with several hundreds of thousands of customer premises. These reference networks will be the basis for LR-PON studies in the optical distribution network.

With the objective to create anonymised, i.e. non-operator specific, but realistic reference topologies, public and non-public data sources should be combined. In this way, network operators within the DISCUS consortium do not have to disclose their complete nation-wide network infrastructure (e.g., customers, today's cabinet, and central office structure, existing fiber topologies). Instead, the idea is to combine some operator-specific key-information with publically available data (e.g. population statistics and street or building data).

atesio aims at providing (i) networks for different geo-types (nation-wide, urban, suburban, rural) and different countries (Italy, Spain, UK), (ii) a proper specification of the data interface, such that each partner will be enabled to use this data with basic I/O functionality and execute similar studies on its own or for other operators.

Progress of Task 2.3 in this first phase of DISCUS can be summarized as follows:

(i) Investigation and Derivation of publically available geo-data from public sources for specific areas in potential reference countries (Italy, Spain, UK) (ii)

Identification of requirements about the data to extract. (iii) Development of data-models to store geo-referenced data, e.g. data from open street maps (nodes with coordinates, trails/streets with their geographical representation, buildings) (iv) Implementation of tools that allow to process, simplify, and store geo-referenced data (v) Implementation of a process that is able to combine geo-data with a set of arbitrary coordinates for specific locations to compute a realistic network topology.

Eventually, it should be possible to demonstrate the functionality and usefulness of the developed approach by computing a nation-wide reference network for Italy which combines data from open street maps and data from Telecom Italia. This reference network, its creation, and the used data are described in the sequel in more detail.

4.1 Data from Open Street Maps

To compute realistic fiber topologies of nation-wide networks we use geo-referenced data from street networks. We believe that this approach is reasonable for the following reasons: (i) We cannot expect that the network operators within DISCUS will provide all partners with all details about the topology of their networks. (ii) In fact, when studying alternative architectures and new structures it may not be clever to start from existing topologies. We rather need 'reasonable' potential locations to store equipment and 'reasonable' potential fiber routes. (iii) With open street maps (OSM) there exists extensive data sets that are open source (Open Database License = 'Share Alike') and include fine-grained information down to residential roads and buildings structures. (iv) Laying fibers is typically done along streets. (v) Street networks reasonably reflect dense and sparse structures (towns and rural areas) and they reflect 'forbidden' fiber-routes as across mountains or rivers. (vi) In principle, these data can be combined with additional information such as the location of central office or cabinets, and population statistics.

atesio developed methods and algorithms that allow to extract and to process information provided by openstreetmap.org (OSM). In general, OSM data contain a wide variety of data types, are of good quality, but not necessarily error-free, and can be considered only as a raw data-source, which needs processing. The data within OSM is organized and tagged using layers. With the developed methods and tools we are able to extract individual such layers from OSM and process them further. Examples of the infrastructures which can be and have been extracted can be seen in Figure 4-1.

For the countries Italy, Spain, and Great Britain, Table 4-1 shows the level of detail of the extracted data by stating the corresponding number of 'nodes'. A node, in this context, does not refer to a node in the mathematical sense of a graph but to a geographical coordinate which is typically obtained by GPS tracking. In fact, one of the central tasks in the data processing is to transform this geo-referenced information to a mathematical graph, keeping crucial information such as the coordinates of important locations and the length of potential fiber-routes.

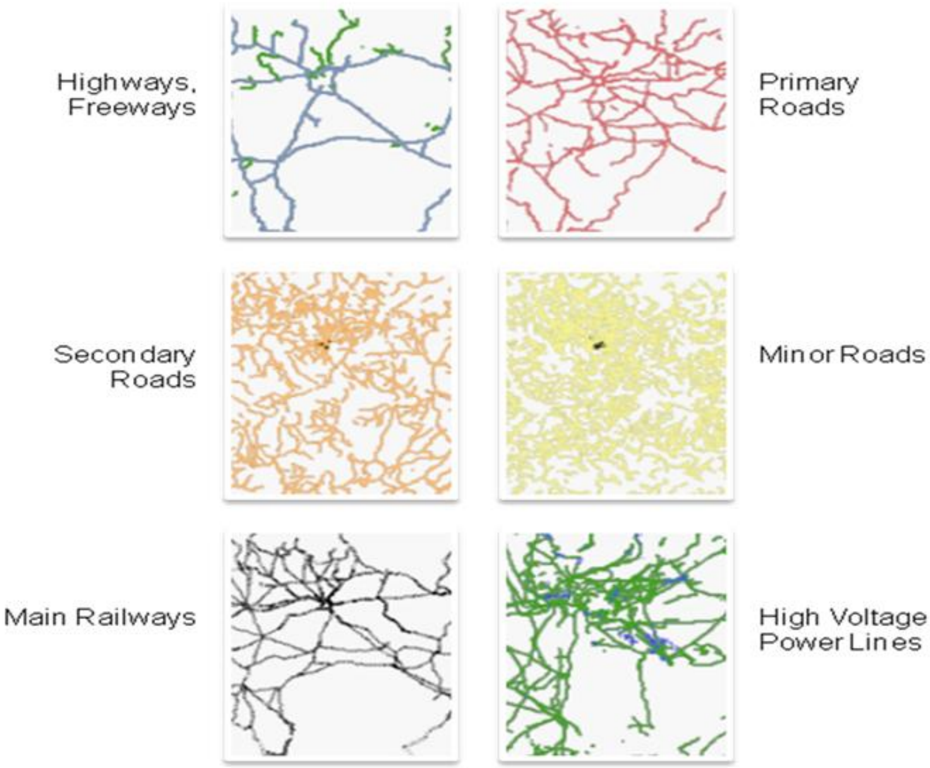

Figure 4-1: Typical layers in data from OSM.

Layer	Italy	Spain	Great Britain
Major Highways, Freeways	219202	517723	214507
Highways	182912	349628	599869
Primary Roads	624284	401889	724798
Secondary Roads	1243500	750852	719918
Minor Roads	2171799	2106013	1176412
Residential Roads	2404214	3170378	4485160
Main Railways	366291	158956	421821
High Voltage Power Lines	184190	112312	295294

Table 4-1: The number of nodes for different layers in OSM data.

4.2 Data from Telecom Italia

Telecom Italia provided different data that turned to be extremely useful for the activities in Task 2.3. The data includes: (i) 20 Italian regions given by their boundaries as polygons see Figure 4-2. (ii) 10,709 Central office locations with anonymized coordinates (Latitude, Longitude) (see Table 4-2), number of connected cabinets, number of connected residential customers, number of business customers, information about whether the CO is connected to the network by dual homing or not.

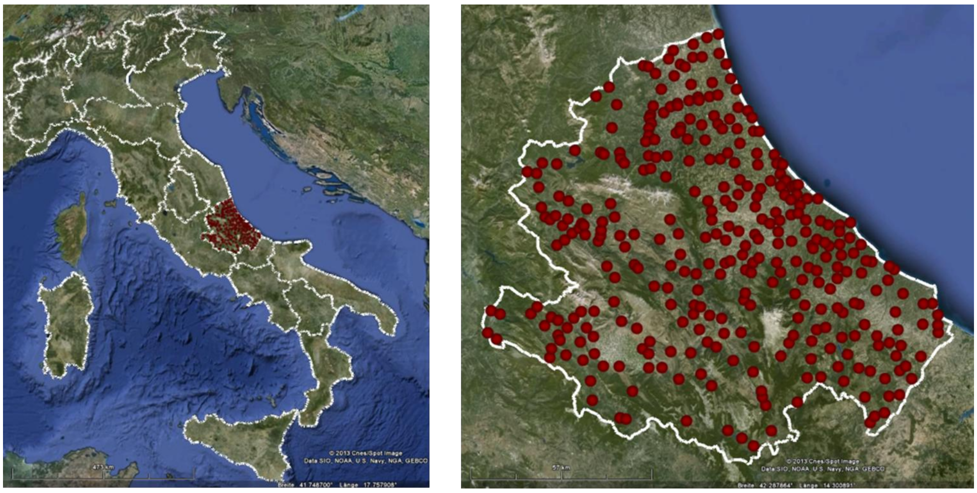

Figure 4-2: Left: Italian regions with their boundaries. Right: Region Abruzzo with anonymized coordinates for central office locations.

	CodISTAT	ComuneISTAT	Latitude	Longitude
Archi 1	13069002	Archi	42.10492	14.37314
Ari 1	13069003	Ari	42.29285	14.26097
Ari 2	13069003	Ari	42.28416	14.26446
Arielli 1	13069004	Arielli	42.26022	14.31262
Ateleta 1	13066005	Ateleta	41.85649	14.19991
Atessa 1	13069005	Atessa	42.07065	14.45421
Atessa 2	13069005	Atessa	42.12721	14.43378
Atessa 3	13069005	Atessa	42.13099	14.41699
Atri 1	13067004	Atri	42.57869	13.99300

Table 4-2: A typical table containing locations in Abruzzo, Italy and anonymized coordinates.

4.3 An Italian reference network

We were able to combine the different layers of the OSM data described in Section 4.1 with the data provided by Telecom Italia from Section 4.2 to create an Italian nation-wide reference fiber topology. Besides data processing and resolving artifacts or errors in the OSM data (missing elements, etc.), we essentially had to solve two critical issues: (i) As already explained OSM data are normally extremely detailed and contain a huge number of nodes. We had to reduce the number of nodes without losing the information about the network structure, important locations and the length of potential fiber routes. (ii) The coordinates provided by Telecom Italia had been anonymized. We had to find a way to include these coordinates as nodes in the OSM based network.

The main process has 4 important steps:

1. Extract data from OSM and create a base-network for 20 regions
2. Connect the given CO sites with the network (shifting) for 20 regions
3. Connect the 20 regions
4. Reduction and cleanup

This process is fully automated, which enables its use also for other countries or territories. Notice that Steps 1 and 2 are done for every of the 20 regions individually. The regions are connected in Step 3. In the following we describe all Steps of the network generation in more detail.

4.3.1 *Extract data from OSM and create a base-network*

The Italian data set from OSM contains roughly 2Gbyte of data containing detailed geo-referenced information about streets, railway systems, power lines, and buildings. In the first step of the network generation we preprocess the data and transform it into our own structured data formats for further processing. In particular we decompose the data into regions and into its individual layers. For the network generation we mainly use the following layers: (i) Highways/Freeways, (ii) Primary roads, (iii) Secondary roads.

We also keep more fine-grained street-structures such as tertiary roads, minor roads, and residential roads but these will only be used if necessary, see below. All other layers are removed from the data set.

In addition to preprocessing (which includes error correction) and decomposition we also perform a first conservative reduction on the data, e.g.: (i) trails with the same end-nodes become one trail, (ii) nodes with degree 2 are removed but only if the main street structure is kept (turns, curves).

These simple reductions and the removal of unnecessary layers already lead to a reduction of around 50% in the number of nodes.

4.3.2 *Connect the given CO sites with the network*

In the next step we make the given (anonymized) coordinates of central office locations to nodes of the network. This is done within two sub-steps: (i) *Shifting:* First we try to move a given CO to the closest higher layer street (only the layer of secondary streets or higher layers are allowed), see Figure 10-9. This is done, however, only if the distance is at most 500m. *Shortest paths:* For all other COs (not in a 500m distance to a higher layer road) we also allow for lower layer streets when shifting. We then compute a shortest path from the shifted CO to the network of higher layer roads, see Figure 10-10. Only this path remains in the network. In fact, to cope with dual homing requirements, we also try to compute a second path, which is ‘maximally’ disjoint from the first (first path links get a large weight in the second shortest path computation), see Figure 10-11.

4.3.3 Connect the 20 regions

Because of the large data sets and limited computing power, all the previous steps are carried out for individual regions only. As a result we get a clean and detailed network topology based on streets with the given central office locations appearing as nodes for each of the 20 regions, see Figure 10-12. Unnecessary fine-grained lower layer streets have been removed and simple reductions/repairs have been carried out. To get a nation-wide network, the individual regional networks are connected. This is essentially done using the highest OSM street layer, that is, by using inter-connecting highways and freeways, (see Figure 10-13). To our knowledge, this is in line with the network architecture of Telecom Italia, where regional networks are interconnected by fibre routes that follow large national highways or rail-way systems.

4.3.4 Reduction and cleanup

The nation-wide network that we obtain with the last step still contains a huge number of nodes and links (in the order of millions) because it still displays the original shape of street routes. The task of the final step is to reduce the structures to a graph in the mathematical sense that connects the important locations, that is, high degree crossings and central office locations. It suffices to have one link between two important locations together with the information how long in kilometer this connection is in the original street network, instead of having several hundred nodes originating from a GPS trace and following the course of the street.

To obtain the required structure we perform two main procedures: (i) *Merging links:* Every node with a degree two that is not a central office location is removed see Figure 10-14. The two links are merged to one link, while we keep the information about the total length. (ii) *Merging nodes:* Nodes within a radius of 500 that are no central office locations get merged, see Figure 10-15.

As a result of these procedures we obtain a clean Italian reference network reflecting a realistic nation-wide fiber topology down to the level of central office locations. The final network has (i) *29,981* nodes with 10,708 COs, (ii) *39,615* links and is displayed in Figure 4-3 (Italy) and Figure 10-17 (Toscana as a regional sub-network).

Figure 4-3: An Italian reference network.

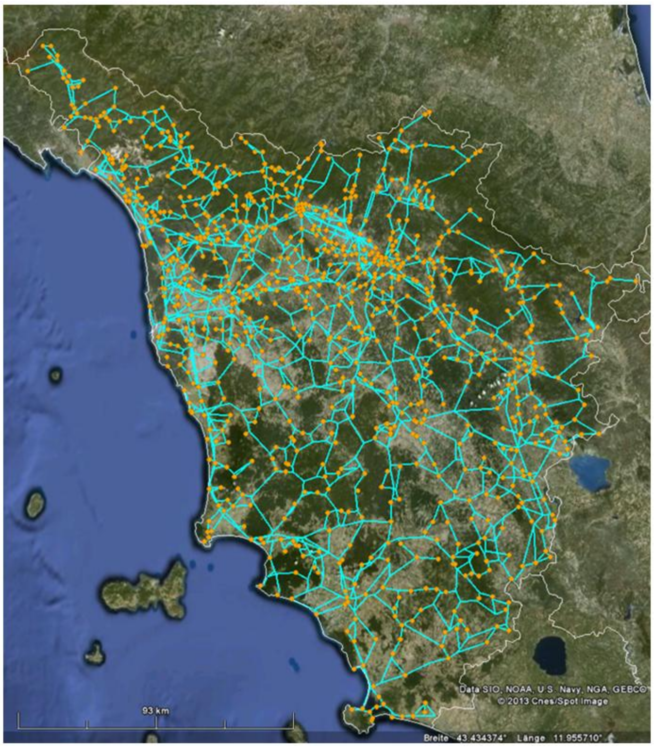

Figure 4-4: Toscana -- a regional reference sub-network.

5 Resilience, Reliability, and Supervision

This chapter describes progress with Task 2.4, regarding (i) reliability assessment; (ii) resilience schemes; (iii) supervision techniques. The Resilience, Reliability, and Supervision study is important because a highly-branched LR-PON in DISCUS architecture needs to serve big areas and hence any single fault may affect a large number of end users. Furthermore, a cable cut like in a conventional optical backbone network would interrupt a large amount of traffic, and the problem of providing protection against outside plant cut remains. To differentiate from work on resilience defined in Task 7.5, this task targets the access segment (interacting with WP4, mainly Task 4.3 optical layer supervision and management).

5.1 Activity 1: Reliability assessment

In this activity, we investigated the methodologies for reliability performance evaluation. These methodologies will be further used for the schemes developed in other activities to assess the corresponding reliability performance.

5.1.1 Resilience measures

This sub-section describes the evaluation methodology for reliability performance assessment. From the operators' point of view, the reduction of the impact of failure (i.e. to decrease a risk that a large number of end users are affected by any failure) should be considered in the first place. It is because a high-impact failure harms the company's reputation and could result in negative press releases [11]. Meanwhile, customers (in particular business users) require a certain level of connection availability (which typically is included in service level agreement signed with the operators), in order to guarantee service continuation. With this in mind, two reliability performance parameters, namely availability and failure impact factor (FIF) defined in [12][13], are taken into account here, which can represent the perspective of the user and operator, respectively.

Furthermore, several scenarios are presented for reliability performance analysis. We analyzed failure impact and unavailability of each segment by mapping the considered hybrid WDM/TDM PON based LR-PON solution to the various scenarios and identified its most important part for protection.

We assessed unavailability and FIF (see sub-sections 10.3.1.110.3.1.2 and 10.3.1.2 for definitions) of each segment by mapping the considered hybrid WDM/TDM PON based LR solution to the various deployment scenarios and identified the need of protection.

With respect to long reach (for node consolidation) it is of importance to understand the impact of reliability performance. The consolidation of COs implies that several traditional access networks are grouped together to form a new service area, resulting in a wider coverage, i.e. with more users and longer distance. The reliability performance evaluation is performed by mapping the considered LR-PON options to the various scenarios with and without node consolidation which are taken from the OASE project [14]. As a reference case, today's scenario in the context of Deutsche Telekom (DT) with 7500 COs without node consolidation [14] is first considered.

Two scenarios representing low and high degrees of node consolidation are also taken into account, where 7500 COs are assumed to be reduced to 4000 and 1000 nodes, respectively. It means that in the 4000 COs scenario approximately two traditional service areas on average are going to be merged to one new service area while in the case of 1000 COs, around eight traditional service areas will be grouped to form a single new service area. Besides, two types of populated areas that can represent urban and rural cases have also been taken into account for the assessment. It should be noted that though these scenarios are defined based on the German network [14], their topological characteristics and demographic distribution most probably could still be applicable for the large part of the networks in the rest of the world. Table 10-1 presents the average fiber length in the different scenarios as well as the number of users covered by one service area. Here, the feeder fiber (FF) is defined as a fiber section between the old CO (e.g. local exchange) before consolidation and the central access node (e.g. DISCUS metro/core node). Therefore, in the reference scenario of 7500 COs (i.e. without node consolidation), the feeder fiber is not considered, and the OLT is supposed to be co-located with the local exchange.

Furthermore, for the evaluated hybrid PON based architectural option we choose the system configuration from [15] (as follow), which is able to guarantee the average data rate up to 300 Mb/s as well as supporting a sufficient reach for the considered node consolidation scenarios.

5.1.2 Hybrid WDM/TDM PON: 80 wavelength channels and 1:16 power splitter at second stage of remote nodes (i.e. RN2).

Figure 5-1 shows the unavailability of various elements for the hybrid WDM/TDM PON along with the fiber parts in the different scenarios. It can be seen that the unavailability of fiber segments in node consolidation scenarios (i.e. 1000 and 4000 COs) is larger than most of the components regardless of the type of populated areas. Therefore, to achieve higher availability in LR-PON case, fiber protection should always be considered in the first place. Furthermore, the remote nodes (RNs), where only the passive components are located, always have the highest availability thanks to their passive manner. Figure 5-2 shows the results of FIF. Similar to the availability results, fiber in particular in node consolidation scenarios (i.e. 1000 COs and 4000 COs) has obviously higher FIFs than the other network elements due to relatively long feeder fibers. It implies fiber (in particular feeder segment in node consolidation scenarios) protection should be considered in the first place in order to effectively reduce failure impact. Furthermore, the OLT in hybrid PON has a significantly higher FIF than the ONU, since any single failure occurring at the OLT could affect all the connected end users.

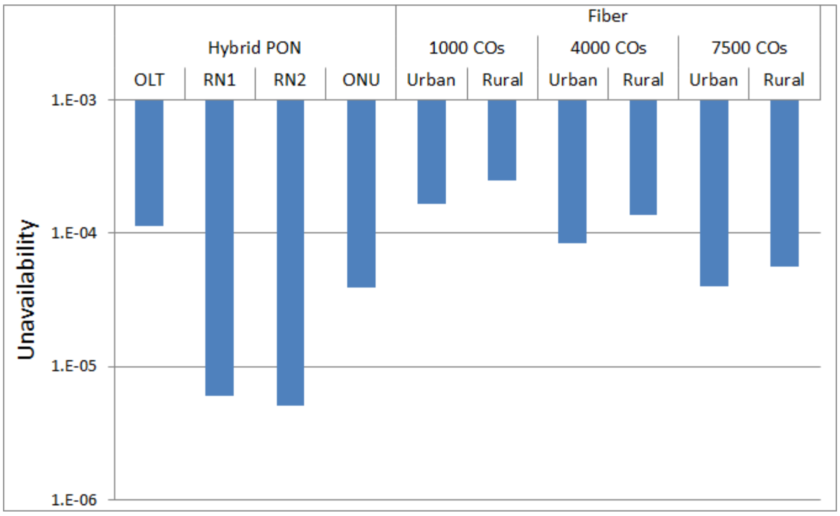

Figure 5-1: Unavailability for each network element without any protection.

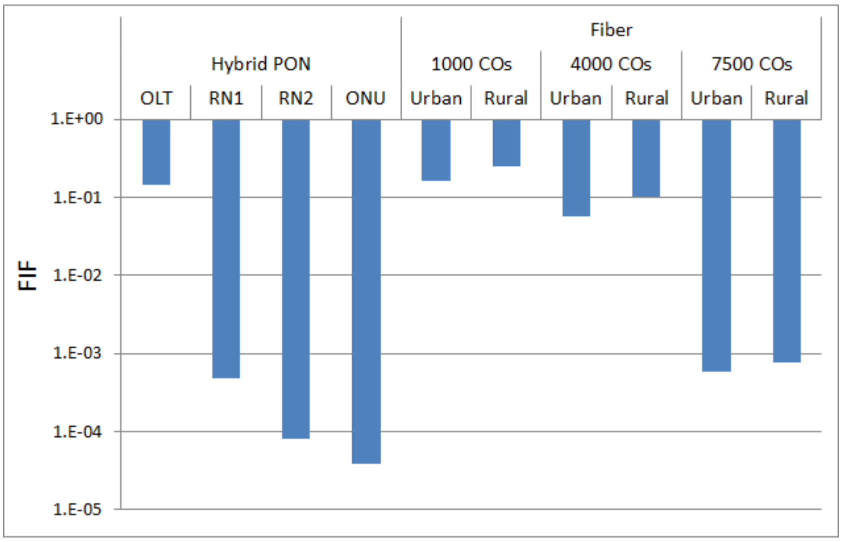

Figure 5-2: FIF for each network element without any protection

As a conclusion, it is extremely important to provide protection of feeder fibers in long reach scenarios as well as backup for the OLT in order to efficiently improve reliability performance of hybrid PON.

5.1.3 Models of power efficiency vs. reliability performance

In this sub-section, we present our recent work [16] on modelling power-efficiency versus reliability performance from the cost perspective.

The worldwide energy consumption is rising, which could translate into huge energy costs to run networks. On the other hand, the access network segment typically experiences high traffic variations with a low average utilization of network resources, making it important to improve efficiency of use of the access energy resources. With respect to this problem a number of power efficient mechanisms have been proposed in the literature [17][18][19], and the topic of energy efficiency has also been addressed in standardization bodies [20]. Most of the proposed schemes try to adapt device's energy consumption to the traffic conditions using the so called *sleep mode* functionality, i.e. switch the device to a low-power (sleep) mode when the traffic is low.

However, a frequent switching between a working and a sleep state may also increase the risk for equipment failure, which in turn translates to higher operational expenditures in terms of an additional reparation cost and potential service interruption penalties. We are in the presence of a tradeoff between the gain associated with the introduction of power efficient schemes and the potential losses one has to face to maintain devices with an increased failure rate. This is particularly true in the access segment where both the number of devices (i.e. the number of end users) and the number of on/off transitions due to traffic fluctuations are potentially higher than in the core part. A methodology has been proposed in [16] to quantify to what extent the energy saved as a result of a specific scheme can be maximized while keeping the extra reparation costs below the potential reduction of the electricity bill.

A number of use cases are identified for an access segment scenario based on wavelength division multiplexing (WDM) based passive optical networks (PON), where both residential and business users are considered. With the help of the proposed methodology we show that it is indeed very important to consider the equipment reliability performance degradation. This is particularly true in those scenarios where the cost for reparation and service disruption is so high that even small variations in the device failure rate may potentially overcome possible saving coming from the energy efficient scheme under exam.

5.1.3.1 Cost analysis

The block diagram shown in Figure 5-3 presents the main steps in our study. The impact on the reliability performance is measured in terms of variation of the mean time between failures (MTBF) of a device. MTBF is the sum of the mean lifetime (referred to as the mean time to first failure (MTTFF)) and the mean time to repair (MTTR). In this study MTTR is assumed to be constant, therefore the MTBF variations are only due to changes of the MTTF. If the maximum allowable value of MTBF variation is relatively high, it means that significant energy savings can be achieved without considering the impact on reliability performance. If, on the other hand, the maximum allowable MTBF variation is low, there is a risk that a given energy efficient scheme may not be beneficial from an overall cost perspective.

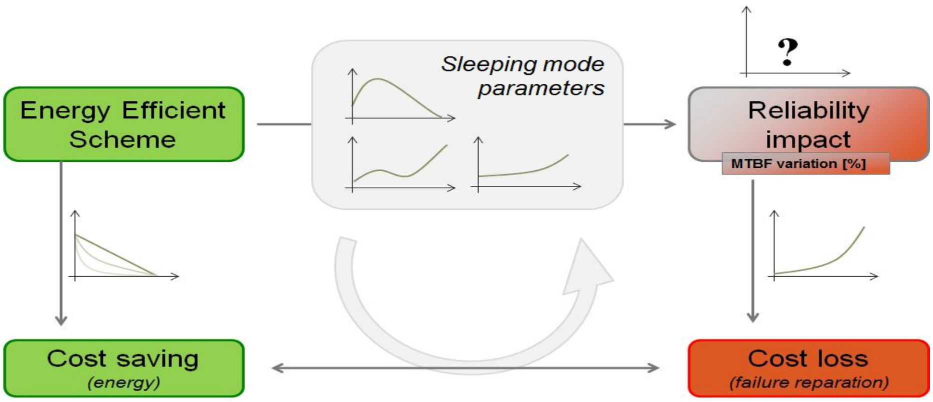

Figure 5-3: Cost analysis [16]

5.1.3.2 Energy related cost saving

In any power efficient scheme based on the sleep mode concept, the energy saved over a period of time is a function of how long a device stays asleep, which in turn strongly depends on the traffic conditions (with high traffic is not possible to go to sleep and consequently no energy can be saved). For this reason energy saving is often presented in the form of an energy profile, which shows the device's normalized energy consumption in function of the traffic load. Given the device's energy profile it is then possible to compute the energy consumption, still as a function of traffic load. Then using the information about the energy price it is also possible to calculate the energy related cost saving per year (noted hereafter as $\Delta Cost_{energy}$, which is also in function of the traffic load).

5.1.3.3 Case studies

Here we focus on WDM-PON based access networks. They are in fact considered as the most promising candidates for LR-PON considered in DISCUS architectures. The case studies under exam are differentiated based on the customer profile (i.e. residential or business) and on the location of the failure. For residential customers, it is assumed that only the ONUs are switched on/off to save energy. As a result only ONUs might be affected by the energy saving mechanisms. On the other hand, for business customers, two different cases are considered. In the first one, only the ONUs are switched on/off to save power. If an ONU malfunctions, only one customer at a time is affected, similarly to the residential case. However, since we are considering business costumers the *failure_cost* parameter includes an additional penalty for service interruption. In the second case it is assumed that only the OLT is switched on/off in order to save energy. Since the OLT serves more than one customer, its failure has a relatively larger impact compared to the failure of an ONU. In this work it is assumed to have one OLT that is connected to 80 business customers. All of them are out of service at the same time if the OLT fails.

For all three scenarios presented in the previous section (one for residential and two for business users) we consider the power saving scheme proposed in [22]. The value of cost of energy used in the simulation study, as well as the power consumption of an ONU/OLT in operational and sleep mode, in addition to other cost related parameters are presented in [21].

The value of V_{MTBF} (MTBF variation, see sub-section 10.3.1.4 for more info), as a function of the traffic load is presented in Figure 5-4 and Figure 5-5 for the residential and the two business scenarios, respectively. The value of V_{MTBF} decreases for increasing values of the traffic load in all three scenarios. This is because the energy saving become smaller for higher traffic loads and consequently failure related costs become less affordable. V_{MTBF} reaches its maximum value when the energy saving is maximized, i.e., when the traffic load is minimal. On the other hand, in maximum load traffic conditions $V_{MTBF} = 0\%$ in all scenarios. This is because with such high traffic conditions device never enters the sleep mode, and without energy saving there is no room to afford any MTBF variations.

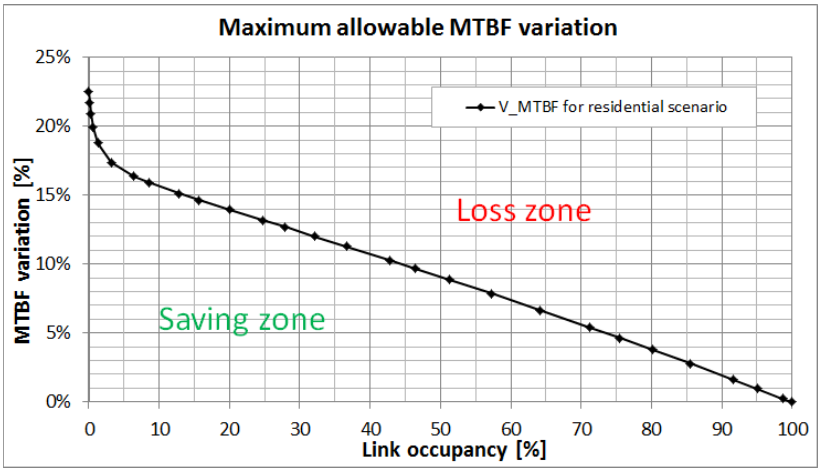

Figure 5-4: Residential customer scenario.

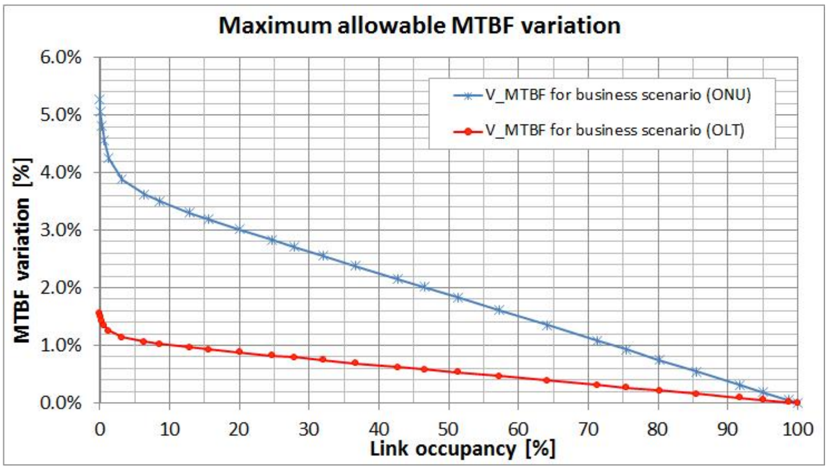

Figure 5-5: Business customer scenario

When looking at all three scenarios at the same time it is possible to notice that the value of V_{MTBF} is higher in the residential costumer scenario, where V_{MTBF} reaches up to 22.51%. Such big MTBF variation is possible because of the fairly low value of the *failure_cost* parameter, which does not include any penalty for service interruption. In fact in the business scenarios, where the value of *failure_cost* is higher, V_{MTBF} is smaller than in the residential case. For business ONU scenario, i.e. when an ONU malfunctions, V_{MTBF} reaches values up to 5.28%. For the business OLT case, i.e. when OLT can malfunction, the maximum V_{MTBF} value is even smaller and of 1.57%.

Since V_{MTBF} represents the value of v_{MTBF} such that $\Delta Cost_{failure} = \Delta Cost_{energy}$ it can also be seen as a value representing the boundary between the cost saving conditions (i.e. values of $v_{MTBF} < V_{MTBF}$ represented on Figure 5-4 as *Saving zone*) and the cost loss conditions (i.e., values of $V_{MTBF} < v_{MTBF}$ represented on Figure 5-4 as *Loss zone*).

5.2 Activity 2: Resilience schemes

This activity concentrates on developing on appropriate resilience schemes for DISCUS architecture. Three sub-activities have been defined as follow: (a) Design of resilient fibre layout; (b) Investigation of hybrid protection technique, where different user types, e.g. residential/business users and mobile backhauling, may have different requirements for resiliency; (c) Optimised layouts and traffic off-loading techniques in order to minimise routing and protection switching capacity required within the metro-nodes.

In this deliverable, we report the latest progress of the all three sub-activities, which have been initialized. Besides, as shown in sub-section 5.1.1, for LR-PON scenarios, the protection of shared part should be considered in the first place. Therefore, up to now we mainly put our efforts on protection of the FF and OLT and plan to extend this work towards end-to-end resilience for some selected users (e.g. business users who require high reliability performance).

5.2.1 Design of resilient fibre layout

The deployment cost of fiber infrastructure is the dominating part of the capital expenditures (CAPEX) and should be minimized by a proper fiber layout. In [23][24] a geographical model is devised aimed at taking advantage as much as possible of the fiber infrastructure sharing where trenching/ducts can be shared by different fiber links. With consideration of resilience, we also proposed a cost-efficient way [25] to provide protection down to the RN is proposed taking advantage of CAPEX reduction caused by the opportunity of sharing the same duct by both working and protection fibers.

In order to be able to share the fiber infrastructure as much as possible, we consider different FFs going through the Feeder Cable (FC) ring while the distribution fibers (DFs) associated with the same PON goes through the Distribution Cable (DC) ring. A CO node (e.g. DISCUS metro/core node) usually supports more than a single PON (hence, it accommodates more than one optical line terminal (OLT) and connects to more than one RN. The reasons for this approach are cost, scalability and efficiency where an operator concentrates all the FF terminations at an optical fiber distribution frame (ODF) in the basement of a CO so that it is easier to be handled. In the PON, RN consists of a power splitter that broadcasts the downstream signal to all the optical network units (ONUs) at user premises.

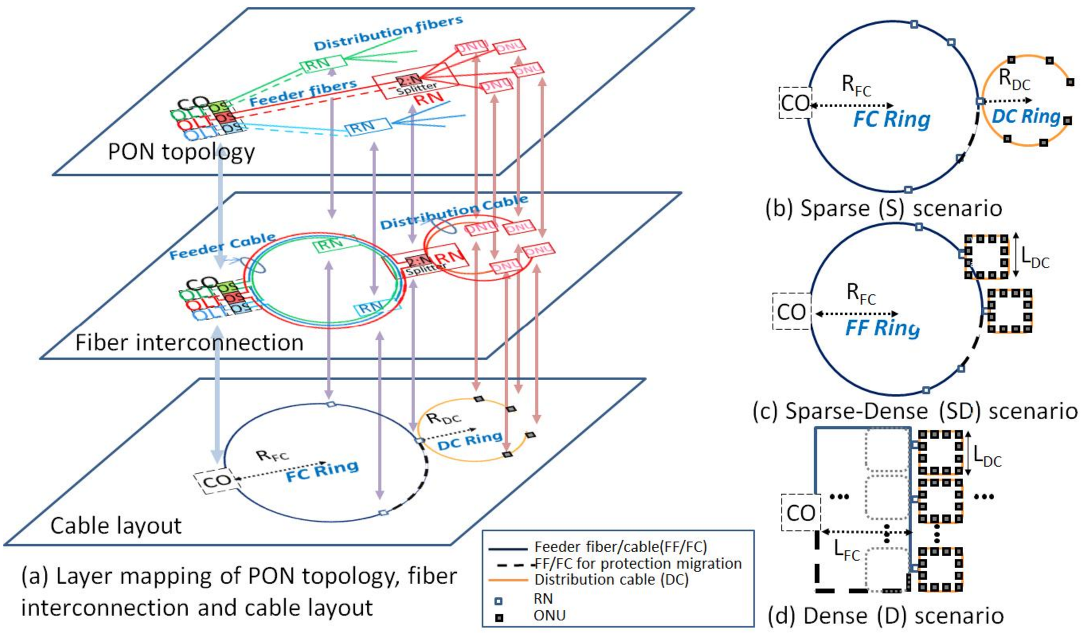

Figure 5-6: Fiber interconnection and resilient cable layout 1 [25]. (a) Mapping of PON topology, fiber interconnection and cable layout, and proposed resilient cable layout for differently populated areas: (b) Sparse (S), (c) Sparse-Dense (SD) and (d) Dense (D).

The fiber layout to interconnect the CO with the different PONs and their users depends on the type of area and the distribution of users within the area. Figure 5-6 illustrates the fiber interconnection and cable layout for the considered scenarios. Figure 5-6 (a) shows mapping of tree PON topology, fiber interconnection and the proposed cable layout. In this study, three population scenarios have been considered: (i) *Sparse Scenario "S"* (subscribers/km^2 < 410 [26])**:** In rural areas, users are far away from each other. In general, RNs are located as close as possible to the users so that the DF installation costs which are directly associated to a single user can be minimized. (ii) *Sparse-Dense Scenario "SD":* A mixed scenario of rural and urban area has been considered, which could be the case of giving access to villages or neighbor communities. In that case, RNs are interconnected through a ring topology, and the users, which are living in the village, are close to each other forming a block with length LDC (see Figure 5-6 (c)). (iii) Dense Scenario "D" (subscribers/km2 > 2048 [26]): In urban areas, users are very close to each other and located along streets. In this study, the Manhattan network model [27] has been used, where users are distributed in blocks separated by parallel streets as shown in Figure 5-6 (d).

It should be noted the current cable layout design concentrates on the FF protection without any OLT protection. For the next step, we plan to extend this work to dual parenting scenario, where working and protection OLTs are located at different places (i.e. different DISCUS metro/core nodes).

5.2.2 N:M OLT Protection Switching to Optimize Backup Capacity

In this Section we propose a mechanism for reducing the number of backup OLTs required at the metro/core node in the DISCUS architecture. Conventional 1+1 protection schemes are implemented by statically connecting a dedicated backup OLT at the end of each feeder fibre that protects for the active feeder fibre of each PON. This leads to a duplication of the total number of OLTs in the network. More efficient

N:M OLT backup schemes can instead be implemented if we introduce an optical fibre switch between the feeder fibres and the OLTs, like shown in Figure 10-20.

While the possibility to use M backup OLTs to protect for N backup feeder fibres (where M<N) is certainly economically attractive, the problem of deciding how many backup OLTs are required at each MC node needs to be tackled. The main parameter to be considered is the identification of the worst-case scenario in term of simultaneous OLT failures within a given area. Here we consider as worst-case the complete failure of a MC node area, which could occur if all electronics in a MC node fail simultaneously (e.g. due to catastrophic events such as fire, flooding, earthquakes,…). Our fundamental protection strategy is based on the dual-homing of each 1st stage splitter, as in Figure 10-20, so that primary and backup feeder fibres are connected to adjacent MC nodes. Each MC can only protect feeder fibres of an adjacent metro node where their coverage areas overlap (intended as the area between the metro node and all the 1st stage splitters). The number of required backup OLTs will depend on the metro node placement strategy in addition to methods to increase OLT sharing in the network. In previous work [28][29][30] we have carried out optimisation of MC nodes placement for minimising the overall IP router protection capacity in the network. Here we extend this work to minimise the number of backup OLTs in the network.

Figure 10-21 shows a basic example of a protection strategy for a LR-PON deployment case, where the coverage areas of MCa and MCb are shown as red hexagonal areas. The general rule is that where an overlap exists between two MC nodes, the 1st stage splitters are connected for primary service to the closest of the two MC nodes, and for backup to the furthest of the two. So a MC node would only provide active services to PONs within the large triangular area (filled with triangular shapes in the figure), while provide backup services to PONs outside this triangle, but inside the hexagon (filled in with square shades in the figure, for MCa). So in Figure 10-21 for example, MCb offers primary connectivity to the exchanges in the P3 area, for which MCa offers feeder protection. Considering this simplified honeycomb-style deployment model, we can see that any MC node can be fully protected by at least 3 overlapping MC nodes.

We now discuss more in details potential protection strategies for sharing backup OLTs. Considering Figure 10-21, MCa provides protection for three adjacent nodes (MCb being one of these), on the areas P1, P2 and P3. With our assumption that any one MC node can fail at any one time, MCa will need to provide enough backup OLTs to protect all the exchanges in P1 or P2 or P3. Thus the minimum number of backup OLT required is max {PON_P1, PON_P2, PON_P3}, where PON_Px indicates the number of PONs in the area Px. It is easy to calculate the number of required backup OLTs in the simplistic (and optimal) case where the location of PONs is uniformly distributed and all MC nodes serve the same number of PONs. Since a MC node is protected by three adjacent nodes, each serving and protecting the same number of PONs, if a node fails, the three adjacent nodes will all provide for one third of the backup OLTs. Thus the overall number of backup OLT required in the network is 33% compared with 1+1 protection. In practice however, considering non-uniform PON location distribution and non-uniform size of MC nodes, this value will be considerable above 33%. Some initial results suggest that for Ireland for example, this number might be as high as 55%.

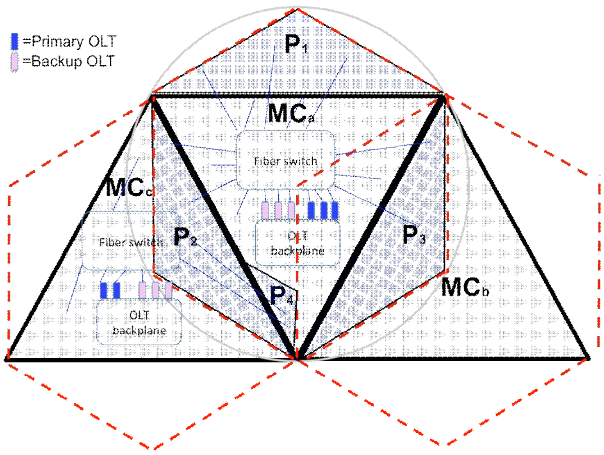

Figure 5-7: Example showing the principle of our OLT offloading strategy to share backup OLTs among the entire network.

The main contribution of this work is to try and further reduce the number of backup OLTs, using ideas similar to those in [28][29][30], but extending them to the PON layer. The main idea is shown in Figure 5-7. Following up from the previous example, after MCb fails, MCa will protect all PONs in the area P3 (notice that the remaining PONs of MCb will be protected by overlapping nodes on the right hand side and below MCb, which are not reported in the figure). The idea is then for MCa to free some active OLTs in the area P4 and redirect them to provide backup to the area P3. This way MCa can reduce the number of backup OLTs required. MCc on the left-hand side of the figure will protect those PONs in the area P4 that MCa has released. This mechanism can be repeated throughout the network and allows MC nodes to share their active and backup OLTs to tackle for failures anywhere in the network, with the result of reducing the overall number of required OLTs. Our initial results show that for Ireland this mechanism can reduce the overall number of OLTs down to 35%.

One of the major issues to consider for the proposed protection mechanism is the time required to switch from active to backup OLTs, especially as our method disrupts active and functioning OLTs in order to spread the failure over the entire network. This time should be kept to below 200ms, ideally below 50ms. Some work on PON protocol carried out in Task 4.1 has already shown that PON can be reactivated in couple of milliseconds. Further work on control plane in Task 6.3 will test how fast a PON can be switched from active to protection, over layers 1, 2 and 3.

5.3 Activity 3: Supervision techniques

Physical layer monitoring techniques and systems are very relevant in a highly branched fiber optic network, such as Long Reach PONs, in order to reduce the operation and maintenance (O+M) costs as much as possible. Due to the high value of the splitting ratio and the use of active elements in the fiber distribution network, it is a challenging matter to detect, identify and locate a physical layer failure in a LR-PON, such as a fiber attenuation or an amplifier failure.

Not only optical fibers, but also some information from active elements, such as amplifiers and ONUs, need to be taken into account, in combination with the topological information of the fiber network.

In this activity, the most suitable approaches for LR-PON supervision are analysed and the most cost-effective integration between resilience schemes and monitoring system are investigated.

Generic PON supervision tools have been identified, whose impact in network resilience and cost is suitable for optimization studies. Among those tools, the following have been identified: (i) *Optical Time Domain Reflectometers* (OTDR) embedded in OLTs and/or ONTs. These OTDRs are, in principle, optimal for feeder fiber and last-drop fibers supervision, respectively. In the latter case, it may be required a backup fiber or wireless connection for reported the trace measurements to the network O+M systems. (ii) *External OTDRs.* These may be located in Metro-Core DISCUS nodes (for supervision of fibers interconnecting the node with other Metro-Core nodes) and in amplified splitter locations. (iii) *2xN splitters in the last splitting point of the LR-PON.* By allowing in-service monitoring using portable OTDRs measuring from the input of a power splitter, cost-efficient fiber fault detection and location may be achieved in comparison with other centralized OTDR measurement approaches. (iv) *Active and Passive demarcation points.* These are distributed points where some kind of supervision element, active or passive, may be located in order to support the PON supervision systems. (v) *In-line supervision systems*, where alarms and optical transceivers monitoring information from amplifiers and ONUs may be gathered and analysed in order to detect and prevent failures. (vi) *Dark fiber supervision.* Attached to the PON in-service fiber network, fibers reserved for supervision can be employed to detect and locate major fiber faults, such as cable bendings or cuts. In this case, the optimization of the dark fiber supervision network topology is a key issue.

This activity will be fed from the results of future Deliverable D4.4, where optical supervision techniques will be analysed in full detail.

6 Power Consumption Modeling

6.1 Power consumption modeling

This chapter describes current status of progress in the power consumption studies of Task 2.5, studying the end-to-end architectures, i.e. including all the main sub-networks e.g. access, and metro/core nodes, and core network. A more detailed work on power consumption shall be provided in deliverable D7.1 scheduled for Month 15. In this chapter we describe two of the studies that have been performed: (i) The first study involves study of core network power consumption. As the network expands, there could be increasing practical problems with supplying large amounts of energy to large network nodes. Power-aware design of networks must therefore include power-aware protocols, such as the proposed approach, to help distribute power consumption at network nodes. This approach could be useful for real network implementations in which each node location is constrained by a limited electricity power supply, for example areas with large population where we want to avoid power shortages. For example, in the UK there is a danger that the energy demand will surpass energy supply, and there'll be shortage of electricity possibly in less than 10 years [31], if no new power stations are built. We show here by using non-uniform traffic that by routing more traffic through the inner core network, we could achieve 76% reduction in power consumption requirement for the outer core nodes. We also show that sparse wavelength conversion placement in the inner core nodes increases network capacity by 27% compared with uniform traffic. Localization of power consumption in the inner core nodes and links in this study allows additional resources to be efficiently and cost-effectively provided. Utilization of inner core network ensures sufficient electricity can reach the inner code nodes, reducing burden on the other core nodes. The same approach can be useful to redistribute power evenly within the network, so that it is almost similar in all nodes. (ii) The second study involves power consumption in the access network. A statistical model is developed for power consumption estimation of high speed connectivity. As the traffic load increases the equipment of the service provider needs to be properly dimensioned in order to guarantee certain QoS, and this dimensioning affects the energy consumption of the service provider. Therefore this study calculates the access network power consumption at the CO. Several PON technologies are considered: GPON/EPON, 10G PON, XLG-PON, TWDM-PON, OFDM-PON and Coherent detection Ultra DWDM (Co UDWDM-PON).

6.2 Static and dynamic power consumption in core networks

In order to minimize power consumption and cost of upgrading the core network, a low hop-count inner core or backbone network can be created from where the outer core nodes can route through. We further show that non-uniform traffic flows in the inner core network, and placement of wavelength converters at those nodes can increase network capacity.

The optical network is shown in Figure 6-1, consisting of wavelength routers interconnected with fiber links, where each link carries a set of wavelength channels using WDM.

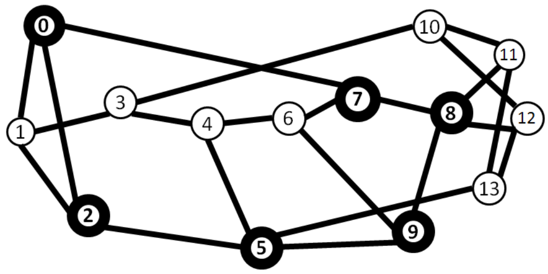

Figure 6-1: Showing the core network: solid circles are the subset of core nodes {0, 2, 5, 9, 8, and 7} that have 10x probability of being selected as source or destination nodes, and sparse wavelength conversion can be applied there.

In each core node location, an IP router is connected to an optical switch node by short-reach interfaces. Core IP routers aggregate data traffic from low-end access routers and connect an optical switch node via short-reach interfaces. The transponders are assumed to be part of the router interfaces. Each transponder has OEO processing capability. Full wavelength conversion can be achieved using a pair of transponders. In the optical layer, the use of lightpath bypass and optical islands minimizes OEO conversion. Lightpath bypass approach is shown that allows IP traffic whose destination is not the intermediate node to directly bypass intermediate router via cut-through lightpath. Lightpath bypass reduces energy consumption and reduces number of required IP router ports. Strategy of lightpath bypass can significantly save power consumption in the range of 25% to 45% [32] over non-bypass designs. Such saving increases with the increasing network size. Lightpath bypass strategy could help minimize required IP router ports [32] [33][34].

In the uniform-traffic case the program chooses at random the start and destination nodes, with equal probability for all the nodes. In the non-uniform traffic case the algorithm increases the probability that the inner core nodes are selected for source and destination, by 10×. This inevitably increases the traffic in the inner core network. Because non-uniform traffic routing localizes traffic deeper in the network core, the provisioning of additional resources there could efficiently and cost-effectively increase network capacity. Additional resources at these congestion nodes could be e.g. in the form of overlay fibres on the links [35], or wavelength converters in the inner core nodes to potentially reduce blocking. Wavelength conversion removes wavelength continuity constraint allowing the lightpath to use another wavelength at a node where the wavelength blocking occurs.

If all-optical wavelength converters are considered too expensive for the network operator, sparse wavelength conversion can be considered where only some network nodes have wavelength conversion capability. However the algorithms for optimal placement of converters in arbitrary mesh networks is considered to be complex, i.e. NP-hard, and heuristic algorithms have been suggested [36].

6.2.1 Routing and Wavelength Allocation Program

Figure 10-22 shows a flow diagram of the algorithm. The algorithm first creates routing tables that specify an optimum path and a number of alternative paths. When a path is blocked the algorithm tries to reroute using alternative paths. If it cannot find an alternative path in the routing table, it calculates an alternative path. The routing algorithm chooses the minimum power consumption lightpath. In addition we include a factor, where k=1.7, to minimize the blocking. However, we found that reducing number of hops doesn't necessarily reduce the total power consumption. The wavelength allocation algorithm allocates the first available wavelength in a fiber. If a wavelength is used in a fiber, it cannot be re-used in that fiber unless the wavelength is deleted. When all the wavelengths in a fiber are used up blocking for that fibre occurs for further connections. Network blocking however occurs when the algorithm cannot find an alternative end-to-end path.

6.2.2 Dynamic power consumption

It is possible to reduce power consumption [37] by including sleep-mode functionality in routers and switches during situations when there is low traffic load. This allows links, individual line-cards, and even whole nodes (i.e. full routers) to be put in stand-by mode, while guaranteeing QoS constraints, such as maximum links utilization. The major power consumption occurs in the OEO at the nodes.

The power consumption model used is based on core nodes that have power consumption scaling with the number of channels, and link power consumption based on inline amplifiers.

We have assumed that EDFAs can either be switched on all the time ('awake' mode) or switched off ('hibernating' mode) at the start of the traffic allocation or when not in use. Switching off amplifiers when not being used helps to reduce the OPEX. For example, for low numbers of connection allocation in the network this results in significant reduction in power consumption.

In the hibernating mode operation, the amplifiers are switched off and are switched on when the first wavelength is used in a fiber. Each lightpath is assumed to have a limited lifetime. When a lightpath is deleted, the amplifiers in the links remain turned on, because the amplifiers support multiple wavelengths, unless they are not carrying any lightpaths. Conversely we assume that once EDFAs are switched on in a link, additional wavelengths do not then require more EDFAs.

6.3 Results

The results that follow assume 8 wavelengths per fiber. For more wavelengths the results can be linearly scaled [35]. We assume that power consumption of source and destination nodes due to electronic routers is 5W/Gb/s. We have not included the power consumption of the metro-core node equipment. The algorithm calculates number of EDFAs required in the links based on 80 km span lengths [38]. We assume that the EDFAs consume 8W independent of the total line rate.

Figure 10-23 shows the effect of hibernating mode equipment on network power consumption. We found that hibernating mode operation of amplifiers is important only for low line rates. For higher line rates power consumption of router nodes becomes dominant. Here, we found that the EDFA power consumption was 35%, 10%, and 4% of total network power consumption for 10Gbps, 40Gbps, and 100Gbps in the network respectively. The power consumption contribution from EDFAs becomes significant only when the network contains low number of connections.

This can be useful when the nodes are in remote locations that have limited supply of power. The high priority nodes increase in power consumption by 68.8%. However there are fewer of these high priority nodes and sufficient resources can be provided in those locations. Alternatively if we wanted to distribute the power equally we could achieve this aim by increasing or reducing the selection probability for the nodes.

It can be seen that dynamic operation can reduce power consumption significantly. Figure 6-2 shows this for various dynamic traffic allocations.

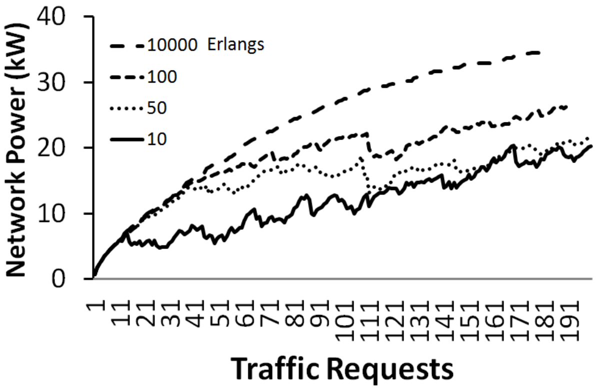

Figure 6-2: Comparison between dynamic and static operation with normal and hibernating-mode operation using Uniform traffic at 10Gbps.

Figure 6-3 compares the node powers using uniform and non-uniform traffic allocation and 10Gbps.

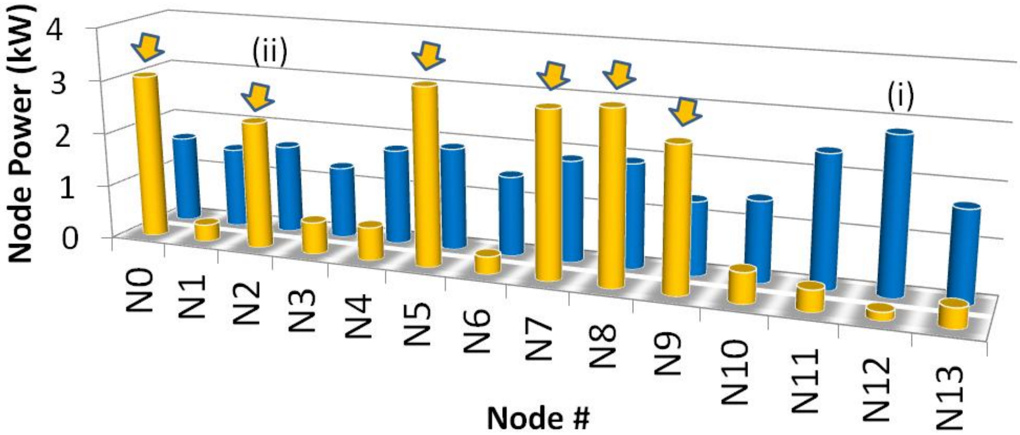

Figure 6-3: Non-Uniform traffic at the indicated nodes (ii) leads to increase in their power consumption and reduction in power consumption in the other nodes. Comparison of power distribution with uniform traffic (i) model.

In summary we found that dynamic operation of the network with 'hibernating' equipment results in significant reduction in power consumption. We found that increasing the selection probability for the inner core nodes increases the power consumption in those nodes and reduces the power consumption in the other nodes, in this case by 76%.

6.4 Statistical model for power consumption estimation of high speed connectivity

While ONU power consumption in customer premises, apart from sleep modes, is constant with traffic load, the equipment of the service provider needs to be properly dimensioned in order to guarantee certain quality of service. This dimensioning may also affect the energy consumption of the service provider, as it will be shown in the following study.

The access network power consumption at the CO can be calculated as the sum of three contributions: (i) OLT PON ports: #OLT ports x power consumption per port (ii) Layer 2 switching, packet processing and traffic management: #OLT chassis x PONs/chassis x bandwidth (DS+US) x 1 W/Gbps; (iii) Uplink ports: #OLT chassis x uplink energy consumption. The uplink energy consumption depends on the required uplink capacity and is obtained by combining bidirectional uplink ports with capacities 1, 10, 40, 100, 400 and 1000 Gb/s which consume 7, 38, 105, 205, 560 and 1100 W respectively.

Several PON technologies are considered in this study: GPON/EPON, 10G PON, XLG-PON, TWDM-PON, OFDM-PON and Coherent detection Ultra DWDM (Co UDWDM-PON). For more details on the power estimation and the bandwidth/reach performance of these PON technologies, please refer to [39].

The equipment count (number of OLT ports & OLT chassis) and required uplink capacity are calculated based on the user demand and QoS scenario. In this study, we consider a best effort internet traffic dominating the traffic of the PON, where a maximum bandwidth, namely B_{target}, is offered to each customer with a minimum percentage of time of availability, namely $p_{avail,min}$, and offering the same priority to each customer.

We only model downstream bandwidth, assuming the upstream bandwidth scales with downstream bandwidth following the technology-dependent PON symmetry ratio. We adopt a user behavior model where each user has the same probability p_{act} to be active. We assume that users request a fixed target bandwidth B_{target} when they are active.

For the Time Division Multiple Access (TDMA) technologies, we assume perfect dynamic bandwidth allocation (i.e. without packet loss in the PON section) in both upstream and downstream direction. When k active users from N total independent users are demanding or delivering traffic from/to an OLT interface, the maximum bandwidth that can be offered to each user is Bmax=(PON_BW)/k, (k=1…N). Due to statistical gain, the value of Bmax is much higher than the fixed bandwidth that can be offered to each connected user, calculated as Bmin=(PON_BW)/N.

For the QoS estimation of the internet access service, two parameters are considered: $p_{avail,min}$ (%), the minimum percentage of time that the target bandwidth should be available for each connected user; and MPL (Maximum Packet Loss), the maximum ratio of packets discarded over packets offered in the uplink interface of an OLT chassis (from the OLT to the aggregation network). In our analysis we focus on a best-effort internet service, with moderate Quality of Service requirements: MPL is fixed at 10^{-3}, and $p_{avail,min}$ = 20%.

Once the user demand and QoS values are fixed, we use two different approaches to compare the power consumption of the various PON technologies.

In the first approach, we look at the performance of the solutions without modifications of the ODN, considering a fixed legacy optical power split ratio of 1:64 (64 homes passed per PON). For each solution, we calculate p_{avail} and check if the QoS requirement can be satisfied. The results of power consumption in this approach for the considered PON technologies offering internet access speeds of 600Mb/s and 1Gb/s are shown in Figure 6-4 and Figure 6-5.

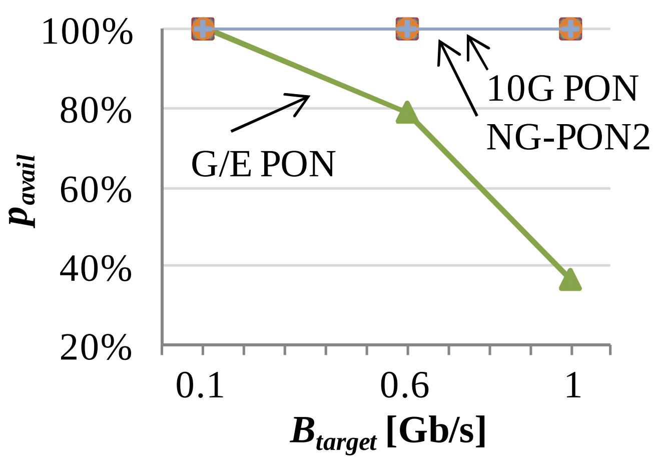

Figure 6-4: Availability of the PON solutions for varying target bandwidths in case of low user activity (pact = 0.1), using an existing ODN with split ratio 1:64. Source: [39].

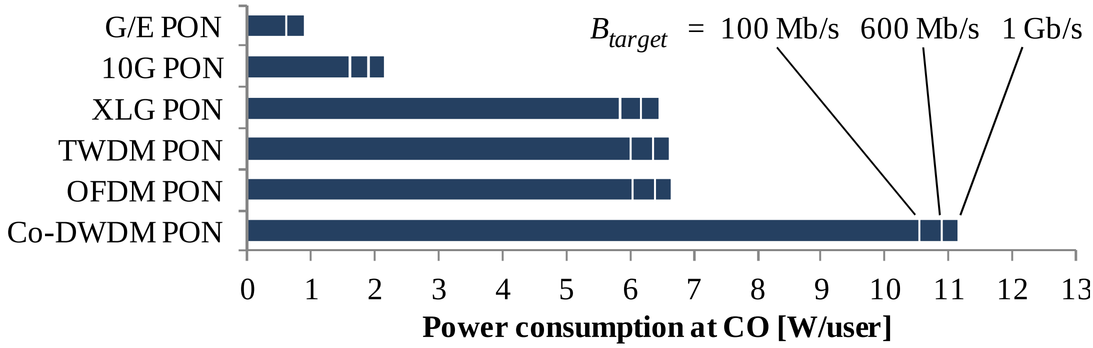

Figure 6-5: Power consumption of the PON solutions for varying target bandwidths in case of low user activity (pact = 0.1), using an existing ODN with split ratio 1:64. Source: [39].

It can be seen how the increase of the offered speed of internet access increases the power consumption of the CO equipment. Keeping legacy GPON/EPON technologies is an energy efficient approach if a reduction in the availability time of the offered bandwidth is accepted up to 20%.

For an increased user activity (pact=0.5), neither legacy GPON/EPON technologies support the availability threshold of 20% time for the offered bandwidths, see Figure 6-6 and Figure 6-7, thus NGPON solutions such as XLG-PON, TWDM-PON and OFDM-PON are required, at the expense of increased energy consumption. A Co-UDWDM-PON technology, with lowest latency and jitter values, is the most energy demanding solution at the CO.

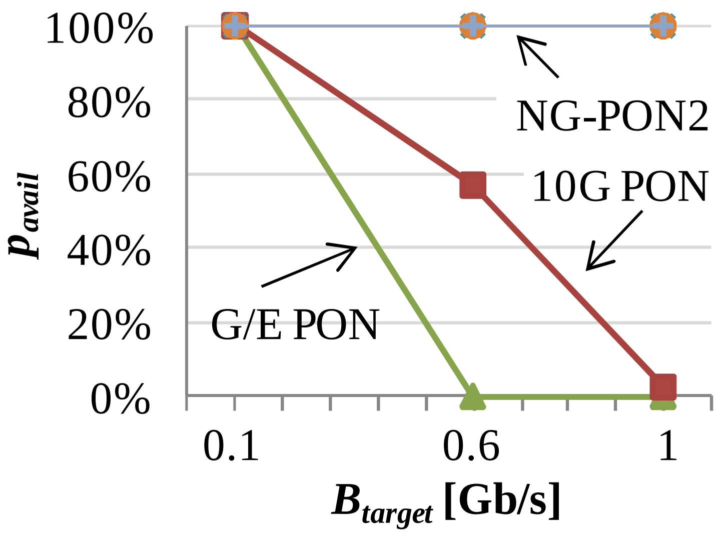

Figure 6-6: Availability of the PON solutions for varying target bandwidths in case of high user activity (pact = 0.5) using an existing ODN with split ratio 1:64. Source: [39].

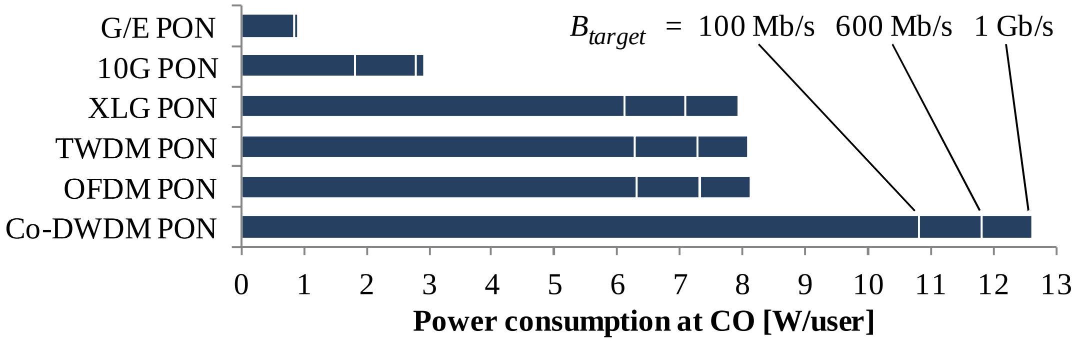

Figure 6-7: Power consumption of the PON solutions for varying target bandwidths in case of high user activity (pact = 0.5) using an existing ODN with split ratio 1:64. Source: [39].

In the second approach, we determine the maximal split ratio at which $p_{avail,min}$ can be guaranteed for each technology (note that this split ratio may be higher or lower than the legacy value of 1:64, depending on the user demand, the offered bandwidth and the PON technology). There is a trade-off between availability (QoS) and power consumption: increasing the split ratio will decrease availability, but it will also decrease power consumption as the OLT equipment is shared by more users, see Figure 6-8 and Figure 6-9.

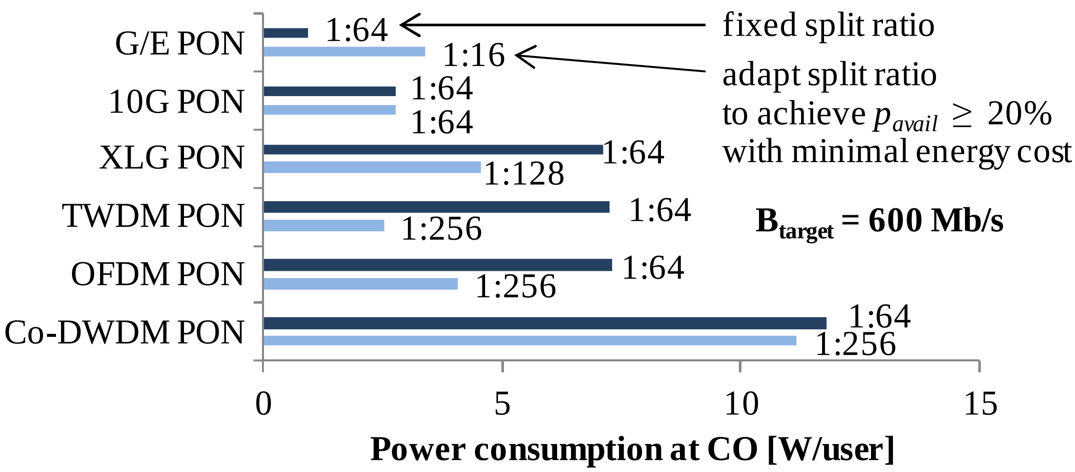

Figure 6-8: Power consumption of PON solutions for target bandwidth 600 Mb/s in case of high user activity (pact = 0.5): results for an existing ODN with split ratio 1:64 (dark bars) versus a flexible ODN (light bars). The chosen split ratios are indicated next to the bars. Source: [39].

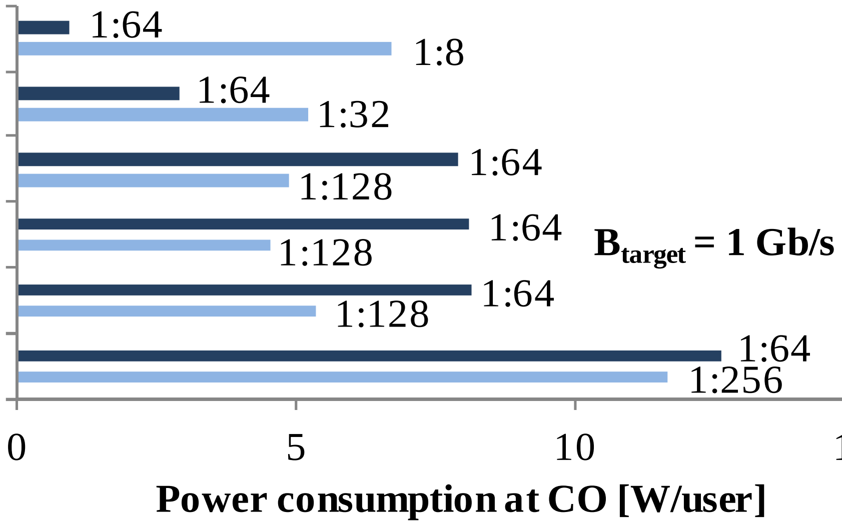

Figure 6-9: Power consumption of the PON solutions for target bandwidth 1 Gb/s in case of high user activity (pact = 0.5): results for an existing ODN with split ratio 1:64 (dark bars) versus a flexible ODN (light bars). The chosen split ratios are indicated next to the bars. Source: [39].

It can be seen that the user behavior is of key importance in order to dimension the Central Office equipment of a PON system in an energy efficient way.

For low user activity probability (10%), legacy GPON/EPON systems can be used for up to 1 Gb/s internet access if a reduction up to 20% availability time of the maximum offered speed is accepted.

Nevertheless, when user activity probability increases up to 50%, then NG-PON2 technologies with 40 Gb/s or higher bandwidth capacity per PON port are required, at the expense of an increase in the energy consumption.

Energy efficiency can also be achieved for NGPON2 technologies by increasing the power split ratio of the outside plant to typical values of 1:128 and 1:256.

7 Traffic and Service Modeling

7.1 Introduction

This chapter describes the progress in Task 2.6 regarding the traffic and service modeling. Two studies are described: In the first study we look at IPTV for live video content over Passive Optical Networks. We calculate the probability that a user will select a new channel versus number of channels continuously broadcast. We also calculate the capacity required in the PON vs. the number of channels continuously broadcast. We base our traffic modeling on estimation of application and service usage by end-users. In order to consider the capacity requirements of a PON, we assign each PON user a specific profile according to a probability distribution. We then run the model to simulate a typical PON usage during the busy period. We are currently improving the model by taking into account additional indicators of population distribution such as persons per household and age distribution, and are currently investigating additional ones.

7.2 Service oriented Traffic demands

Often network dimensioning and simulations are based on scaling existing traffic matrices. Such methods present two main drawbacks: firstly, scaling traffic matrices is usually done based on analysis of traffic growth trend on the past few years. These methods can be very inaccurate and have lead in the past to serious misinterpretation of growth estimates (i.e. it is believed that the estimate of Internet traffic doubling every three months was among the main contributors to the telecommunication bubble at the beginning of the century). The second problem is that traffic matrices are inherently tied to the specific architecture of the network where they originated. Thus they are not reliable if applied to networks built on different architectures.

For this reason we have based our traffic modeling on the estimation of application and service usage by the end-users. The main advantages of this approach are that on the one side the input parameters can be directly associated to user behavior which can be more reliably verified than aggregated traffic matrices. On the other side the models are completely independent of the network architecture that delivers the services and can thus be applied to every network scenario.

Although we consider different types of applications, multimedia video content is believed to be the service that will consume more bandwidth in the near to medium term. In fact video content distribution is, after peer-to-peer, the service that consumes most of the network capacity. Indeed if we consider that most peer-to-peer content is also video content, we find that this becomes unilaterally the highest consumer. Each video transmission can typically occupy an average capacity between 1 and 3 Mb/s, and last between 30 minutes and 2 hours, moving data files of sizes between hundreds of MB and a few GB. Higher quality and definition content could in future easily produce over 30Mb/s (i.e. blue-ray quality).

Traffic reports [40] show that, due to the widespread use of IP technology to deliver multimedia services (due to its inherent unicast nature), users are switching from watching broadcast television towards personalized content (i.e. from user generated content available on YouTube to more ordinary video content available from Netflix and other similar providers). While it is envisaged that in the near future personalized video will dominate over broadcast content, currently the latter still dominates. It is predictable thus that FTTH provider will still distribute live video content over Passive Optical Networks. For this reason besides our main goal of modeling distribution of personalized content (i.e. Video on demand and other multimedia services) we also consider traffic generated by IPTV type of services (i.e., distribution of live content).

7.2.1 IPTV

IPTV is commonly intended as the distribution of live TV channels, similarly to current satellite and cable television, but delivered over the IP protocol. In principle IPTV could be considered a unicast type of service, as each user requests a copy of the content to a server, and could be modeled similarly to other video-on-demand content distribution. However, due to the broadcast nature of PONs, it is envisaged that FTTH operators will use broadcast and select techniques to deliver IPTV content to PON users in order to reduce the overall capacity required.

The fact that for IPTV content can be requested by users however generates a trade-off: on the one hand the operator wants to broadcast the minimum amount of channels required in order to reduce the overall PON capacity used by IPTV; on the other hand it wishes to keep user satisfaction high by providing content as quick as possible (thus transmitting popular channels independently on whether they are currently being watched). In fact if a channel is not currently being broadcast, a user requesting it will incur a longer delay (up to several seconds) before receiving it, a common cause of complaint among IPTV customers [41].

Many techniques have been proposed to reduce such latency, mostly involving continuous broadcast of a number of popular channels ([41][42][43] are an example). We have designed a statistical model to compute the trade-off between capacity consumed on the PON network vs. user satisfaction. The results are plotted in Figure 7-1 and Figure 7-2. Figure 7-1 shows the probability that a user will select a new channel (this is a measure of user dissatisfaction as this operation will incur further delay) vs. the number of channels continuously broadcast. Figure 7-2 shows instead the capacity required in the PON, assuming every channel can be encoded to an average of a 5 Mb/s capacity, again vs the number of channels continuously broadcast. In our study we have considered a number of TV sets equal to 1,000, i.e., considering 500 households with two TV sets each. The different curves represent the probability of a TV set being on (varying between 1% and 50%, i.e. respectively between 10 and 500 TV sets turned on). The total number of channels considered was 127.

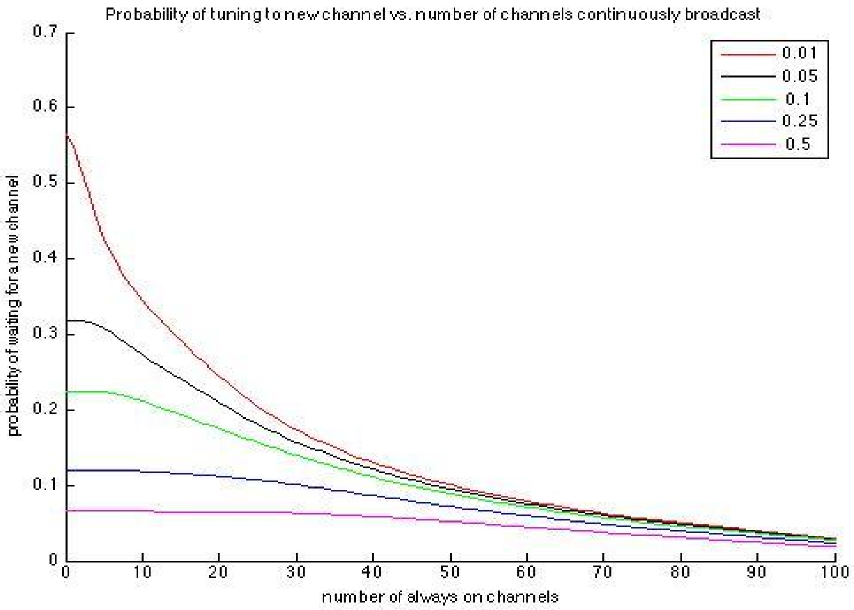

Figure 7-1: Probability of a user tuning to a channel not currently broadcast.

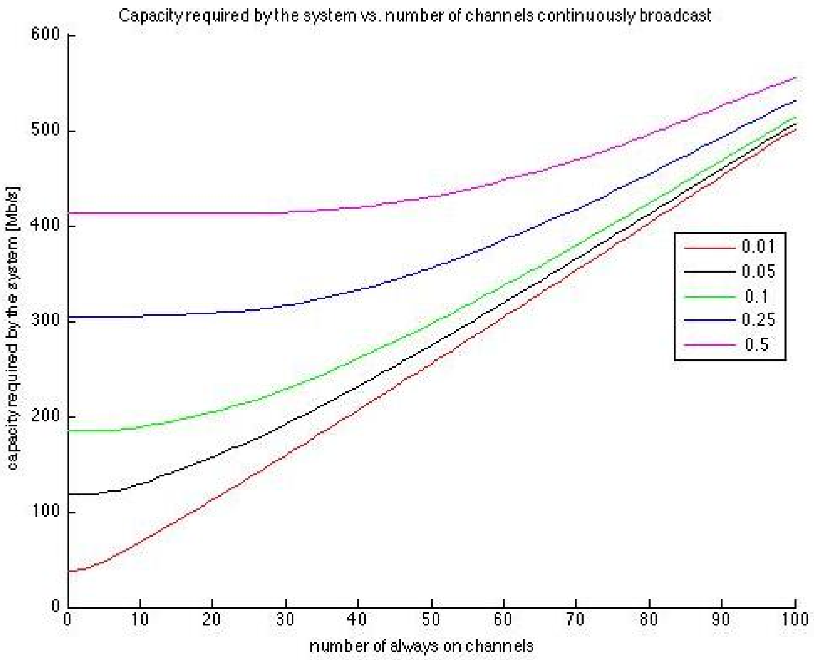

Figure 7-2: Average capacity required as a function of the number of always-on channels, for an average channel bit rate of 5Mb/s.

7.2.2 Unicast services

The aim of the unicast model is to account for high-capacity personalized services. Our initial model targets residential user services, as these represent, once aggregated, the heaviest users of network resources.

The first step in our model is to create a number of different user profiles. Each profile determines the probability that a certain user might subscribe to a given set of services, the probability of using each service, and the typical daily usage. Starting from such profiles, random variables are used to simulate the starting time of a user requests as well as the service duration. Depending on the user profile, multiple services might operate simultaneously with different probabilities. Since our model is service-based, we assume each service to require a constant capacity throughout its duration (each service or application is characterized by different bandwidth requirements). In addition, the model differentiates usage by time of day, although our main target is to analyse the requirements for the network busy period (i.e. typically late afternoon to late evening).

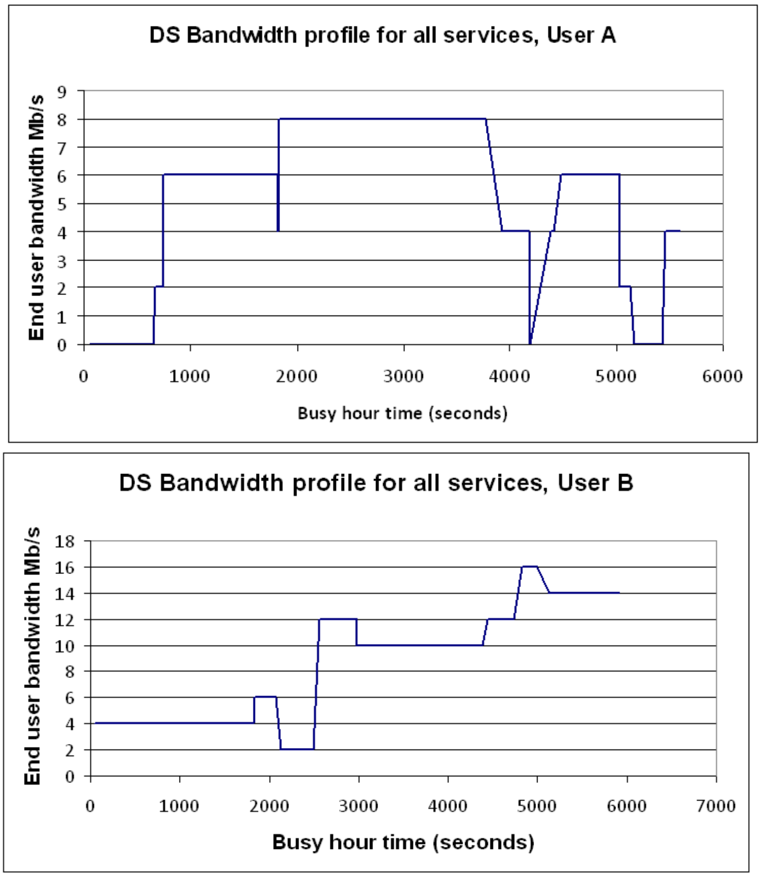

Figure 7-3: Random bandwidth profile example for two different users

In order to consider the capacity requirements of a PON, we assign each PON user a specific profile according to a probability distribution. We then run the model to simulate a typical PON usage during the busy period. Example of user bandwidth profiles over a busy period generated by the model can be seen in Figure 7-3. The changes of capacity used over time is due to overlap of multiple services, each of different duration and each starting at a random time.

We are currently improving the model by taking into account additional indicators of population distribution such as persons per household and age distribution, and are currently investigating additional ones. Age seems indeed a primary indicator for differentiating users profiles (i.e. type services/apps used as well as average time spent on line). The aim is to modify user profiles depending on the country being considered.

As we previously mentioned, traffic generated from business users tend to be lower than residential one, thus in principle it is the latter that drives network capacity dimensioning. However this is only valid under the assumption that capacity can be redirected from business users (mainly active over daylight working hours) to residential users (mainly active in the evening). In our model we do not make such assumption for two reasons: firstly because its validity depends on the architecture considered, whether (and at which point in the network) allows reallocation of capacity to diverse users. Secondly because it also depends on the business models in use: it is in fact quite common for a business to request “fixed bandwidth pipes”, which statically allocate capacity to specific services independently of its usage. For this reason we are currently expanding the model to also include additional business-oriented services.

Finally, video index reports [40] show that video content is increasingly moving from fixed platforms such as TV and PC, to mobile platforms (i.e. mobile phones and tablets). Thus, new busy hours have started to appear in the early morning as users consume video content during the commute. As additional capacity in mobile networks will be made available through the deployment of a much larger number of smaller cells, we envisaged that PON networks, due to their ubiquity, will become the most cost-effective means to offer mobile backhauling. For this reason we are planning to also integrate current and future estimates of mobile backhaul traffic into our traffic model.

8 Summary/Conclusions

This deliverable described the current progress with the various tasks in WP2. Chapter 2 produced a summary of the all-optical architectures developed in Task 2.1 that use optical networking to span and eliminate electronic layers between access, metro, and core layers, resulting in a complete end-to-end approach with a common protocol. Chapter 3 described the techno-economic model developed in Task 2.2, which currently includes only the access network. The metro-core node model will be added later and this will be described in further deliverables. The techno-economic study compared various optical access network solutions including long-reach PONs (LR-PONs), Gigabit/s PONs (GPONs) with 21cn backhaul, Fibre-To-The-Cabinet (FTTC), GPON with Reach Extender (XRGPON), and Point-to-Point (Pt-Pt). Chapter 4 described the end-to-end network optimisation performed in Task 2.3. Activities have been related mainly to modelling reference topologies at different levels of detail, from CO sites to metro/core, and from local exchange to buildings. A non-operator specific and nation-wide reference network for Italy has been derived combining data from Telecom Italia and Open Street Maps. Chapter 5 described the progress with resilience, reliability and supervision. Reliability studies include impact of failure, and connection availability, in various WDM/TDM PON hybrid PON architecture implementation scenarios in the context of Deutsche Telekom (DT) network. Impact of sleep-mode operation on energy saving and reliability was also studied. Resilience schemes include design of resilient fibre layout, because the cost of fiber infrastructure is the dominating part of the capital expenditures (CAPEX) and should be minimized by a proper fiber layout. Progress with resilience also included a more efficient N:M OLT backup schemes by introducing an optical fibre switch between the feeder fibres and the OLTs, instead of conventional 1+1 protection schemes that lead to doubling the total number of OLTs in the network. Progress with LR-PON supervision techniques included identifying various generic PON supervision tools, including Optical Time Domain Reflectometers (OTDR), External OTDRs, Active and Passive demarcation points, and Dark fiber supervision. Chapter 6 described initial progress in power consumption modeling. The first activity described was related to the core network, work performed between Tasks 2.5 and 7.1. We showed that non-uniform traffic flow can create an inner core network, and placing wavelength converters there could increase capacity compared with uniform traffic. It was proposed that because non-uniform traffic routing localizes traffic deeper in the network core, the provisioning of additional resources there could efficiently and cost-effectively increase network capacity. Application of this strategy allows power consumption in various nodes of the optical networks to be adjusted. As the network expands, increasing practical problems can be encountered with supplying large amounts of energy to large network nodes for example areas with large population where we want to avoid power shortages. A power-aware network can help equalize power consumption of network nodes. We provided results for “static” and “dynamic” power consumption models based on power consumption of equipment required to implement a particular architectural solution and traffic load. “Dynamic” power consumption model took into consideration traffic level dependent power-down or power reduction strategies to take advantage of short-term variations in traffic load. The second activity that was described was power consumption in the access network. We described progress of statistical model for power consumption estimation of high speed connectivity for properly dimensioning service provider equipment with traffic load in order to guarantee certain QoS. The access network power consumption at the CO was calculated for several PON technologies including GPON/EPON, 10G PON, XLG-PON, TWDM-PON, OFDM-PON and CO-UDWDM-PON). Details on power estimation and the bandwidth/reach performance of these PON technologies were provided. More detailed study of power consumption in the core and access networks will be presented in the month 15 deliverable D7.1. Finally, Chapter 7 described the progress in Task 2.6 regarding the traffic and service modeling. Two studies were performed: In the first study we looked at live video content over Passive Optical Networks using IPTV. We calculated the probability that a user selects a new channel versus number of channels continuously broadcast. We also calculated the capacity required in the PON vs the number of channels continuously broadcast. In order to consider the capacity requirements of a PON, we assigned each PON user a specific profile according to a probability distribution. We also studied a typical PON usage during the busy period.

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10 Appendices

10.1 Appendix (a): Techno-economic Studies

10.1.1 Comparison of various technologies

Figure 10-1 below shows the cost per customers connected for various parts of the network. Most of the metro-node equipment and buildings costs are not yet included in the model except for the backhaul transmission system terminating equipment (i.e. GE and 10GE line cards). The duct and cabling contain most of the costs.

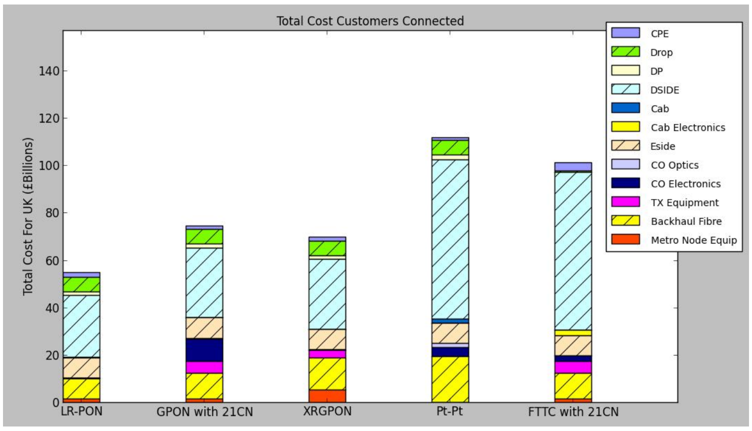

Figure 10-1: Comparison of cost per customer connected for architectures modelled (Exchange population=24645, take-up rate=30%, D-side distance= 0.597km, E-side distance= 1.1 km, Backhaul distance= 140km, Max sustained bandwidth= 100 Mb/s/customer)

Figure 10-2 shows the costs per customer passed, including all the costs except the drop costs. The heights of the bars are much lower than those for the customers connected because of the 30% take-up rate, which is assumed to be the national average.

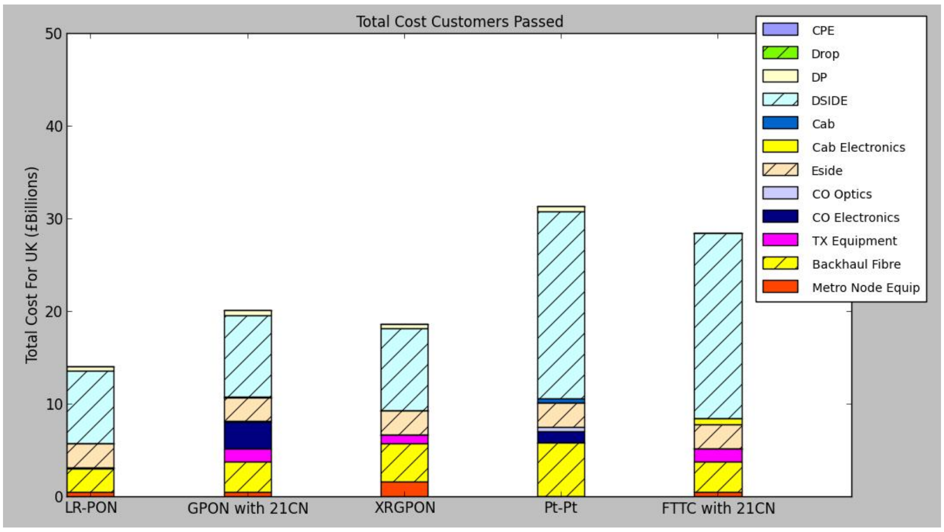

Figure 10-2: Comparison of cost per customer passed for architectures modelled (Exchange population= 24645, take-up rate=30%, D-side distance=0.597 km, E-side distance= 1.1km, Backhaul distance=140 km, Max sustained bandwidth= 100 Mb/s/customer).

Figure 10-3 shows the variation of cost per customer versus take-up rate. It can be seen that the cost per customer passed increases gradually with take-up rate, because most of the costs are included in passing all the customers. However the curves for the cost per customer connected increases with lower take-up rates. The reason for this is that the number of customers passed is equal to 100% of the LE/CO population, whereas the number of customers connected is only 30% and therefore the network equipment is more expensive because it is shared less.

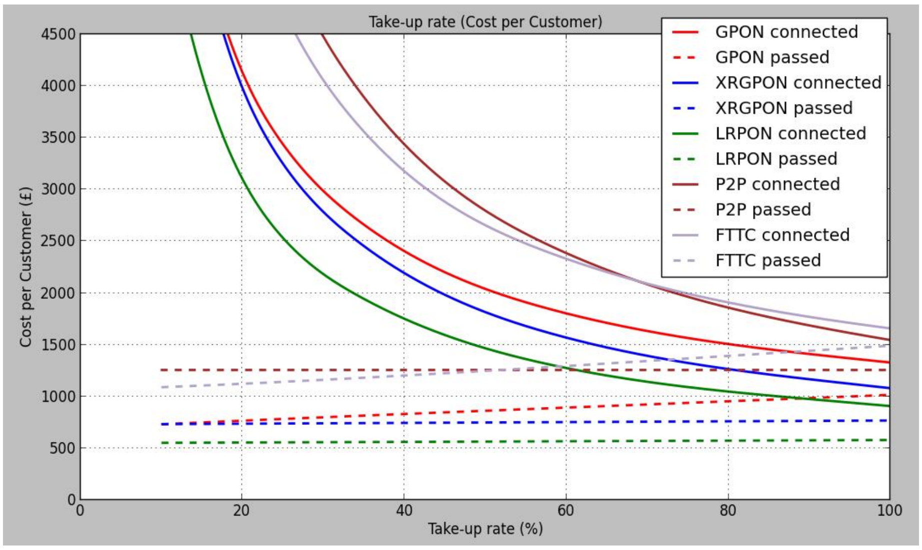

Figure 10-3: Comparison of cost per customer versus take-up rate (Exchange population= 24645, D-side distance=0.597 km, E-side distance= 1.1km, backhaul distance=140 km, max sustained bandwidth= 100 Mb/s/customer).

Figure 10-4 shows a comparison of the total cost for LE with Exchange population.

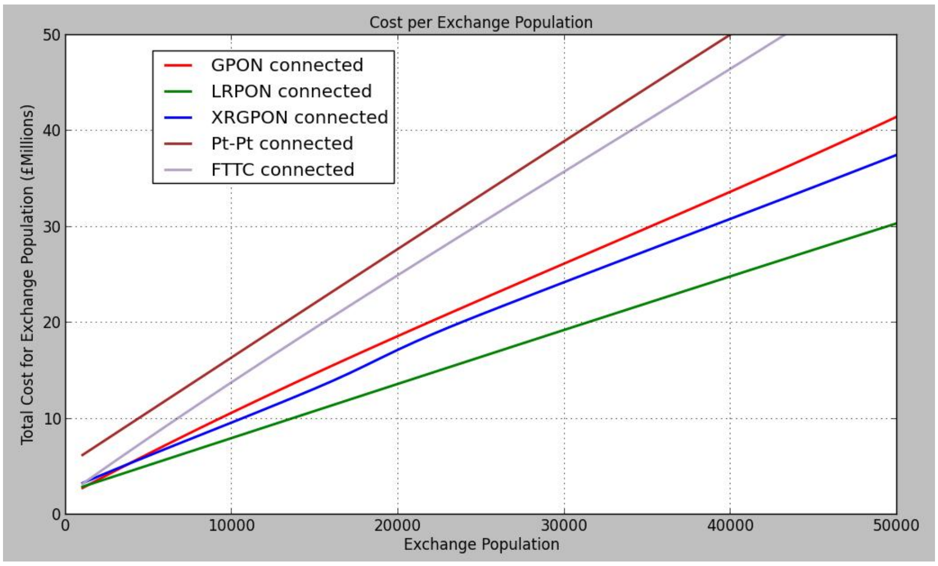

Figure 10-4: Comparison of total cost versus exchange population (D-side distance=0.597 km, E-side distance= 1.1km, backhaul distance=140 km, max sustained bandwidth= 100 Mb/s/customer).

Figure 10-5 shows a comparison of the total cost for LE with take-up rate.

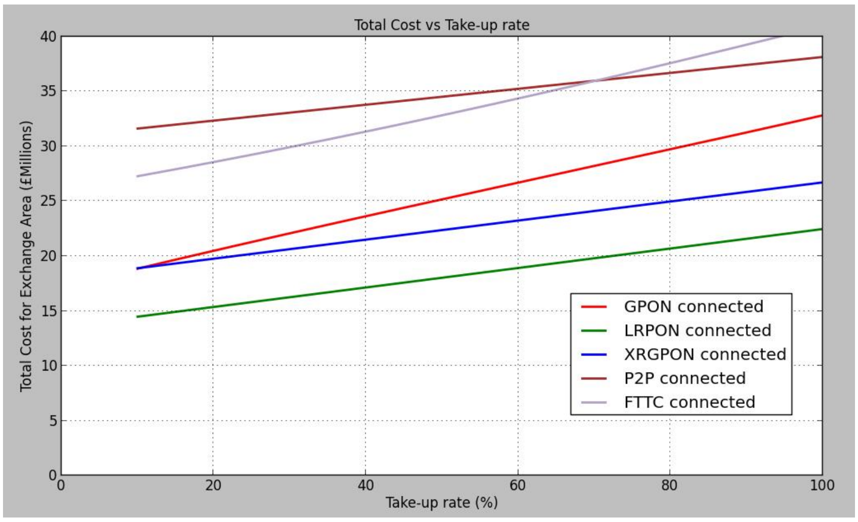

Figure 10-5: Comparison of total cost versus take-up rate (Take-up rate= 30%, Backhaul distance=140 km, E-side distance= 1.1km, D-side distance=0.597 km, max sustained bandwidth= 100 Mb/s/customer).

Figure 10-6 shows the comparison of the time-to-positive cash flow versus take-up rate.

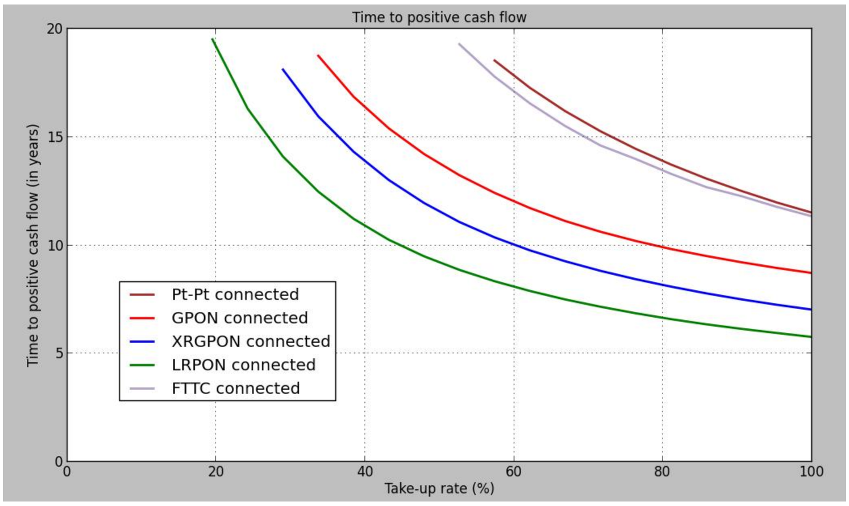

Figure 10-6: Comparison of the time to positive cash flow versus take-up rate (Exchange population= 24645, Backhaul distance=140 km, Take-up rate= 30%, D-side distance=0.597 km, E-side distance= 1.1km,, max sustained bandwidth= 100 Mb/s/customer).

Figure 10-7 shows the time-to-positive cash flow versus initial revenue.

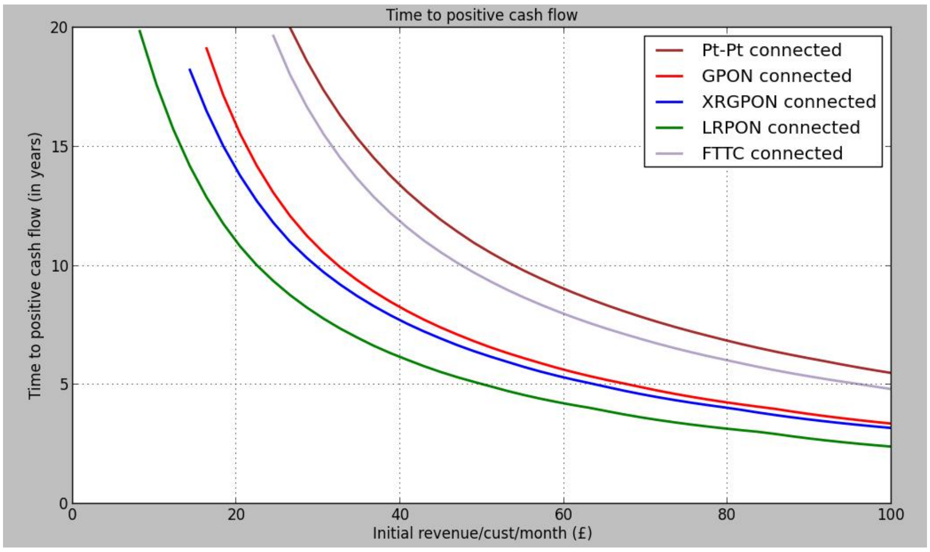

Figure 10-7: Comparison of the time to positive cash flow versus initial revenue for architectures modelled (Exchange population= 24645, Backhaul distance=140 km, Take-up rate= 30%, D-side distance=0.597 km, E-side distance= 1.1km,, max sustained bandwidth= 100 Mb/s/customer).

Figure 10-8 shows the total cost for LE/CO with % new copper required for 10% copper duct. It can be seen that for no additional copper build FTTC is the lowest cost solution, otherwise LR-PON appears to be the best solution in this case.

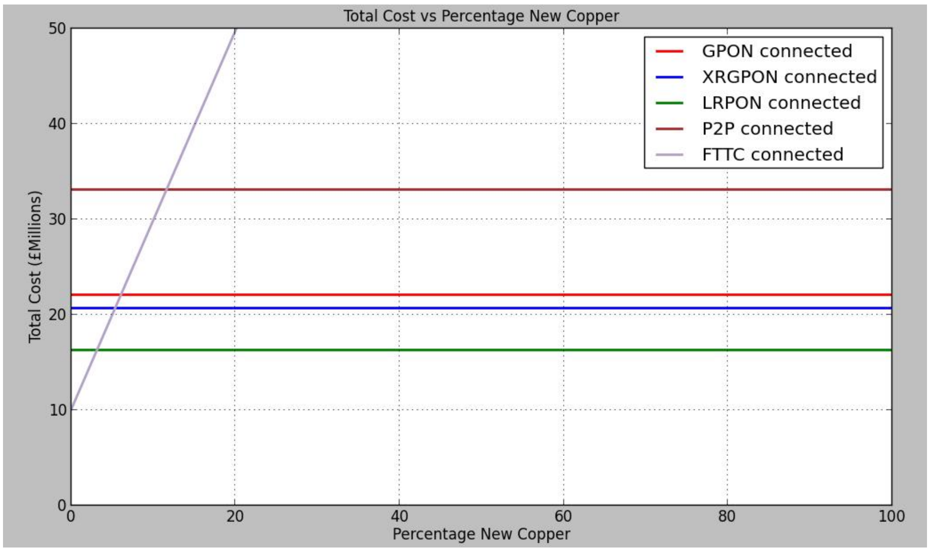

Figure 10-8: Comparison of total cost versus revenue for architectures modelled (10% copper duct build required) (Exchange population= 24645, Backhaul distance=140 km, Take-up rate= 30%, D-side distance=0.597 km, E-side distance= 1.1km,, max sustained bandwidth= 100 Mb/s/customer).

10.2 Appendix (b): End-to-End Network Architecture Optimisation

10.2.1 Extract data from OSM and create a base-network

The Italian data set from open street maps contains roughly 2Gbyte of data containing detailed geo-referenced information about streets, railway systems, power lines, and buildings. In the first step of the network generation we preprocess the data and transform it into our own structured data formats for further processing. In particular we decompose the data into regions and into its individual layers. For the network generation we mainly use the following layers:

- Highways/Freeways
- Primary roads
- Secondary roads

We also keep more fine-grained street-structures such as tertiary roads, minor roads, and residential roads but these will only be used if necessary, see below. All other layers are removed from the data set.

In addition to preprocessing (which includes error correction) and decomposition we also perform a first conservative reduction on the data, e.g.:

- trails with the same end-nodes become one trail,
- nodes with degree 2 are removed but only if the main street structure is kept (turns, curves).

These simple reductions and the removal of unnecessary layers already lead to a reduction of around 50% in the number of nodes.

10.2.2 Connect the given CO sites with the network

In the next step we make the given (anonymized) coordinates of central office locations to nodes of the network. This is done within two sub-steps:

1. Shifting: First we try to move a given CO to the closest higher layer street (only the layer of secondary streets or higher layers are allowed), see Figure 10-9. This is done, however, only if the distance is at most 500m.

Figure 10-9: A central office is moved to the closest street within 500m.

2. Shortest paths: For all other COs (not in a 500m distance to a higher layer road) we also allow for lower layer streets when shifting. We then compute a shortest path from the shifted CO to the network of higher layer roads, see Figure 10-10. Only this path remains in the network. In fact, to cope with dual homing requirements, we also try to compute a second path, which is 'maximally' disjoint from the first (first path links get a large weight in the second shortest path computation), see Figure 10-11.

Figure 10-10: A CO is connected to the network by using a lower layer streets.

Figure 10-11: A CO is connected by two disjoint paths to the network.

10.2.3 Connect the 20 regions

Because of the large data sets and limited computing power, all the previous steps are carried out for individual regions only. As a result we get a clean and detailed network topology based on streets with the given central office locations appearing as nodes for each of the 20 regions, see Figure 10-12. Unnecessary fine-grained lower layer streets have been removed and simple reductions/repairs have been carried out.

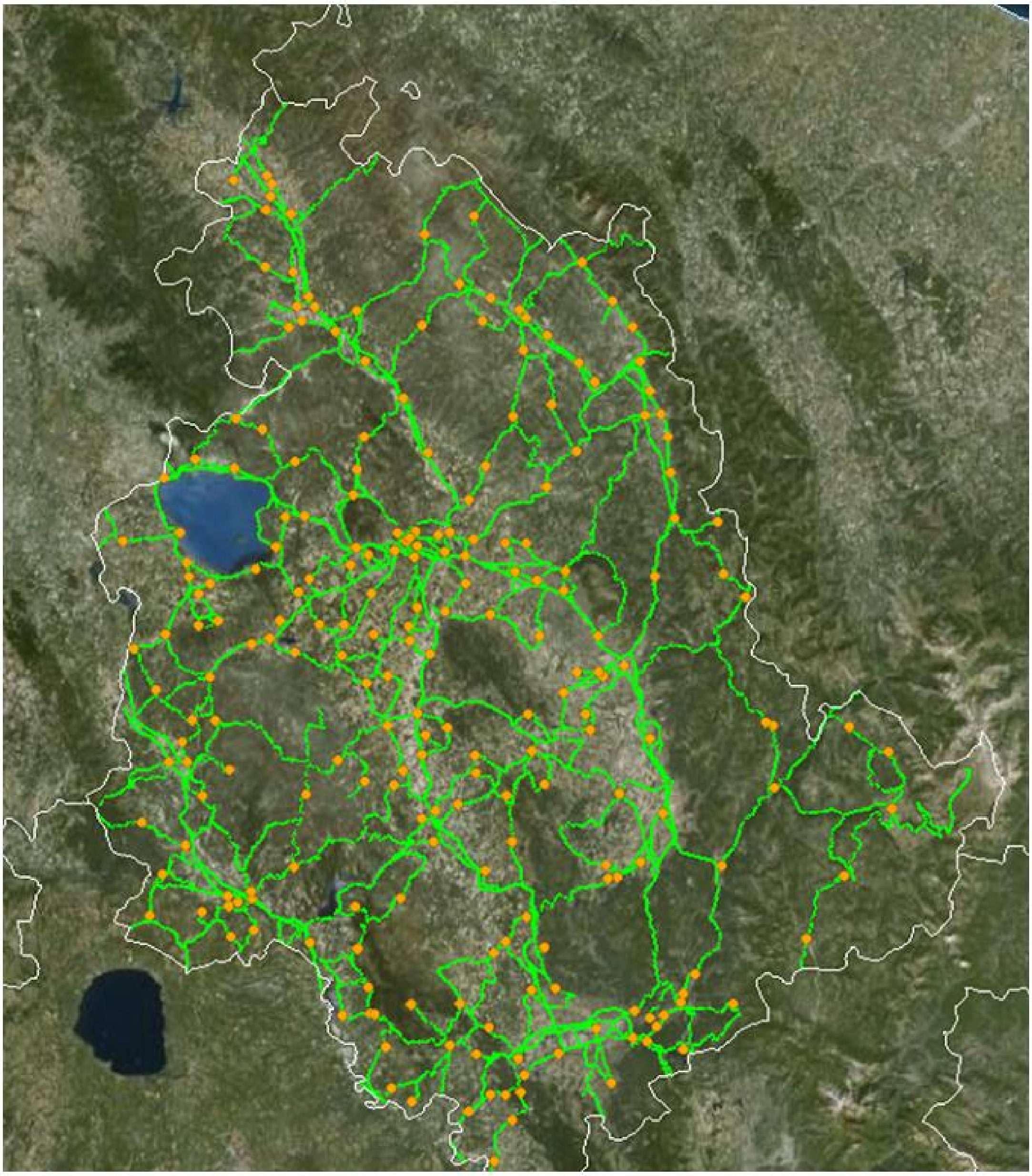

Figure 10-12: Network topology based on streets for region Umbria. Streets appear in green and central office locations in orange. Unnecessary fine-grained lower layer streets have been removed and simple reductions/repairs have been carried out.

To get a nation-wide network, the individual regional networks are connected. This is essentially done using the highest OSM street layer, that is, by using interconnecting highways and freeways, see Figure 10-13. To our knowledge, this is in line with the network architecture of Telecom Italia, where regional networks are interconnected by fibre routes that follow large national highways or railway systems.

Figure 10-13: Highways and freeways (in white) are used to interconnect the regional networks (coloured).

10.2.4 Reduction and cleanup

The nation-wide network that we obtain with the last step still contains a huge number of nodes and links (in the order of millions) because it still displays the original shape of street routes. The task of the final step is to reduce the structures to a graph in the mathematical sense that connects the important locations, that is, high degree crossings and central office locations. It suffices to have one link between two important locations together with the information how long in kilometer this connection is in the original street network, instead of having several hundred nodes originating from a GPS trace and following the course of the street.

To obtain the required structure we perform two main procedures:

1. Merging links: Every node with a degree two that is not a central office location is removed see Figure 10-14. The two links are merged to one link, while we keep the information about the total length.
2. Merging nodes: Nodes within a radius of 500 that are no central office locations get merged, see Figure 10-15.

Figure 10-14: Polygonal chains are merged to one link. Distance information is kept.

Figure 10-15: Very close nodes get merged. This removes complicated structures such as roundabouts and motorway junctions.

As a result of these procedures we obtain a clean Italian reference network reflecting a realistic nation-wide fiber topology down to the level of central office locations.

The final network has

- 29,981 nodes with 10,708 COs
- 39,615 links

and is displayed in Figure 10-16 (Italy) and Figure 10-17 (Toscana as a regional sub-network).

Figure 10-16: An Italian reference network.

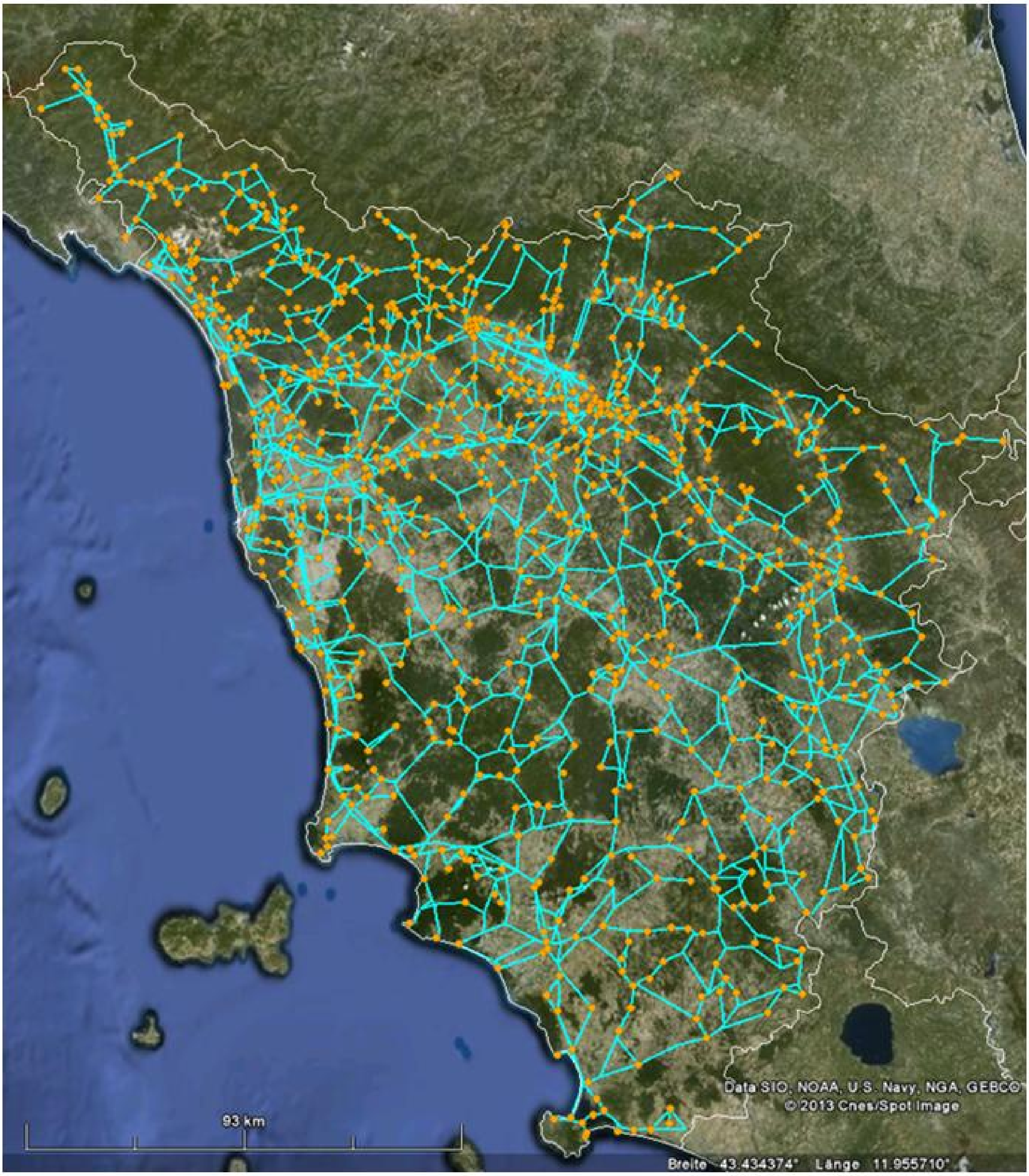

Figure 10-17: Toscana -- a regional reference sub-network.

10.2.5 Outlook

In the next reporting period, it is the target to create national reference topologies also for Spain, Great Britain, and Ireland. In principle we can use the developed methods also for these countries. However, the eventual process will depend on the data which can be provided by the network operators and also on the quality of the OSM data for the corresponding regions.

Another target of the next reporting period is the investigation whether it is reasonably possible to generate reference topologies for more local structures. The target is to generate data on the "town-level" (as shown in Figure 10-18 for Turino, Italy). If these topologies can be generated, then it will also be possible to optimize local structures of an end-to-end future network and study the optical distribution network (ODN) of the DISCUS LR-PON architecture. The big challenge at that point will be the generation of realistic building and household data.

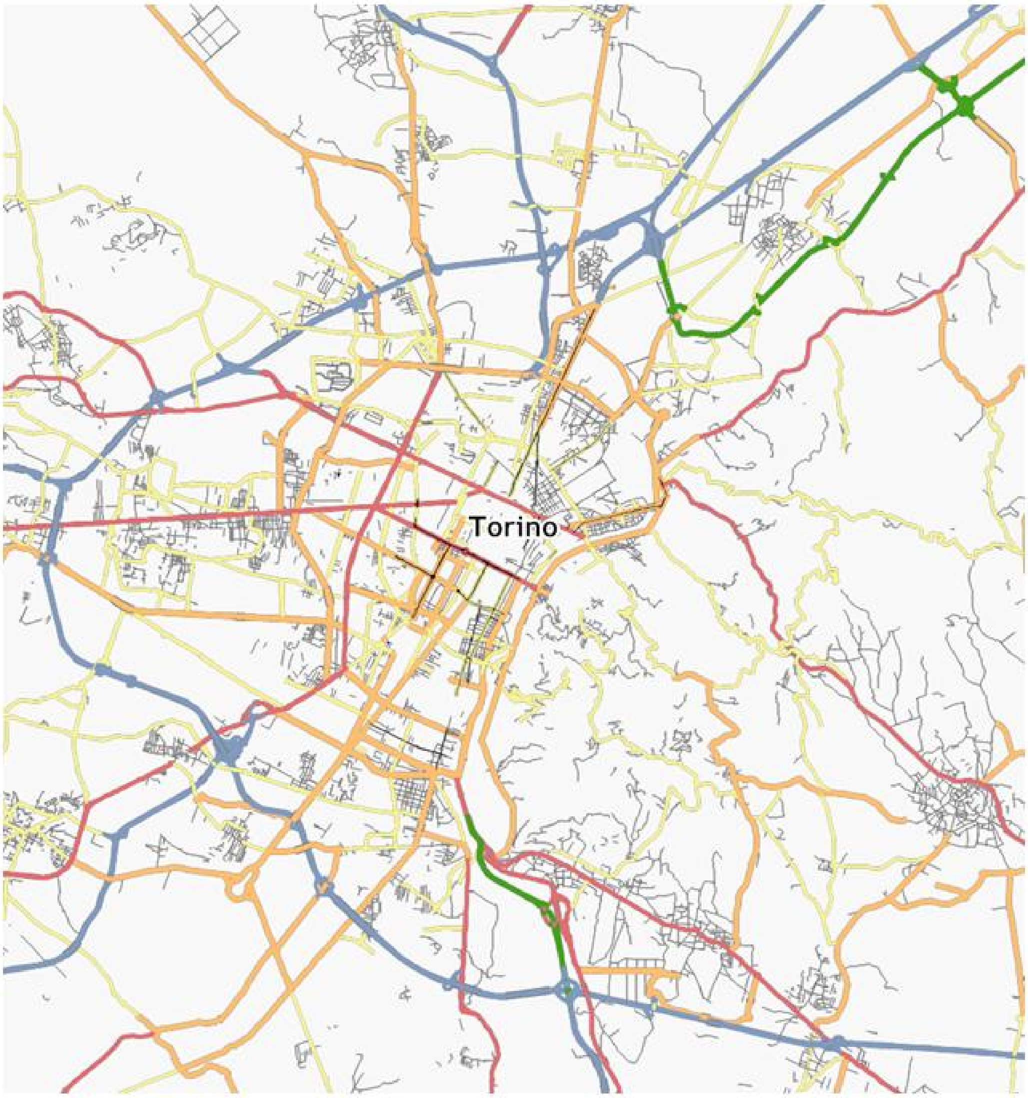

Figure 10-18: Local networks down to the level of cabinets and buildings could be used to study the ODN section of the DISCUS LR-PON architecture.

10.3 Appendix (c): Resilience, Reliability, and Supervision

DISCUS architecture builds on the concept of Long-Reach Passive Optical Networks (LR-PON) in the access segment, and a flat optical core arranged into islands of transparency. It exploits the low transmission loss of fibre to bypass or eliminate electronic equipment as much as possible, making the network inherently more reliable than the conventional optical network architectures. However, a highly-branched LR-PON in DISCUS architecture needs to serve big areas and hence any single fault may affect a large number of end users. Furthermore, a cable cut like in a conventional optical backbone network will interrupt a large amount of traffic, and the problem of providing protection against outside plant cut remains. Therefore, resilience, reliability and supervision will form an important aspect of the proposed DISCUS architectural design. Task 2.4 started from M3 of the project, i.e. 1st January 2013 and finish in M30, i.e. 30th April, 2015. The task was planned to conduct architectural design and modelling focusing on aspects of resilience, reliability and supervision. To differentiate the work on resilience defined in Task 7.5, this task targeted access segment (interacting with WP4, mainly T4.3 optical layer supervision and management). Three activities have been planned in this task: Activity 1 reliability assessment; Activity 2 resilience schemes; Activity 3 supervision techniques. This chapter reports the latest progress of all three activities in the task.

10.3.1.1 Availability and connection availability

Asymptotic availability (A) is defined as the probability that a component is operable at an arbitrary point of time, while asymptotic unavailability (U) is defined as the probability that the component is not operable. The equation of system availability A and unavailability U can be expressed, as in equations (10-1) and (10-2), respectively:

$$A_{component} = \frac{MTTFF}{MTBF} \tag{10-1}$$

$$U_{component} = 1 - A_{component} = \frac{MTTR}{MTBF} \tag{10-2}$$

where MTTR stands for mean time to repair, MTTFF denotes mean time to the first failure (represents the mean life time of the component/system) and MTBF stands for mean time between failures (where MTBF=MTTFF+MTTR). Typically MTTFF is much larger than MTTR, which is dominated by the time for certain operational processes.

Connection availability means the probability that a logical connection (e.g. a connection between the OLT and ONU) is operable. There are two basic configurations for the connection availability calculation, namely series and parallel [44]. The series configuration consists of two or more components (units) connected in series from the reliability point of view. It means that a series system fails if one or more components (units) fail. The parallel configuration consists of two or more components (units) connected in parallel from the reliability point of view. It means that a parallel system fails if, and only if, all of the components (units) fail.

Expressions for the connection availability A for the series and parallel configurations are shown in equations (10-3) and (10-4), respectively:

Series configuration:

$$A = \prod_i A_{component,i} \tag{10-3}$$

Parallel configuration:

$$U = \prod_i U_{component,i} \tag{10-4}$$

where A_i and U_i stand for availability and unavailability of a certain component (unit) *i* in the connection, respectively.

10.3.1.2 Failure impact factor (FIF)

The FIF includes two important factors relevant to resiliency [12]. The first one is failure penetration range (FPR). FPR is defined as the number of users affected by the failure of a certain component simultaneously. For instance, if the OLT is failed, all the connected users are affected while in case that ONU is down, only one user loses the connection. The second one is the unavailability (U), which indicates how often a connection is unavailable due to a failure of a component or fiber link. The definition of unavailability is given in equation (10-2). The FIF of a component is defined as [12]:

$$FIF_{component} = FPR \times U_{component} \tag{10-5}$$

A high FIF corresponds to a larger impact on the network reliability performance of the considered component/system.

The FIF of a path, consisting of a sequence of components is defined as follows:

$$FIF_{path} = \sum_i FIF_{component,i} \tag{10-6}$$

where $FIF_{component,i}$ represents the FIF of a component (as defined by equation (10-5), connected in a series configuration in the path.

Scenarios		7500 COs		4000 COs		1000 COs	
		Urban	Rural	Urban	Rural	Urban	Rural
Feeder fiber (km)	Working	--	--	2.5	5	7	12
	backup	--	--	9	20	16	32
Distribution fiber (+last mile fiber) (km)		2.5	3.5	2.5	3.5	2.5	3.5
Number of users in one service area		8900	3500	14200	7300	51000	33000

Table 10-1: Summary of fibre length and the number of users in different scenarios [15]

10.3.1.3 Cost analysis

From the cost perspective, the analysis of the impact of energy saving mechanisms on the reliability performance can be divided into two parts. The first one considers the gains related to the reduction of the energy consumption while the second part estimates the additional fault management cost associated with the reliability performance degradation of the device. Once the results from both analyses are combined, it is possible to provide an answer to whether a given sleep mode based scheme is beneficial from the overall cost perspective.

10.3.1.4 Failure related loss caused by MTBF variation

In the proposed methodology the impact on the equipment reliability performance is measured in terms of MTBF variation. We introduce the parameter v_{MTBF}, which varies in the range [0, 1]. The $v_{MTBF} = 0$ corresponds to no impact on MTBF, on the other hand the high value of v_{MTBF} (close to 1) refers to a large decrease of MTBF. The new value of MTBF (denoted hereafter as $MTBF_{new}$) can be calculated in the following way:

$$MTBF_{new} = MTBF_{ref} * (1 - v_{MTBF}) \qquad (10\text{-}7)$$

$MTBF_{ref}$ is the MTBF of a device operating without any energy efficient scheme implemented. The cost related to failure reparations (denoted hereafter as $Cost_{failure}$) can be calculated as:

$$Cost_{failure} = (operation\_period \,/\, MTBF_{ref}) * failure\_cost \qquad (10\text{-}8)$$

The *operation_period* is the considered period of time for our cost analysis; in our case it is equal to one year to be comparable with energy related cost saving (i.e., $\Delta Cost_{energy}$). The *failure_cost* represents the average cost to repair one failure and it includes: reparation manpower, travel, and also a penalty to compensate for the service interruption, typically used for business customers only. We calculate the extra cost caused by MTBF variation (denoted hereafter as $\Delta Cost_{failure}$) as the difference between the fault management cost in the case when an energy saving mode is applied (i.e. $Cost_{failure}$ with $MTBF_{new}$) and the cost when no energy efficient scheme is considered (i.e. $Cost_{failure}$ with $MTBF_{ref}$). Therefore, $\Delta Cost_{failure}$ can be expressed by the following equation:

$$\Delta Cost_{failure} = Cost_{failure} * v_{MTBF} \,/\, (1 - v_{MTBF}) \qquad (10\text{-}9)$$

10.3.1.5 Maximum allowed MTBF variation

The value of the maximum allowable MTBF variation (denoted hereafter as V_{MTBF}) is calculated when the energy related saving completely compensates the failure related loss i.e., $\Delta Cost_{failure} = \Delta Cost_{energy}$. In such boundary condition it can be calculated in the following way:

$$V_{MTBF} = \Delta Cost_{energy} \,/\, (\Delta Cost_{energy} + Cost_{failure}) \qquad (10\text{-}10)$$

As the $\Delta Cost_{energy}$ is computed as a function of traffic load the V_{MTBF} is also traffic dependent.

10.3.1.6 Case studies

Here we focus on WDM-PON based access networks. They are in fact considered as the most promising candidates for LR-PON considered in DISCUS architectures. The case studies under exam are differentiated based on the customer profile (i.e. residential or business) and on the location of the failure. For residential customers, it is assumed that only the ONUs are switched on/off to save energy. As a result only ONUs might be affected by the energy saving mechanisms. On the other hand, for business customers, two different cases are considered. In the first one, only the ONUs are switched on/off to save power. If an ONU malfunctions, only one customer at a time is affected, similarly to the residential case. However, since we are considering business costumers the *failure_cost* parameter includes an additional penalty for service interruption. In the second case it is assumed that only the OLT is switched on/off in order to save energy. Since the OLT serves more than one customer, its failure has a relatively larger impact compared to the failure of an ONU. In this work it is assumed to have one OLT that is connected to 80 business customers. All of them are out of service at the same time if the OLT fails. Table 10-1 provides a number of details about the scenarios. The costs corresponding to failures are calculated based on the data presented in Table 10-2.

Scenario	**Description**	**Mean travel and reparation times as well as persons involved in the process**	**Penalty**	**Failure cost** [USD]	**MTBF** [h]
Residential *(ONU)*	Sleep mode applied at ONU side ONU failure affects one customer	Mean travel time – 2h & 1 person Mean reparation time – 1h & 1 person	n/a	570	236 842 [15]
Business *(ONU)*	Sleep mode applied at ONU side ONU failure affects one customer	Mean travel time – 2h & 1 person Mean reparation time – 1h & 1 person	2h & 1 customer	2 970	236 842 [15]
Business *(OLT)*	Sleep mode applied at OLT side OLT failure affects 80 customers	No travel time Mean reparation time – 2h & 1 person	2h & 80 customers	192 380	214 286 [15]

Table 10-2: Scenarios

Item	**Value**	**Unit**
Energy cost	0.27 [45]	USD/kWh
ONU's power On/Sleep	3.85 / 1.70 [20]	W per device

OLT's power On/Sleep	98 / 43.3 [20]	W per device
Personal cost	190 [21]	USD/(h*person)
Penalty cost	1 200 [21]	USD/(h*customer)

Table 10-3: Cost calculation parameters

10.3.2 Activity 2: Resilience schemes

This activity concentrates on developing on appropriate resilience schemes for DISCUS architecture. Three sub-activities have been defined as follow:

a) Design of resilient fibre layout;

b) Investigation of hybrid protection technique, where different user types, e.g. residential/business users and mobile backhauling, may have different requirements for resiliency;

c) Optimised layouts and traffic off-loading techniques in order to minimise routing and protection switching capacity required within the metro-nodes.

In this deliverable, we report the latest progress of the all three sub-activities, which have been initialized. Besides, as shown in sub-section 5.1.1, for LR-PON scenarios, the protection of shared part should be considered in the first place. Therefore, up to now we mainly put our efforts on protection of the FF and OLT and plan to extend this work towards end-to-end resilience for some selected users (e.g. business users who require high reliability performance).

10.3.3 Flexible resilient schemes

In this section, we discussed different backup options [11] based on results presented in sub-section 5.1.1 and then proposed some reliable architectures, supporting the shared part of PON (i.e. FF and OLTs). We are keeping in mind the possibility to offer cost-efficient full protection to some selected end users (i.e. business access who typically requires high reliability performance) and plan to include a comprehensive study in the future deliverable.

Protection at the OLT

As shown in Figure 5-2 the FIF for the unprotected OLT has the highest value after FFs. Therefore, it is crucial to provide protection at the node, where the OLT is located. It should be noted that full OLT duplication needs inter-OLT signaling to control the switching for protection.

Protection between the OLT and local exchange

Protection between the OLT and local exchange (LE) is most significant for long FF. Normally, FF protection duplicates the fiber, and the backup FF should be laid in a disjoint duct with minimal geographical overlap. Moreover, a FF cut affects the large customer base and hence impacts the FIF significantly.

Protection between the local exchange and end-user

As it is already clear that the protection between the LE and end-users does not significantly affect the failure impact, the network operators will generally be not in favor of protection after the LE. Note that for business customers or some services requiring high reliability such as e-health services providing remote consultation of doctors, end-to-end customer protection is required. For the reliable architectures currently studied, we did not yet consider this part, but are keeping in mind a possible extension for the protection between the LE and end-users.

Protected Architecture Designs

In the previous sections, we have identified that protection at the CAN and the FF should be provided in order to have a satisfied connection availability and FOM for the end-users and operators. Moreover, it should be noted when introducing protection for hybrid WDM/TDM PON, the performance degradation in the other aspects, such as reach, supported number of end-users per FF and flexibility on resource allocation, should be avoided. With this in mind, we propose two protected architectures down to RN1 while keeping the performance degradation at a minimum level (see Figure 10-19).

Both approaches in Figure 10-19 have an identical protection scheme down to RN1 where the OLT and FF are duplicated. In the protected architecture shown in Figure 10-19(a) the working and backup FFs are directly connected to one 2:M device at RN1. For a basic hybrid WDM/TDM PON architecture, the device(s) at RN1 can be either a splitter, an AWG, or a combination of WSSs and AWGs according to the type of ODN. In DISCUS architecture, the splitter is preferred in ODN in order to achieve high flexibility. In case of two-fiber ODN approach (i.e. one fiber for one direction mentioned in D2.1), 4:M devices can be considered to connect two working fibers and two protection fibers, respectively. In the second protection approach (see Figure 10-19(b)), two 1:2 3dB splitters are used for connecting the working and backup FFs to RN1. In this case duplicated devices are required at RN1 and the number of splitters located at RN2 needs to be doubled with half of the output port count (i.e. 1:N/2) compared to the scheme in Figure 10-19(a). In case of two-fiber ODN approach, two 2:2 3dB splitters should be used. If needed, REs can be placed at the end of each FF, right before any other component at RN1 in order to offer the sufficient fiber length. The two proposed protection schemes do not affect the maximal number of supported users per FF, flexibility on resource allocation and power budget for the connection between the OLT and ONU. However, they may have different impacts on offering a full protection for some selected end users. In the scheme shown in Figure 10-19(a), remote node 1 (e.g. 2:M splitter) may become the unprotected point for the users who need full protection (i.e. each component along the working path should be protected). A comprehensive analysis will be included in future deliverable.

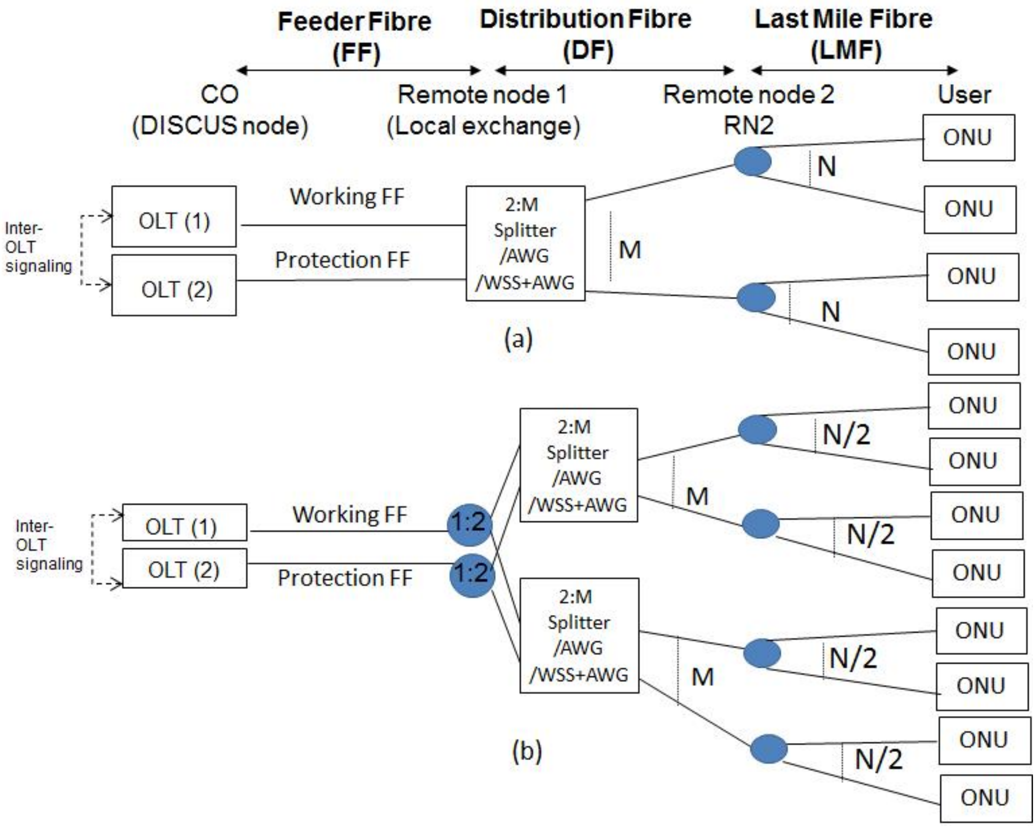

Figure 10-19: Two proposed reliable architectures for all hybrid WDM/TDM PON (a) without 3 dB splitter (b) with 3 dB splitter.

10.3.4 N:M OLT Protection Switching to Optimize Backup Capacity

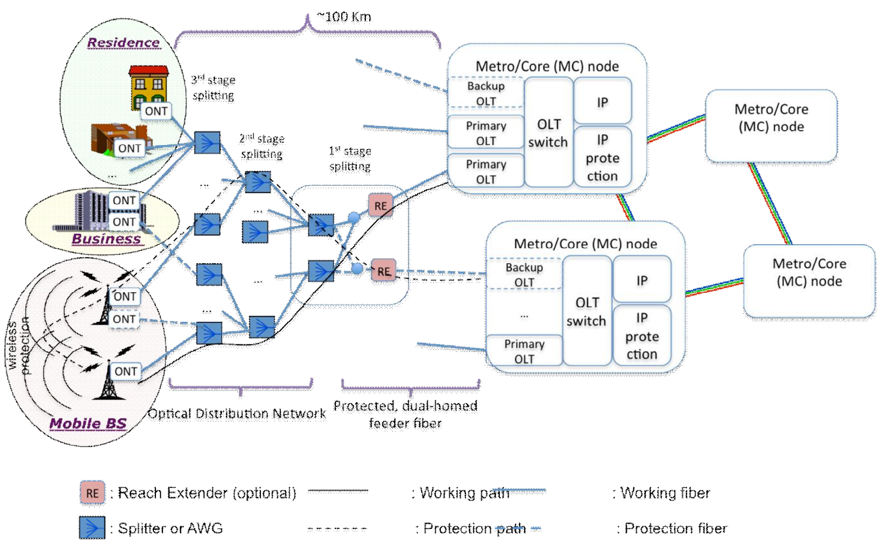

Figure 10-20: N:M OLT backup strategy for using an optical switch in a dual-parented LR-PON architecture.

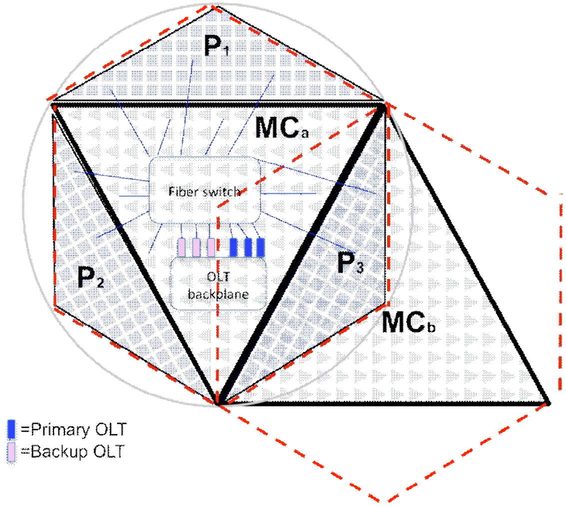

Figure 10-21: Example of MC nodes overlap areas for feeder fibre protection purpose.

10.4 Appendix (d): Power Consumption Modeling

10.4.1 Flow diagram of RWA program

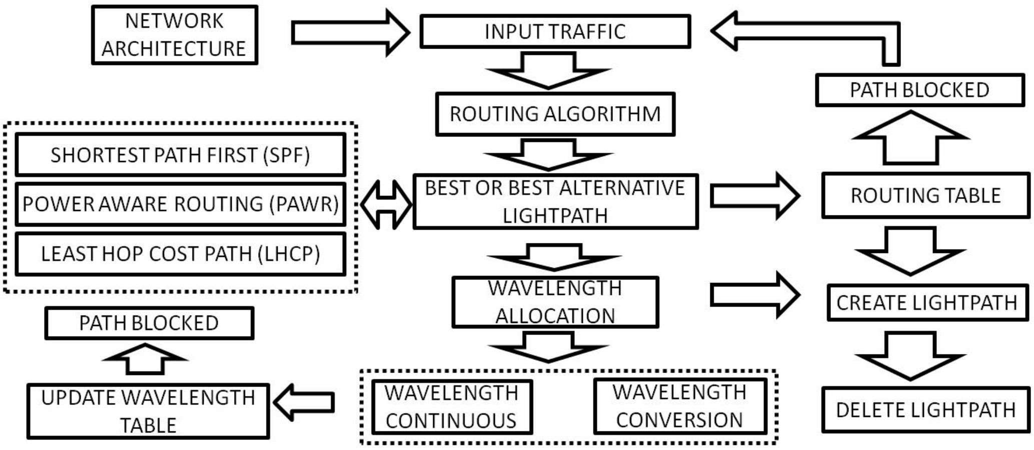

Figure 10-22: Flow diagram of routing and wavelength allocation program.

10.4.2 Dynamic power consumption

It is possible to reduce power consumption [37] by including sleep-mode functionality in routers and switches during situations when there is low traffic load. This allows links, individual line-cards, and even whole nodes (i.e. full routers) to be put in stand-by mode, while guaranteeing QoS constraints, such as maximum links utilization. The major power consumption occurs in the OEO at the nodes.

The power consumption model used is based on core nodes that have power consumption scaling with the number of channels, and link power consumption based on inline amplifiers.

We have assumed that EDFAs can either be switched on all the time ('awake' mode) or switched off ('hibernating' mode) at the start of the traffic allocation or when not in use. Switching off amplifiers when not being used helps to reduce the OPEX. For example, for low numbers of connection allocation in the network this results in significant reduction in power consumption.

In the hibernating mode operation, the amplifiers are switched off and are switched on when the first wavelength is used in a fiber. Each lightpath is assumed to have a limited lifetime. When a lightpath is deleted, the amplifiers in the links remain turned on, because the amplifiers support multiple wavelengths, unless they are not carrying any lightpaths. Conversely we assume that once EDFAs are switched on in a link, additional wavelengths do not then require more EDFAs.

10.4.3 Results

Figure 10-23 shows the effect of hibernating mode equipment on network power consumption. We found that hibernating mode operation of amplifiers is important only for low line rates. For higher line rates power consumption of router nodes becomes dominant. Here, we found that the EDFA power consumption was 35%, 10%, and 4% of total network power consumption for 10Gbps, 40Gbps, and 100Gbps in the network respectively. The power consumption contribution from EDFAs becomes significant only when the network contains low number of connections.

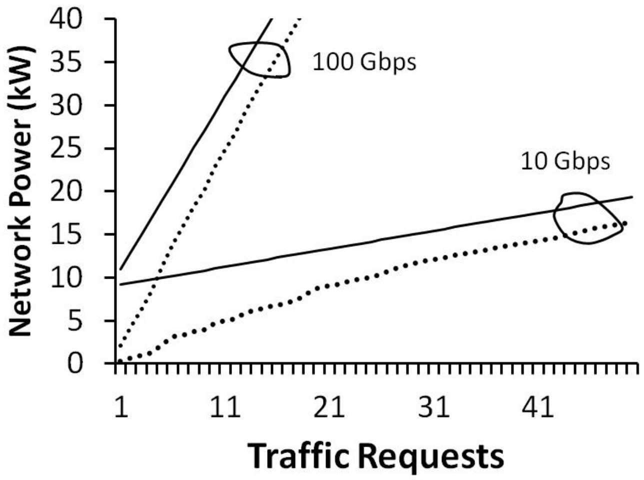

Figure 10-23: Comparison of hibernating mode (dotted) and normal mode operation on network power consumption.

Figure 10-24 shows that the power consumption increases linearly at first with transmission rate. However as blocking increases, the rate of increase in power consumption becomes more gradual.

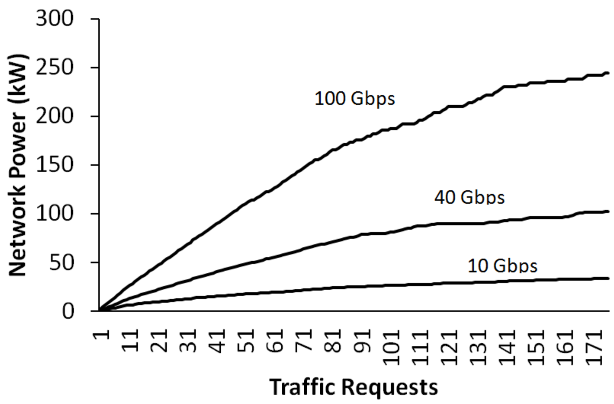

Figure 10-24: Variation of network power with increasing transmission rates using uniform traffic.

Figure 10-25 shows comparison of power consumption for static and dynamic operation assuming that amplifiers and router ports are switched off when not in use. We observe that the power consumption in the selected nodes increases. However the average power consumption of the low priority nodes has reduced by 76%.

This can be useful when the nodes are in remote locations that have limited supply of power. The high priority nodes increase in power consumption by 68.8%. However there are fewer of these high priority nodes and sufficient resources can be provided in those locations. Alternatively if we wanted to distribute the power equally we could achieve this aim by increasing or reducing the selection probability for the nodes.

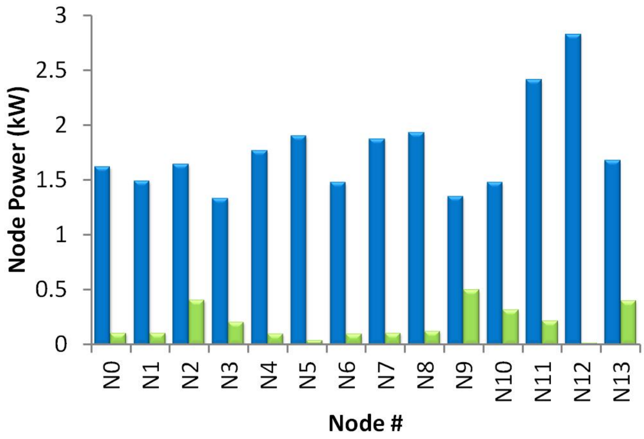

Figure 10-25: Node power consumption reduction for dynamic (10 Erlangs) operation compared with static operation (10000 Erlangs) assuming uniform traffic at 10Gbps.

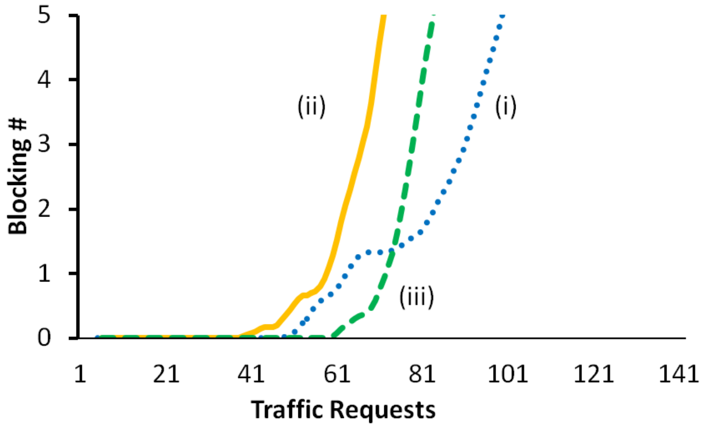

Figure 10-26: Showing the improvement achieved using wavelength conversion. (i) Uniform traffic, (ii) Non-uniform traffic. (iii) Non-uniform+ wavelength conversion (27% blocking-free advantage over uniform traffic case).

Figure 10-26 summarizes this work. It shows that non-uniform traffic increases the blocking, and wavelength conversion reduces the blocking over the uniform traffic case.

DISCUS

11 Abbreviations

ALA	Adaptive Loading Algorithms
ALUD	Alcatel-Lucent Deutschland AG
APD	Avalanche Photo Diode
APS	Automatic Protection Switching
ASE	Amplified Spontaneous Emissions
ASK	Amplitude Shift-Keying
ASTON	Aston University
ATESIO	Atesio GMBH
AWG	Arrayed Waveguide Grating
BER	Bit Error Rate
BGP	Border Gateway Protocol
BMRx	Burst-Mode Receiver
BW	Broadband Remote Access Server
BW	Bandwidth
CAB	Cabinet
CAGR	Compound Annual Growth Rate (CAGR)
CAPEX	Capital Expenditure
C-band	Band in the wavelength range 1530–1565 nm
CC	Continuity Check
CD	Chromatic Dispersion
CDN	Content Distribution Networks
CO	Confidential, only for members to the consortium (including Commission Services)
CO	Central Office
CO-OFDM	Coherent OFDM
CO-UDWDM	Coherent detection Ultra DWDM
Co-WDM	Coherent-WDM
CV	Connectivity Verification
DACs/ADCs	Digital-to-Analogue/Analogue-to-Digital Converters

DBA	Dynamic Bandwidth Assignment
DCF	Dispersion Compensating Fibre
DISCUS	The DIStributed Core for unlimited bandwidth supply for all Users and Services
DP	Distribution Point
DP-BPSK	Dual Polarization Binary Phase-Shift Keying
DP-QPSK	Dual Polarization Quaternary Phase-Shift Keying
D-side	Distribution side
DSL	Digital Subscriber Line
DSP	Digital Signal Processer
DWA-side	Dynamic Wavelength AssignmentThe distribution side of the access network, from cabinet location to distribution point
DWDM	Dense Wavelength Division multiplexer
EDC	Electronic Dispersion Compensation
EDFA	Erbium Doped Fibre Amplifier
E-Line	Ethernet Virtual Private Line
EON	Elastic Optical Network
EPON	Ethernet Passive Optical Network
E-side	The access network from the local Exchange side site to the cabinet location
E-Tree	Ethernet Virtual Private Tree
FEC	Forward Error Correcting
FFT	Fast Fourier Transform
F-OFDM	Fast Orthogonal Frequency Division Multiplexing
FTTC	Fibre to the Cabinet
FTTH	Fibre to the Home
FTTP	Fibre to the Premises
GA	Grant Agreement
GHG	Green House Gases
GMPLS	Generalised Multi Protocol Label Switching
GPON	Gigabit Passive Optical Network
GPS	Global Positioning System (GPS)
ICT	Information Communications Technology
IETF	Internet Engineering Task Force

IFFT	Inverse Fast Fourier Transform
III-V	III V Lab GIE
IM/DD	Intensity Modulation/Direct Detection
IMEC	Interuniversitair Micro-Electronica Centrum VZW
IP	Internet Protocol
IPoE	IP over Ethernet
IQ	In-phase Quadrature-phase
ISI	Inter-symbol Interference
ISSU	In Service Software Upgrade
ITU	International Telecommunications Union
ITU-T	ITU's Telecommunication Standardization Sector
KTH	Kungliga Tekniska Hoegskolan
LAN	Local Area Network
L-band	Band in the wavelength range 1565–1625 nm
LBMRx	Linear Burst-Mode Receiver
LDP	Label Distribution protocol
LE	Local Exchange
LO	Local Oscillator
LR-PON	Long Reach Passive Optical Network
LSP	Label Switching Protocol
MAC	Media Access Control
MBW	Modulator Bandwidth
MC	Metro-core
MIMO	Multiple-input Multiple-output
MPLS	Multi-Protocol Label Switching
MPLS-TE	Multi-Protocol Label Switching Traffic Engineering
MPLS-TP	Multi-Protocol Label Switching Transport Profile
MSAN	Multi-Service Access Node
MS-SPRing	Multiplex section shared ring protection
NFV	Network Function Virtualization
NGN	Next Generation Network
NRZ	Non Return to Zero
NSN	Nokia Siemens Networks

OAM	Operation Administration and Management
OASE	FP7 project “Optical Access Seamless Evolution”
ODN	Optical Distribution Network
OEO	Optical-Electronic-Optical (conversion)
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA-PON	PON based on OFDM access
OLO	Other Licenced Operators
OLT	Optical Line Termination
ONT	Optical Network Termination
ONU	Optical Network Unit
OOK	On-off keying
OOFDM	Optical Orthogonal Frequency Division Multiplexing
OPEX	Operational Expenditure
OSNR	Optical signal to Noise Ratio
OSM	Open Street Maps
P2P	Point to Point
PAPR	Peak-to-Average Power Ratio
PAYG	Pay As You Grow
PC	Private Circuits
PCP	Primary Cross Connect
PE	Provider Edge
PIEMAN	FP7 project “Photonic integrated extended metro and access network”
PIN-Rx	Positive Intrinsic Negative Receiver (Receiver with PIN photodiode)
PM	Phase Modulator
PMD	Polarization Mode Dispersion
PM-QPSK	Polarization Multiplexing QPSK
POLATIS	Polatis Ltd
PON	Passive Optical Network
PoP	Point of Presence
POTS	Plain Old Telephony Service
PP	Restricted to other programme partners (including Commission Services)

PPP	Point to Point Protocol
PPPoE	Point to Point Protocol over Ethernet
PSC	Protection State Coordination
Pt-Pt	Point to Point
PU	Public
PW	Pseudowires
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RE	Restricted to a group specified by the consortium (including Commission Services)
RF	Radio Frequency
ROADM	Re-configurable Optical Add Drop Multiplexer
RSVP-TE	Resource Reservation Protocol - Traffic Engineering
RTT	Round Trip Time
SBS	Stimulated Brillouin Scattering
SDH	Synchronous Digital Hierarchy
SDN	Software Defined Networks
SNC/S	Sub-Network Connection Sub-Layer
SNCP	Subnetwork Connection Protection
SNR	Signal to Noise Ratio
SOA	Semiconductor Optical Amplifiers
STRONGEST	Fp7 project "Scalable, Tunable and Resilient Optical Networks Guaranteeing Extremely-high Speed Transport"
TCD	Trinity College Dublin
TDMA	Time Division Multiple Access
TDM-PON	Time division Multiplexed Passive Optical Network
TF	Tuneable Filter
TI	Telecom Italia S.p.A
TID	Telefonica Investigacion Y Desarrollo SA
T-LDP	Targeted-LDP
UCC	University College Cork
UD	Ultra-dense
UK	United Kingdom
UNI	User Network Interface

VLAN	Virtual Local Area Network
VLAN ID	Virtual Local Area Network IDentification
VN	Virtualised Networks
VoD	Video on Demand
VoIP	Voice over IP
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing
WDM-PON	Wavelength Division Multiplexed Passive Optical Network
WSS	Wavelength Selective Switch
XRGPON	Extended reach GPON
xDSL	The suit of access techniques based on DSL