"Description and Assessment of the Architecture Options"

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Abstract:
This document presents the final outcomes resulting from the tasks: T3.1, description of architecture options; and T3.3, assessment of architectures. An overview of the OASE selected next generation optical access network architecture options is provided along with the comprehensive performance evaluations in terms of key architectural aspects: energy consumption, resilience, operational aspects, control and management, impact on the aggregation network, and resource allocation.

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Executive summary

The main objective of this deliverable is to present the final outcome of tasks T3.1, description of architecture options, and T3.3, assessment of architectures for the "2020" time horizon. This document provides a brief overview of the four selected next generation optical access (NGOA) architecture options: WDM-PON, hybrid WDM/TDM-PON, two-stage WDM-PON, and NG-AON, as defined in the earlier OASE deliverable D3.1. Subsequently, a detailed description of the associated key architectural performance aspects under evaluation is provided. These aspects include the impact on the aggregation network, energy consumption, resilience, operational aspects, control and management, resource allocation, migration and open access.

As the project has progressed, we have decided against reducing the number of architecture options, so as to select only one or two of the most promising ones which may provide an overall most advantageous utility. This is because all of the main OASE architecture options that we have explored have their own distinctive benefits and deficits according to the different deployment scenarios, topologies and contexts that they are best suited. For instance, one of key findings in this deliverable is that the passive NGOA architectures, i.e. WDM-PON and hybrid WDM/TDM-PON tend to consume more power on a per-user basis than their active counterparts, namely the two-stage WDM-PON and NG-AON; however, the passive architectures exhibit a higher resiliency than the active approaches. Hence, we have chosen to keep all four of the main OASE architecture options, and to map them to the various deployment scenarios. A comprehensive quantitative and technical comparison has been carried out with respect to the different architecture aspects, so as to indicate what the best architecture options are according to the different deployment scenarios.

In parallel to this deliverable D3.2, two other WP3 deliverables are also being issued in 2012, namely the OASE deliverables D3.3 (Cooperation models) and D3.4 (Migration paths), where the additional substantive and important related architecture aspects, open access and migration, are described in more detail.

Referred documents

[1] Project Contract - Annex 1 “Description of the Work” *(DoW)*

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List of figures and tables

Abbreviations

AMGAV	Adaptive Multi-Gate polling with Void filling
AON	Active Optical Network
ATM	Asynchronous Transfer Mode
AWG	Arrayed Waveguide Grating
BR	Bandwidth Reporting
CAN	Central Access Node
CapEx	Capital Expenditure
CDN	Content Distribution Network
C&M	Control and Management
CO	Central Office
CPE	Customer Premises Equipment
DBA	Dynamic Bandwidth Allocation
DBAA	Dynamic Bandwidth Allocation Algorithm
DCN	Data Communications Network
DoW	Description of Work
DSP	Digital Signal Processing
DU	Dense Urban service area
DWDM	Dense WDM
EDFA	Erbium-Doped Fiber Amplifier
E-IPACT	Enhanced Interleaved Polling with Adaptive Cycle Time
FF	Feeder Fiber
FOM	Figure Of Merit
FPGA	Field-Programmable Gate Array
FPR	Failure Penetration Range
GMPLS	Generalized MPLS
GPON	Gigabit PON
G*n*	Group add/drop filters
IP	Internet Protocol
IPACT	Interleaved Polling with Adaptive Cycle Time
ITU	International Telecommunication Union
LEx	Local Exchange
LL	Link Layer
LoS	Loss of Signal
LR-PON	Long Reach PON
LT	Line Termination
MAC	Media Access Control
MD	Maintenance District
MPLS	Multi-Protocol Label Switching
MT	Multi Thread
MTBF	Mean Time Between Failure
MTTFF	Mean Time To First Failure
MTTR	Mean Time To Repair
MO	Maintenance Office
NA+	Newly Arrived frames Plus
NG-AON	Next-Generation Active Optical Network
NGOA	Next Generation Optical Access

NMS	Network Management System
NP	Network Provider
OA	Open Access
OAM	Operation, Administration, Maintenance
OASE	Optical Access Seamless Evolution
ODN	Optical Distribution Network
OLT	Optical Line Termination
OMCI	ONT Management and Control Interface
ONT	Optical Network Termination
OpEx	Operational Expenditure
OSC	Optical Supervisory Channel
OTDR	Optical Time Domain Reflectometer
PtP	Point-to-Point
PCP	Physical Connection Point
PIP	Physical Infrastructure Provider
PM	Performance Monitoring
PON	Passive Optical Network
POP	Point of Presence
PUE	Power Usage Effectiveness
R	Rural service areas
RE	Reach Extender
REAM	Reflective Electro-Absorption Modulator
RN	Remote Node
RTT	Round Trip Time
RV	Request Variable
SDH	Synchronous Digital Hierarchy
SNMP	Simple Network Management Protocol
SP	Service Provider
ST	Single Thread
TCO	Total Cost of Ownership
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
U	Urban service area
UDWDM	Ultra-Dense WDM
UNI	User-Network Interface
USR	Unused Slot Remainders
VLAN	Virtual Local Area Network
WDM	Wavelength Division Multiplexing
WR	Wavelength Routed
WS	Wavelength Selected
WSS	Wavelength Selective Switch

1. Introduction

As specified in the OASE description of work (DoW) [1], this OASE deliverable D3.2 presents the final outcome of the tasks T3.1, description of architecture options, and T3.3, assessment of architectures. This final version of the OASE deliverable D3.2 is being submitted towards the end of 2012 (i.e. month 34 of the project). We already submitted an initial version of the deliverable, D3.2.1, at the end of the second year of the OASE project, which summarized the WP3 work done during 2011. This current document is based on D3.2.1, and is an extension to include the work undertaken in the final year of the project (i.e. as performed during 2012) and presents the final results of the activities carried out in the tasks T3.1 and T3.3.

We first provide a list of activities defined in DoW related to this deliverable, followed in each case by a brief indication of how we have actually approached problem at hand with a summary of what has been done for the corresponding activities.

- A3.1.3 Design of resource allocation algorithm (M13-M31)
    - A survey of the existing resource allocation algorithms along with the challenges of the next-generation optical access (NGOA) architectures has been covered in OASE deliverable D3.1. A new algorithm design to address the challenges and expected functionality of NGOA architectures as well as the associated performance evaluation has been included in the current document (see Sections 3.5, 4.2.5 and 4.4.5).
- A3.1.4 Design of resilience techniques (M7-M31)
    - An initial study was already presented in OASE deliverable D3.1, with the remark that protection of the central access node and feeder fiber needs to be considered in the first place since they represent the possibility for a single point of failure affecting a large number of users and having impact on the whole network operation. Therefore, we started our work on resiliency by considering protection of the network resources between the central office and the remote node. In the current version of the document we now describe those schemes providing protection up to the remote node in each of the OASE architecture options defined in OASE deliverable D3.1. Furthermore, we have also considered two different reliability performance parameters: connection availability and figure of merit (defined in Sections 3.2.1 and 3.2.2). The associated performance evaluation for all four OASE architectures can be found in Sections 4.1.2, 4.2.2, 4.3.2 and 4.4.2.
- A3.1.5: Novel network architectures and common platform for residential access, business access and backhaul (M1-M31)
    - Four preliminary OASE architecture options have been identified in OASE deliverable D3.1 for the “2020” time horizon. Initially we planned to reduce the number of the OASE architecture options based on the preliminary evaluation performed in 2011 considering only the first priority criteria, such as energy efficiency, resiliency, open access and migration, in order to be able to perform the detailed evaluation of the selected architectures. However, based on the performance assessment in OASE milestone M3.1 along with input from the other WPs, we found it is hard to

exclude any of the candidate options because we couldn't find a clear winner. The reason was that some were appropriate for some scenarios while not fitting other scenarios well, and vice-versa. Therefore, we decided to keep all four preliminary architecture options presented in OASE deliverable D3.1, to identify the weak points of each option, and to address these. Moreover, our target is now to map each architecture option to the node consolidation scenarios defined in WP2 and WP5. All the considered scenarios are described in detail in this chapter later (see Section 1.1).

- A3.3.1: Performance evaluation of architectures (M7-M34)
  - This activity started with the preliminary assessment of existing architectures, as described in the OASE deliverable D3.1 and the brief evaluation of the OASE architecture options presented in the OASE milestone M3.1. In this current version of the document D3.2 we now show the results of the assessment in terms of energy consumption, resilience, impact on aggregation, and control and management plane, as well as resource allocation. The performance evaluations with respect to open access and migration are included in two other deliverables that are being issued in 2012, namely D3.3 (Cooperation models) and D3.4 (Migration paths), respectively.
- A3.3.2: Operational complexity (M7-M34)
  - The initial outcome of this activity resulted in a general assessment of operational complexity, and was described in the OASE deliverable D3.1. Evaluation of the more operational aspects (i.e. power consumption for operators, footprint, failure rate, and travel) with consideration of different node consolidation scenarios is included in this current version of the document D3.2.

The remainder of this chapter will briefly describe the topological context of node consolidation and distinct populated service areas, including the dense urban (DU), urban (U), and rural (R) contexts, where NGOA architectures will be deployed. As mentioned before, the performance evaluations included in this document are done by mapping the different NGOA architecture options into these considered scenarios. An outline of the remainder of this document D3.2 is presented at the end of this chapter.

1.1 Node consolidation scenarios

In OASE, three different types of service areas have been considered. The differentiation is based on consideration of different population density scenarios: dense urban (DU), urban (U) and rural (R) areas (see OASE deliverable D5.1). Furthermore, traditional service areas from present copper networks have been grouped together to form larger service areas for investigating the potential for and the impact of node consolidation. For parametric studies different node consolidation scenarios are considered. As a reference case, today's scenario in the context of Deutsche Telekom (DT) with 7500 nodes without node consolidation was assumed, so that we have the same access nodes as in a traditional access network. With respect to the possibilities of node consolidation scenarios consisting of 4000 and 1000 remaining nodes were considered. The higher the node consolidation, the more are the traditional access networks grouped together into new service areas, and therefore, wider areas are covered (i.e. with more users and over longer distances). This means that, on average, approximately two traditional service areas are converged to one larger, new service area in the 4000 nodes scenario; whereas in the 1000 nodes scenario, approximately eight traditional service areas are grouped to form a single, much larger new service area. A detailed description of the impact of the different node consolidations on the different areas can be found in Table 6 of the OASE deliverable D5.1.

Although these service areas have been defined based on the German network, we can assume that their topological characteristics will probably still be valid for the large part of other European networks, since the demographic distribution is comparable as well as the types of existing traditional access networks and the numbers of covered users.

Table 1-1 summarizes three node consolidation scenarios considered in the project. Scenario 1 covers the case without node consolidation, whereas the scenarios 2 and 3 represent cases with different levels of node consolidation. The scenarios differ in their coverage areas and in their numbers of users (see Table 1-1)

Table 1-1: Overview of Node consolidation scenarios

	Node consolidation	# of users in dense urban (DU) service area	# of users in urban (U) service area	# of users in rural (R) service area
Scenario 1	No, (7500 Central Office locations)	14800	8900	3500
Scenario 2	Yes, (4000 Central Office locations)	19300	14200	7300
Scenario 3	Yes, (1000 Central Office locations)	44500	51000	33000

Table 1-2 presents the average length of feeder and first mile fiber sections in the different scenarios presented in Table 1-1. For Scenario 1 (without node consolidation), feeder fiber (or regional fiber) is not considered, as the optical line terminal is at a local exchange, i.e. physical connection point (PCP) 5 (see the architecture figures in Chapter 2).

Table 1-2: Summary of fiber length in different node consolidation scenarios.

<table>
<tr><th colspan="2" rowspan="3">Scenarios (with and without node consolidation)</th><th colspan="3">Fiber length (km)</th></tr>
<tr><th colspan="2">Feeder</th><th rowspan="2">First mile (Main+distribution)</th></tr>
<tr><th>Working</th><th>Protection</th></tr>
<tr><td rowspan="3">Scenario 1 (7500 Central Office locations)</td><td>DU</td><td>-</td><td>-</td><td>1.5</td></tr>
<tr><td>U</td><td>-</td><td>-</td><td>2.5</td></tr>
<tr><td>R</td><td>-</td><td>-</td><td>3.5</td></tr>
<tr><td rowspan="3">Scenario 2 (4000 Central Office locations)</td><td>DU</td><td>0.5</td><td>2.5</td><td>1.5</td></tr>
<tr><td>U</td><td>2.5</td><td>9</td><td>2.5</td></tr>
<tr><td>R</td><td>5</td><td>20</td><td>3.5</td></tr>
<tr><td rowspan="3">Scenario 3 (1000 Central Office locations)</td><td>DU</td><td>2</td><td>5</td><td>1.5</td></tr>
<tr><td>U</td><td>7</td><td>16</td><td>2.5</td></tr>
<tr><td>R</td><td>12</td><td>32</td><td>3.5</td></tr>
</table>

1.2 OUTLINE OF THIS DELIVERABLE

The remainder of this document is structured as follows. In Chapter 2 we discuss the four main NGOA network options together with two aggregation concepts to provide the architectural context of the available options being assessed. Furthermore, the impact of the aggregation network on different NGOA network architecture options is presented. Chapter 3 provides the background bases for the different architectural aspects (power consumption, resilience, migration, open access, operational complexity, and control & management) that form the means to assess and compare the different NGOA network options. Both the quantitative and qualitative results of the assessments in terms of various architecture aspects mentioned above are described in Chapter 4, with the subsequent Chapter 5 providing a side-by-side comparative analysis of a subset of the quantitative results for the architecture options. Finally, conclusions are drawn in Chapter 6.

2. OASE Architectures

In this section we present our proposed access architectures that we have been evaluating in the OASE project: WDM-PON, hybrid WDM/TDM-PON, two-stage WDM-PON, and NG-AON. As mentioned before, during the project we realized that it is difficult to reduce the number of architecture options, as all of these four architecture options have their own advantages and disadvantages, and depending on the considered deployment scenario any one of these four architectures can fit better than the other. To select one architecture, which can be considered to be the most overall advantageous, is therefore not an easy task, and each architecture must therefore be considered depending on the scenario. Therefore, we decided to keep all four OASE architecture options, and map them to the different deployment scenarios in order to select the best option for a certain scenario. Furthermore, it should be noted that the architectural scope of WP3 in OASE progresses from the customer side, through the access and aggregation to the edge node of the core network. Therefore, in this section we also cover two aggregation concepts along with their associated impact on different access network architecture options.

2.1 Architectural Scope

The scope of WP3 in OASE is from the customer side to the edge node of the core network, which covers both access and aggregation segments. It does not include any in-house (or in-building) networking or the core network. The optical signal is assumed to be terminated at the customer, but the optical termination point for the remote end is not fixed and depends on the architecture. Higher-level functionalities (such as layer-2 and higher) are also located at the customers' side. In OASE the goal of an average sustainable bandwidth of 300 or 500 Mbit/s per customer is set with the coverage of 100-1000 customers per next-generation optical access (NGOA) network.

2.2 OASE Access Architectures

In this section we briefly present the access architecture options to be evaluated. A more detailed description and discussion of these architectures can be found in the OASE deliverable D3.1.

2.2.1 WDM-PON

Three variants of wavelength division multiplexing (WDM)-based passive optical networks (PONs) are considered for NGOA architecture in OASE. The first two options presented below use the well-known dense-WDM approach, while the third one applies the more recent ultra-dense WDM technology. They all provide high sustainable bandwidth for each customer and can be considered as point-to-point links in the logical level.

Broadcast-and-select WDM-PON

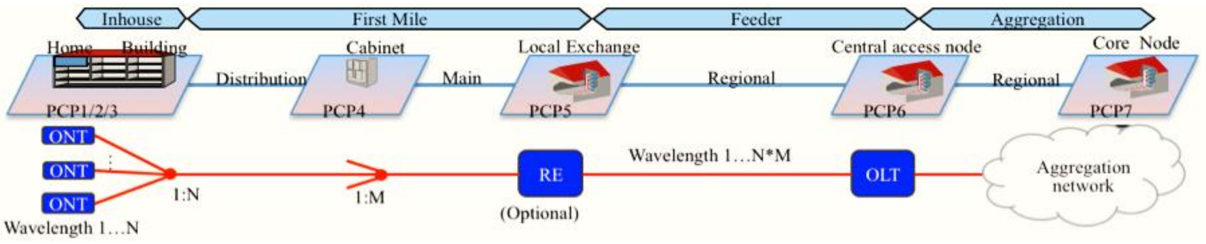


Figure 2-1: A typical configuration of broadcast-and-select WDM-PON

In the broadcast–and-select (i.e., wavelength selected (WS)) variant of WDM-PON (see

Figure 2-1) the devices in the field are passive optical power splitters. This means that all wavelengths are available for each optical network termination (ONT). Therefore, each ONT must select the wavelength to be received as well as the wavelength on which it will send the signal upstream. This selection could be done either statically or dynamically. Tunable WDM filters and tunable lasers in the ONT are required for effective deployment. Each ONT is allocated one wavelength, and the maximum number of ONTs is therefore limited by the number of available wavelengths.

The use of several layers of power splitter in this architecture leads to limitations on reach if high splitting ratios are used. Since all wavelengths are available to all ONTs a security layer is needed to prevent eavesdropping. Furthermore, the energy consumption of the architecture can be high.

WAVELENGTH-ROUTED WDM-PON

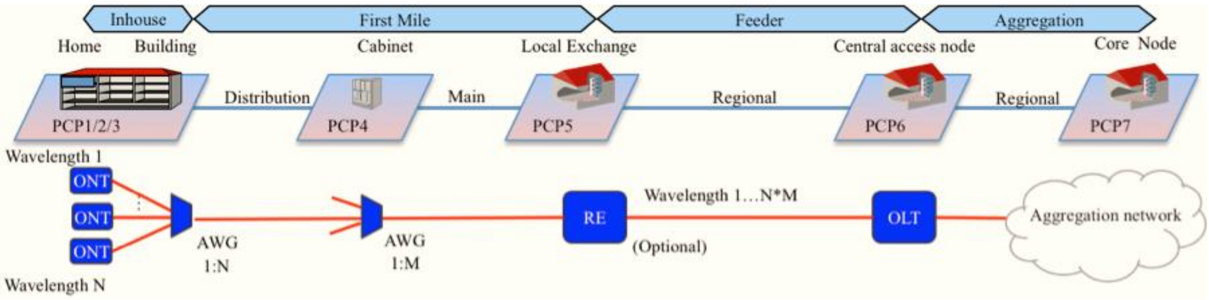


Figure 2-2: The configuration of wavelength-routed WDM-PON, where the passive elements in the field are AWGs

The second variant of WDM-PON, the wavelength-routed (or –filtered) WDM-PON shown in Figure 2-2, consists of the same optical line termination (OLT) architecture but uses one or several passive devices that can multiplex/demultiplex wavelengths, and these devices are deployed in the field. They are usually implemented as arrayed waveguide gratings (AWGs) in actual deployments.

These AWGs make sure that only one wavelength reaches each ONT, thereby removing the potential security issue found in the previous WDM-PON architecture. The ONT could be designed with two types of lasers: with a tunable laser, or with a laser using reflective seeding. A fixed laser, which is fixed to a wavelength, is possible but impractical as it will present problems when deploying the PON network. Wavelength-routed WDM-PON provides the same high bandwidth as the broadcast-and-select variant, but has a better reach.

ULTRA-DENSE WDM-PON

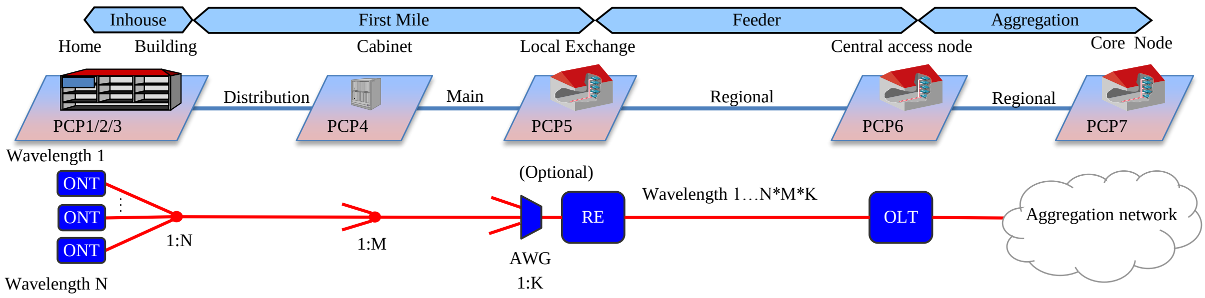


Figure 2-3: The ultra-dense architecture combines power splitter and AWGs

The last architecture of the WDM-PON variants is an ultra-dense WDM-PON that uses more advanced optics, including coherent detection, to provide more wavelengths and therefore improving the fan-out. In the field the architecture can use both power splitters and AWGs, with AWGs or power splitters in the first mile, as shown in Figure 2-3.

This architecture has the advantage of having a higher fan-out as compared to the other WDM-PON solutions, while still proving the same bandwidth. The clear drawback of this variant is that the cost of ultra-dense WDM is high, partly because of the advanced coherent detection required. It may also have a limited reach, depending on the architecture configuration.

2.2.2 *Hybrid WDM/TDM-PON*

According to the usage of passive or active components at the remote node (RN) deployed in the field, hybrid WDM/TDM-PON architectures can be classified into two main categories: passive and semi-passive (see OASE deliverable D3.1). Note that in this document, the semi-passive hybrid WDM/TDM-PON is also referred to as wavelength-switched hybrid WDM/TDM-PON. Moreover, in OASE deliverable D3.1, the term wavelength-routed hybrid WDM/TDM-PON was used for the semi-passive variant, but to avoid confusion with wavelength-routed WDM-PON, only using AWGs in the field, this last term is no longer used in this deliverable.

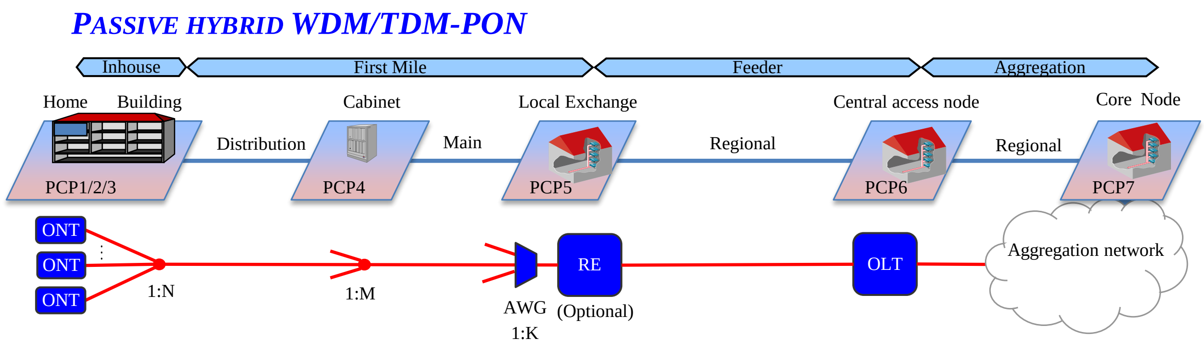


Figure 2-4: The hybrid WDM/TDM-PON architecture, which can use both AWGs and power splitters.

The passive hybrid WDM/TDM-PON architecture (see Figure 2-4) aims to improve the fan-out of the WDM-PON architectures by introducing a TDM layer for multiple-access. As a consequence, several ONTs receive the same wavelength where the TDM layer handles the multiple-access to the wavelength. Each ONT dynamically gets a timeslot where it may receive or send traffic.

This architecture can be deployed with both power splitters and AWGs. When using power splitters (which can also be referred to as wavelength selective hybrid WDM/TDM-PON) each ONT needs to select both wavelengths and a timeslot, while when using an AWG (i.e. wavelength split hybrid WDM/TDM-PON) the ONT only needs to select a timeslot. The former approach has the highest flexibility concerning resource allocation among all hybrid WDM/TDM-PON variants, but at the expense of a huge insertion loss occurred by the high power splitting ratio. Meanwhile, the second configuration is limited in flexibility on wavelength allocation, but it has a relatively long reach due to the low insertion loss of an AWG.

The use of a TDM layer improves fan-out as several customers may share a wavelength, but it introduces some drawbacks. As several ONTs shares a wavelength it also requires a security solution, for example encryption, to prevent eavesdropping between ONTs. Also, each ONT needs to run at the same speed as the combined bandwidth of the TDM layer, which may increase costs. The final drawback is that the sustained bandwidth of each ONT is lower than in WDM-PON as the combined bandwidth of the TDM layer is shared between all the ONTs.

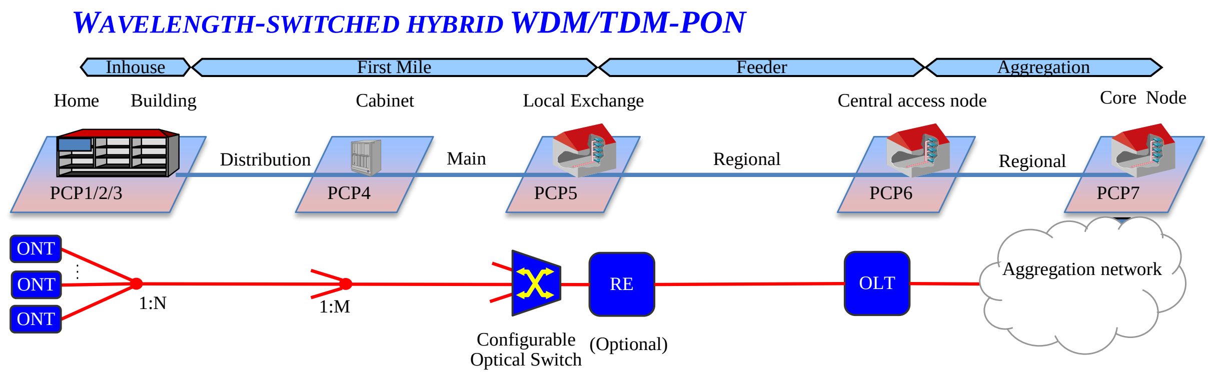


Figure 2-5: The wavelength-switched hybrid architecture where the device in the local exchange is an active optical switch.

The wavelength-switched (or semi-passive) hybrid WDM/TDM-PON architecture (see Figure 2-5) is similar to the passive hybrid WDM/TDM-PON (in Figure 2-4) but with the important difference that the first splitting device is replaced by an active reconfigurable optical switch (e.g. wavelength selective switch, WSS). This active device can switch the wavelength to the different distribution fibers and can therefore allocate resources in a more dynamic way in the PON network.

Compared with the passive hybrid WDM/TDM-PON, this architecture has better security. The active optical switch can reduce the impact of a misbehaving ONT on the TDM layer, as the optical switch could switch to a different wavelength. The architecture can provide high fan-out with better bandwidth usage, as compared to the hybrid WDM/TDM-PON using an AWG in the field, because of the ability to partially change wavelength allocation between ONTs.

2.2.3 Two-stage WDM-PON

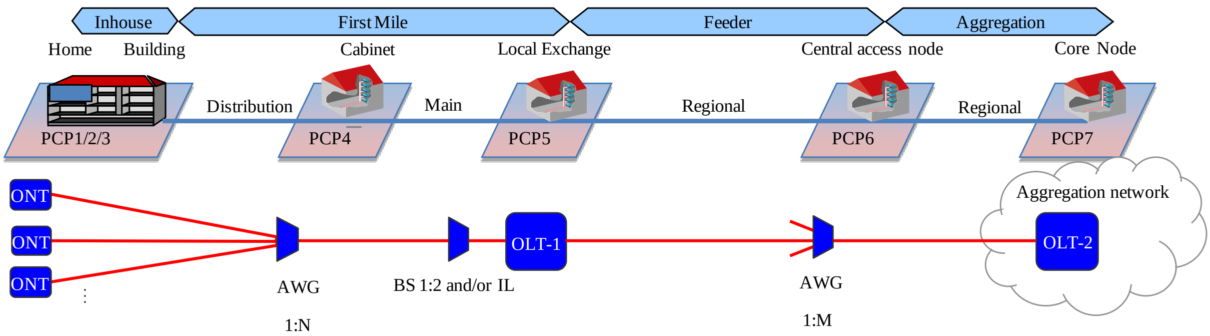


Figure 2-6: The two-stage WDM-PON architecture

In a two-stage WDM-PON (see Figure 2-6) the network consist of two layers of active equipment, first a WDM OLT similar to the OLT in wavelength-routed WDM-PONs, and then a second OLT, which can be of several different types, including a hybrid TDM/WDM OLT or another WDM-PON OLT. One or several wavelengths reach the second OLT, which in turn may be a wide number of active devices.

This architecture gives better reach because of the second active device, and it gives high fan-out for the same reason.

2.2.4 NG-AON

Similar to the two-stage WDM-PON, the next-generation active optical network (NG-AON) has an active remote node, which can be placed either in the building or the cabinet.

The architecture provides very high sustainable bandwidths because of the dedicated fiber to each ONT. The operation of a NG-AON network can also be integrated with the systems of the aggregation and core networks, as the control and management system will be based on the same standards and protocols.

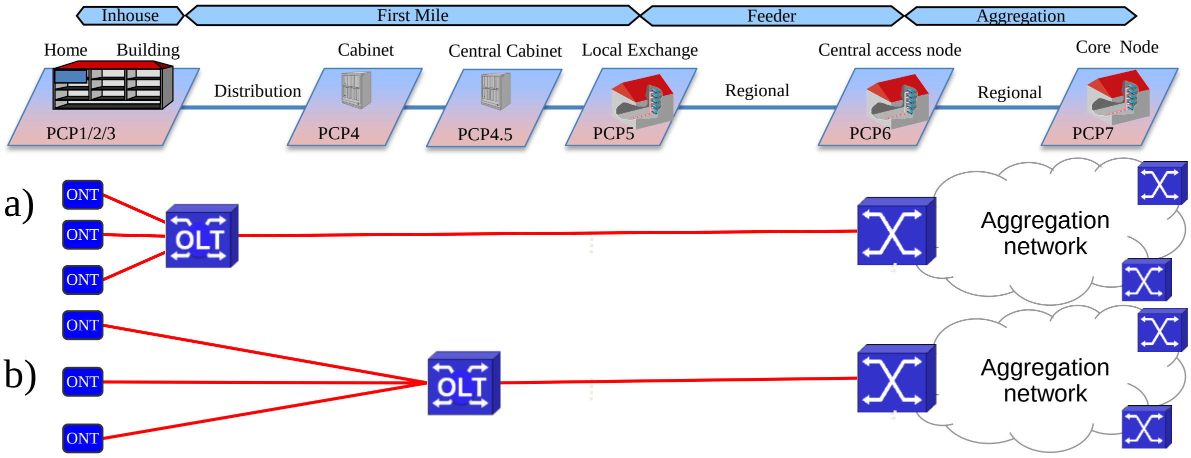


Figure 2-7: The active star variant of AON which has one active switching element either in the building or in the cabinet, with switches on the upper electrical layers.

In the active star type of NG-AON, an active switching element is placed in the distribution network (or first mile), most commonly in the building (Figure 2-6a) or cabinet (Figure 2-6b). Each ONT connects to the switch, where the traffic is switched primarily on layer-2. This switch could also be designed to include other capabilities, for example switching on the higher layers, such as IP, and in principle also on the lower layer, such as the lambda layer.

The uplink between the active remote note and the OLT could use point-to-point WDM, which enables a high number of subscribers on the feeder fiber, and thereby fulfills the OASE requirements. This might be necessary as the requirements state a minimum of 1000 subscribers, combined with minimum requirement of either 300 or 500 Mbit/s sustainable bandwidth per subscriber. The only link technology currently capable of transmitting these kinds of bandwidths is WDM. A second alternative is to backhaul the active remote nodes with WDM-PON. This is described in the next section.

2.3 OASE AGGREGATION/METRO ARCHITECTURES

The NGOA network envisioned in OASE includes either 300 or 500 Mbit/s sustainable bandwidth per customer, this leads to very high aggregated bandwidths in the aggregation network. This requires the aggregation network to also continue its evolution, both in handling the new bandwidth requirements but also to handle the traffic patterns and services of the future access network.

The access architecture may affect the aggregation in several ways: in terms of its consolidation level, its switching level, and on its physical transport technology. A high degree of node consolidation will lead to a higher amount of aggregated bandwidth and a higher number of customers depending on each node in the aggregation network. The selection of switching technology to be used in the aggregation is heavily affected by the switching technology deployed in the access network. For example a layer-3 access network may not work well with a layer-2 aggregation network. It is therefore important that the aggregation network can accommodate the requirements set by the access network in the electrical switching layers. Lastly, the physical transport technology used by the access node affects which can and should be used on the aggregation node.

In this section we propose two different potential architectures for deployment in next-generation optical aggregation networking, namely a simple architecture with focus on node consolidation and cost reduction, and a more advanced architecture which also offers additional features.

2.3.1 Tree architecture

The tree architecture design (see Figure 2-8) has its emphasis on node consolidation and cost reduction with direct point-to-point links to core nodes. The OLTs located in PCP6 are directly connected to the core node with DWDM links in order to support the high bandwidth requirements. The exact forwarding and switch capabilities of the nodes are still under investigation.

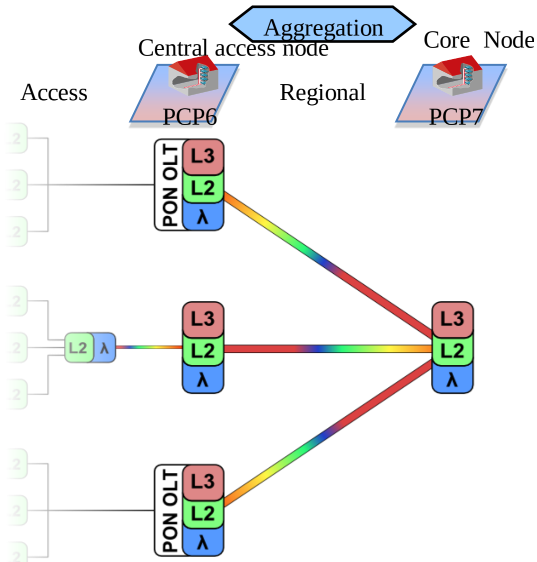


Figure 2-8: In the tree aggregation architecture the OLTs located in PCP6 are directly connected to the core node with DWDM links.

This architecture has a reduced number of aggregation nodes and a lower number of connections to core nodes. Additional links from the central office to the core node can be provided for protection.

An example of a tree topology that fits with the requirements of OASE and indicates a possible migration scenario can be seen in Figure 2-9. In Figure 2-9, the architecture consists of two concurrent and protected point-to-point WDM systems. Between PCP5 and PCP6 is a passive CWDM system, and between PCP6 and PCP7 there is a 10-, 40-, and 100-Gb/s point-to-point DWDM system. It utilizes a transit node (PCP6) in order to aggregate between the two regions/WDM systems. Regeneration in PCP6 can be bit rate retaining or via a muxponder function that multiplexes/de-multiplexes a number of lower bit rate lambdas between the passive CWDM system and the high-capacity DWDM system.

Today there exist approximately 8000 access nodes (PCP5), 1000 aggregation nodes (PCP6), and 10 core nodes (PCP7) in Deutsche Telekom’s network. Depending on the degree of consolidation, OLTs will be moved towards PCP6 and the number of access nodes will be decreased to first 4000, then 2000, and in the end all OLTs will be located in the 1000 PCP6 central access nodes.

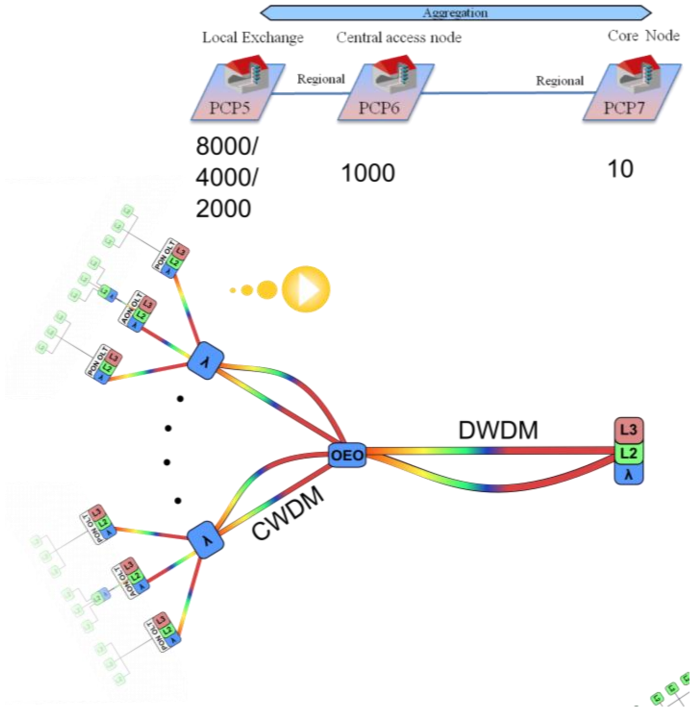


Figure 2-9: Two concurrent and protected point-to-point WDM systems. A passive CWDM system is utilized between PCP5 and PCP6, and a 10/40/100 Gb/s DWDM system between PCP6 and PCP7. The OLT function will be moved from 8000 PCP5 location (today) to the 1000 PCP6 locations.

This configuration has been transferred to WP5 for cost evaluation. In the next section a more advanced and future looking aggregation network architecture will be presented.

2.3.2 Ring architecture

The ring architecture (see Figure 2-10) is designed to provide some more advanced features of the future network, such as handling of local traffic flows and end-to-end energy saving techniques. Moreover, this architecture is better to handle dynamic traffic than the tree architecture.

It is designed around WDM rings with central access nodes connected to the rings. Each ring is connected to at least one core node. Neighboring rings are in turn connected to each other to provide better protection and higher available maximum flow bandwidth for the aggregation nodes. This network could, from a hardware standpoint, be built based on technologies currently in use in core networks, but with more advanced control and management features. This network architecture could also be built progressively out from the core network as the traffic demands increases. Partly technology agnostic, it functions well with all proposed NGOA access architectures. The exact selection of which nodes have upper layer switch capacity is still under investigation.

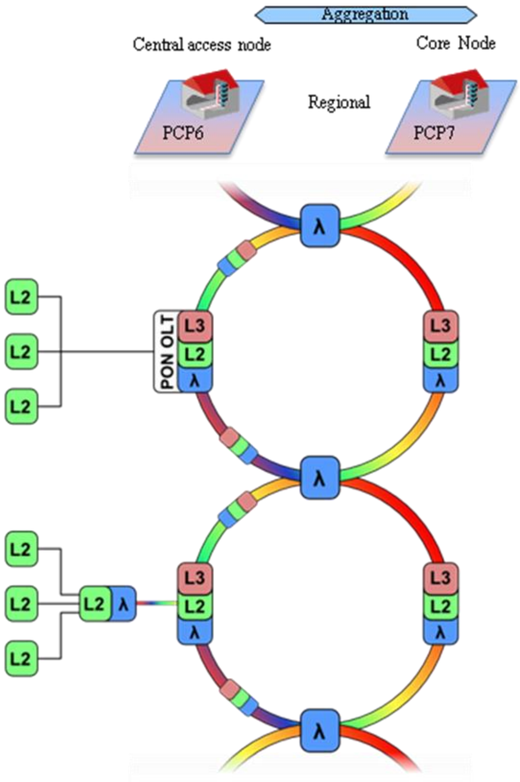


Figure 2-10: In the ring architecture OLTs are interconnected with PCP6 by a ring with λ -capable optical switches interconnecting the WDM rings. Each OLT is capable of reaching several core nodes and traffic can be directly routed between OLTs without putting extra load on core nodes.

The ring aggregation architecture is able to support intelligent bandwidth allocation techniques, as there are several possible paths to the core node. The control plane can flexibly allocate network resources, e.g., in order to reduce the energy consumption during low traffic periods. Moreover, this architecture allows for large amounts of bandwidth to be allocated by a few central access nodes, for example, to handle temporary increases in traffic demand.

Furthermore, the ring architecture enables local flows between parts of the aggregation network, which reduces load in the core network. These local flows can be created by, for example:

- Local services in the network (IPTV etc.)
- Local content distribution network (CDN) nodes
- Local caches
- Peer to peer offloaded protocols

In addition, a high level of resilience can be obtained since each central access node can be connected to several core nodes, and in this way a fast recovery in the optical layer can be provided. Moreover, selective routing is enabled as control plane can bypass routing layers when necessary. Finally, an efficient optical transport and dynamic routing in higher layers allows for reduction of power consumption by shutting down electronic equipment.

Having now discussed the access and aggregation architecture variants currently being studied in the OASE project, we turn in the next section to the architecture aspects common to all architectures, which will allow us to undertake a quantitative comparative analysis of the architecture options.

2.3.3 Impact on aggregation network

The WDM-PON architecture can easily be integrated into the aggregation network from a control and management (C&M) perspective, as a WDM-PON OLT may be operated as a normal layer-2 switch. In the data plane this architecture includes some interesting possibilities, for example it might be possible to forward a wavelength from the WDM-PON OLT through to a higher aggregation node or even to a core node. This could be useful when providing low latency connections.

Passive hybrid WDM/TDM-PON has limited impact on aggregation network and can mostly be integrated into the aggregation network on layer two. Integration on the control plane with the aggregation level might be limited as the TDM layer of the hybrid layer requires C&M functionality that is not present in the aggregation and core network. It is also harder to integrate the data plane of this architecture with the data plane of the aggregation network as the optical signal must be terminated on the PON OLT and may not be forwarded optically to the higher aggregation level. Therefore, the OLT must be integrated with the aggregation network on the bitstream level, for example, on layer two.

Two-stage WDM-PON has a clear impact on the aggregation network, as can be seen from a comparison of the respective architectures and their assignment to the PCPs. Obviously, the two-stage WDM-PON covers PCPs 1-7, i.e. it already includes a first active aggregation layer. This is complemented by inherent long-reach capabilities (which are particularly enabled by the backhaul part). The active, aggregating RNs have two relevant aspects. Firstly, the two-stage approach supports local traffic sharing, and hence relief of the backhaul and aggregation network. Secondly, the inherent aggregation layer of two-stage WDM-PON must be considered, and dimensioned, in the overall network context. From the *systems* viewpoint, a dedicated aggregation switch can be eliminated because it is integrated into the access OLT. From the network viewpoint, this aggregation switch still exists, leading to (high) aggregation for the backhaul, and enabling both long-reach and comparatively low power consumption.

The AON architecture can be built to a large degree with the same technology as the aggregation network, and the integration is therefore easy in both the control plane and in the data plane. The AON control plane can also be fully integrated with the aggregation network, and therefore enable an end-to-end aspect. In the data plane the AON access and aggregation can fully integrate on any switching layer. When the AON network is backhauled with WDM, the aggregation network could forward the access wavelengths in an optical layer and therefore give a lower latency connection for some customers.

3. Architecture Aspects

This chapter provides the underlying methodological approach (assumptions, explicit quantitative approaches, and criteria) that allows us to perform the comparative analysis described in the following chapters of this document. In particular, we focus on the technical architectural aspects of: energy efficiency, resilience, migration, open access, operational complexity, aggregation, and control & management. These are all critical aspects to NGOA architecture design, with different architecture options offering a diverse range (or set) of performance parameters as measured in these various technical aspects. The ultimate choice of deployment of a particular NGOA architecture option will depend on which of these technically-based aspects are to be (preferentially) emphasized, as well as the standard commercial criteria (techno-economic modeling, OpEx/CapEx, business models etc.) and regulatory environment that may be present. These business and regulatory aspects are the subject of the ongoing parallel OASE work packages WP5 and WP6; with the results from these other WPs additionally informing the final comparative analysis and conclusions that will occur towards the end of the project.

3.1 POWER CONSUMPTION AND ENERGY-EFFICIENCY TECHNIQUES

Energy efficiency in next-generation optical access (NGOA) networks is a critical issue, both now and also looking to the future. Currently, access networks are estimated to consume approximately 90% of total (i.e. core+metro+access) power [2], due to its predominantly copper-based infrastructure. Of course, this is likely to reduce substantially as photonic-based technologies are introduced ever more deeply into the access network, e.g. recent work on hybrid VDSL (very high speed digital subscriber loop) -over-optics solutions has indicated more than a factor x1000 improvement in associated energy efficiency [3]. However, looking to the future, data-rates are also expected to increase at an exponential rate similar to Moore's Law (i.e. Nielsen's Law [4]), so that bandwidth capacities are also expected to increase by similar orders of magnitude over the next 10-15 years. With power consumption generally increasing in proportion (or more optimally, to the power of 2/3 with bandwidth capacity [5]) it is clear that energy-efficiency in the access continues to be an important issue. For example, in the UK context, the total current national generating power output is 76.3 GW, with about 1% of that being consumed by incumbent operator BT [6].

When considering power consumption requirements of NGOA architectures, and comparing between the various candidate architectures being examined in the OASE project, there are a number of metrics that can be employed to assist in the analysis. In particular, as discussed later in Section 5, we have adopted various metrics that give different insights into the power consumption performances of the architectures. At the simplest level of the power consumption per end-user of the whole network, we have calculated the power consumption per end-user measured at the ONT (PCPs 1-3), at the intermediate remote node (PCP4), and at the OLT (PCPs 5/6). This gives an immediate understanding of the power consumption per client, so offering a more "personal" insight into the carbon footprint required by each individual client of the network; and so from energy efficiency perspective provides a more directed, individualized incentive to reduce the personal carbon footprint. However, from a more practical perspective, particularly from the operator point of view, aggregated power consumption at each of the PCPs is also a critical metric, so as to understand what is the overall power consumption at the various NGOA network nodes. Hence, using the typical architecture client counts (feeder numbers) we have also calculated the aggregated power consumed at the various PCPs, i.e. at PCPs 4, 5, and 6, which represents the power that must be supplied (and paid for) by the network operator (see also 3.3.1). From the one perspective of dimensioning, the aggregated power at each PCP can be used to give an indication of the types of (potentially renewable) power source that can best supply that particular power requirement. For example, for a central access node (CAN) at PCP6 or central office (CO) at PCP5 that may require of the order of 100 kW of power, various renewable energy generation schemes (e.g. photo-voltaic, PV) with suitable back-up battery (energy storage) infrastructure, or tri-generation plant can be considered [7]. Alternatively, at the RN (PCP4) which tends to have a smaller power requirement, this power can either be supplied remotely, or locally via wind-turbines or PV plant; again with the availability of suitable battery storage or back-up capability. In each of these cases, the absolute value of the power consumption dictates the possible power sources that may be employed, each with a differing carbon footprint and energy efficiency that typically scales with size.

It's also worth pointing out that the aggregated power per PCP (4-6) as related to the network operator are generally lower than the aggregated power at the ONT (PCPs 1-3). From an energy-efficiency perspective this has both pros and cons. On the one hand, the power consumed at the ONT is generally the responsibility of the individual end-user, and although on its own is relatively modest (typically 5-10 W), means that end-user clients can employ their own carbon-footprint reducing schemes at their domestic premises to improve the overall energy-efficiency of operation at their end. However, when aggregated together, the power consumption of the ONTs tends to represent the greatest fraction of the overall NGOA power consumption; but is the least amenable to a single (and cost-effective) approach to minimize carbon footprint. From this perspective, reducing the carbon footprint at the ONT tends to rely on the individual end-user's initiative to reduce their own personal carbon footprint. From the operator perspective, such a large aggregated power does not tend to be their own responsibility, so that the operator does not tend to be liable for the supply and associated carbon-footprint of the (aggregated) ONT power – this has both commercial (cost) and practical (management, C&M) advantages to the operator and also lowers the business risk that normally attends such responsibility.

With regard to NGOA energy efficiency, there are fortunately many technological approaches which can be employed to reduce the overall carbon footprint of the access – certainly, to reduce it in comparison to the rest of the network. Recent studies suggest that 90% of network power will in the future be consumed by the core, in contrast to the current situation where 90% of network power is consumed by the access, since IP routers and switches will increasingly consume greater quantities of power with their greater aggregated bandwidth capacities [8]. However, while naturally enjoying a reduction in the overall share of network power consumption as optical technologies are deployed ever closer to the end-customer, there are still many additional aspects to improving the overall access network energy-efficiency. PON architectures have the benefit of not requiring active equipment at the street level, between end-customers and the central office (or central access node). Thus an important source of energy dissipation, at the street cabinet level, is obviated. At the actual customer premises, the financial cost of power consumption is directly borne by the end-user, so that the motivation for personal low energy consumption is most directly experienced by the end-user (for financial, ecological, practical reasons etc.) rather than by the telecom operator.

Innovation at the customer premises equipment (CPE) to reduce energy consumption is an on-going endeavor, with outcome results reflecting the general reductions in carbon footprint in line with that of consumer electronics in general. In this regard, the greatest energy efficiency savings in the access network environment are to be accrued further up the chain, towards the core, principally in the CO and CAN locations. Here, the largest sources of power dissipation are found in the rack equipment, and similar to the case of core IP routers, the energy consumption is in proportion to the amount of processing that takes place [5]. As such, a key contribution to reducing the power dissipation in the CAN/CO is to minimize the amount of processing that takes place, and minimize overheads associated with any data, e.g. network overheads (such as packet or container labels), network control & management plane resources, signaling, and perhaps most importantly, switching.

However, one means to intelligently reduce overall traffic volumes, in general, passing up and down an access network (or PON) is to use a content distribution network (CDN) overlay such that frequently-accessed or popular data is stored at strategic sites along the access network (e.g. at the various PCP points). This offers an overall reduction in traffic volume across the network (and also access network in particular), since customer requests for particular popular data streams can be serviced close to the end-user (and hence improve access and latency times) and avoid associated heavy traffic issues at the core-access interface; in other words, a single copy of the popular data set can be copied once (or updated once, as and when appropriate) from the core network, and then subsequently spread to a variety of data servers distributed throughout the access network.

Regarding reducing the amount of switching required, improvements in energy efficiency can also be achieved using appropriate aggregation along the access network; however, this necessitates having active equipment located between end-users and the CAN, i.e. a multi-stage approach, as discussed in our two-stage WDM-PON architecture. For example, at the PCP5 (traditionally the CO) and/or PCP4 (cabinet) aggregation and statistical-multiplexing can be used. Here, upstream data from different end-users are aggregated onto the same wavelength (e.g. at a line rate of 10G), before being sent further upstream towards the CAN. Apart from the associated economies of scale, such aggregation also allows equipment (e.g. 10G line cards at the CAN) to be operated at their maximum utilization, which also tends to increase their overall energy efficiency. Thus, by aggregating data onto 10G (and higher) wavelengths, greater energy efficiencies can be achieved (due to the associated economies of scale, and closer to maximal exploitation of system capacity resource) so that an overall lower carbon footprint is enabled.

Detailed description of energy-efficient techniques investigated within OASE project for different NGOA options have been included in the WP4 deliverable D4.4.2, which was delivered before this document. Besides, the associated implementation and performance evaluations have also been presented in D4.4.2.

3.2 RESILIENCE

Resilience in NGOA architectures is becoming increasingly important for two main reasons. On the one hand, higher reliability requirements have to be fulfilled in support of business access, backhaul and some high quality consumer applications, such as remote surgery and healthcare. On the other hand, access networks are evolving towards reduced number of nodes where multiple central offices (COs) are being replaced by a single CO covering larger service areas. This evolution is being driven by operators in order to reduce operational costs. Due to a larger number of subscribers and the longer reach between the legacy local office and the new central access node, an efficient resilient mechanism is required to avoid service interruption in the case of a failure. In addition to the protection of the aggregation equipment at the centralized access nodes, operators require feeder line protection in order to avoid large scale customer outages.

From the operators' point of view, the reduction of impact of a single failure (i.e. to avoid a large number of end users being affected by any single failure) should be considered in the first place. Meanwhile, end users (in particular business users) typically require a certain guaranteed level of connection availability, in order to keep a low risk of service interruption. With this in mind, we take into account two resilience measures, namely, the connection availability and a figure of merit (FOM), which can represent the end-user and the operator perspective, respectively. These two measures are defined below.

3.2.1 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 (asymptotic) availability *A* and unavailability *U* can be expressed, as in equations (1) and (2), respectively:

$$A = \frac{MTTFF}{MTBF} \quad (1)$$

$$U = 1 - A = \frac{MTTR}{MTBF} \quad (2)$$

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 (MTBF=MTTFF+MTTR). Typically MTTFF >> MTTR. MTTR is typically dominated by the time defined for certain operational processes. The values for the MTBF and the MTTR of each element used in this document can be found in the OASE deliverable D4.2.1.

Connection availability means the probability that a logical connection (e.g. the connection between the OLT and ONT) is operable. There are two basic configurations for the connection availability calculation, namely series and parallel. 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 (3) and (4), respectively:

$$\text{Series configuration: } A = \prod_i A_i \quad (3)$$

$$\text{Parallel configuration: } A = 1 - \prod_i (1 - A_i) \quad (4)$$

where A_i stands for availability of a certain component *i* in the connection.

3.2.2 Figure of merit (FOM)

Besides the connection availability, network operators are also interested in the figure of merit (FOM), since this measure reflects both the impact of failure, i.e. the number of end users affected by a failure, and the connection availability of the considered connection (component/system and link). The FOM includes two important factors relevant to resiliency [9]. 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. The second one is the unavailability (*U*), which indicates how often a connection is not available due to a failure of a component or link. The definition of unavailability is given in the previous subsection.

The FOM of a component is defined as [9]:

$$FOM_{component} = \frac{1}{FPR \times U} \quad (5)$$

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

The FOM of a path, consisting of a sequence of components (e.g. OLT, ONT, RN1, RN2), is defined as follows:

$$\frac{1}{FOM_{path}} = \sum_i \frac{1}{FOM_{component,i}} \quad (6)$$

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

3.2.3 Resiliency performance evaluation of basic architectures: need of protection

In this section, we estimate the values of the unavailability and FOM for the various network elements such as OLT, ONT, remote nodes and fiber sections in the basic OASE NGOA architectures in order to identify the part that needs to be protected in the first place. MTBF values are obtained from the deliverable D4.4, while the appendix of this document includes the MTTR numbers provided by industry partners of the project. To compare the failure impact fairly among all the considered NGOA architecture options, we assume 160 customers are subscribed in a single access network.

Figure 3-1 shows the unavailability of various elements for the different OASE NGOA concepts (i.e. passive, semi-passive and active options) 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 CO) is always larger than the component part regardless of the type of populated service area. Therefore, to achieve higher availability, fiber protection should always be considered in the first place. Among various NGOA options, the availability of the OLT or ONT is similar, while passive RNs tend to have a lower unavailability than the active ones.

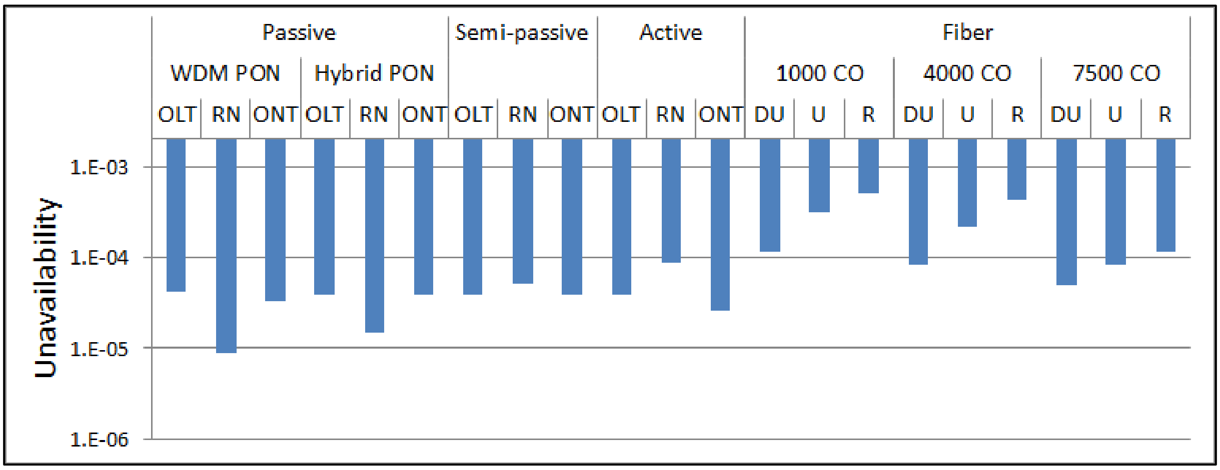


Figure 3-1: Unavailability of various network elements in different OASE NGOA concepts.

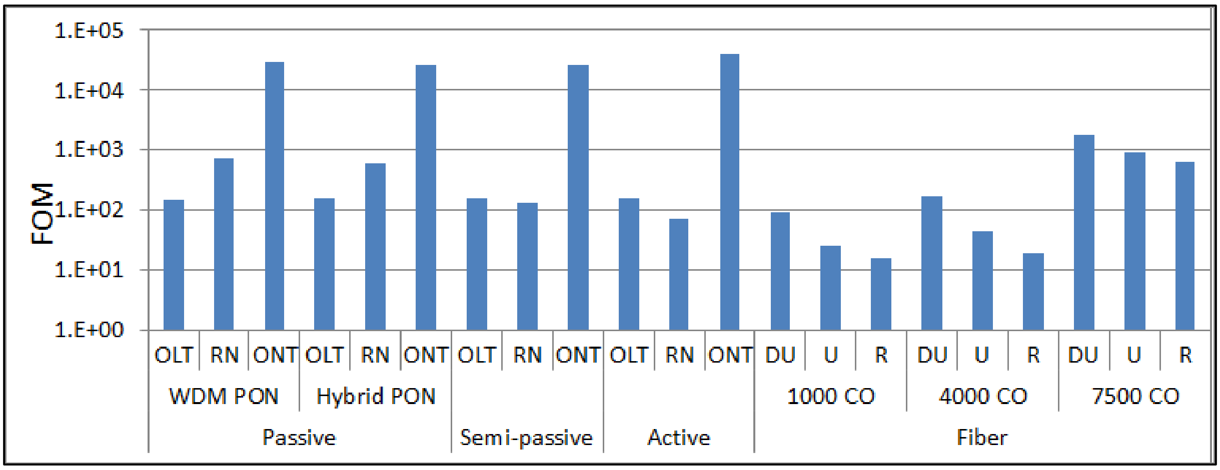


Figure 3-2: FOM of various network elements in different OASE NGOA concepts.

Figure 3-2 shows the FOM of various network elements for different OASE NGOA concepts along with fiber in different scenarios. Similar to the availability results, fiber in particular in node consolidation scenarios (i.e. 1000 and 4000 CO) has a lower FOM than the other network elements, regardless of the type of populated service area. Therefore, to achieve a higher FOM, fiber (in particular feeder fiber) protection should be considered in the first instance. Furthermore, the OLT has a significantly lower FOM than the ONT, since any single failure occurring at the OLT affects a large number of end users. Compared to passive approaches, the active remote nodes of semi-passive and active architectures also have an apparently lower FOM due to their low unavailability.

As a conclusion of the resiliency performance evaluation of different network elements for NGOA without any protection, it is extremely important to provide protection of feeder fibers in node consolidation scenarios, as well as OLT backup for all the considered NGOA architectures. Furthermore, for semi-passive and active approaches, protection of the active components at the RN is also recommended.

3.3 Operational aspects

With respect to architecture the placement of either passive or active equipment at different locations and physical connection points (PCPs) within the network, and the impact of this placement in terms of operator related energy consumption, footprint, expected failure rate, and travel distance is of importance, particularly in combination with node consolidation.

Operational aspects are also studied in WP4 and WP5. However, in the framework of WP3 we consider the operational complexity of the architecture options, whilst in WP4 operational aspects of components and systems are analyzed, and in WP5 the related impact on the overall cost is quantified.

3.3.1 Operator related energy consumption assessment in node consolidation

The main advantage of node consolidation is the reduction of traditional access nodes (i.e. node concentration at so-called metro access nodes). Although the number of consolidated access nodes is fewer than traditional access nodes, the total operator related power consumption may not decrease. Therefore an energy assessment evaluation should be performed to compare the increase of power consumption at the consolidated access node due to the fact that it will serve a higher number of users and therefore need a higher number of components, with the savings of consuming energy at all the former access nodes. The energy consumption evaluation needs to be based on an accurate network dimensioning, while the energy consumption considered within operational aspects is operator related. For instance, energy consumption at PCP1/2/3 (i.e. user side) is not considered as operator-related energy consumption.

3.3.2 Footprint assessment in node consolidation

A reduction of traditional access nodes will impact the footprint as follows: the reduction of floor space of the access nodes will cause an increase of the required space at the consolidated access node. This increase may imply a cost which is lower than the expected savings from the traditional access nodes. However, other issues such as the use of the abandoned access nodes by other technologies or purposes, whether they can be rented or sold, etc. should be also taken into account for the techno-economic studies of WP5.

3.3.3 Failure rate in node consolidation

Node consolidation will allow higher compactness and better utilization of active systems with an expected positive effect on the failure rates (i.e. fewer failures). Nevertheless, the increase of the customer count per system may impose the need for redundancy mechanisms to limit the maximal failure penetration range. Redundancy requires, in total, more network components resulting in more potential failures (without service impact, but still needing to be repaired). Furthermore, the quantity of fibers in the feeder part (formerly aggregation part) will become higher, and new passive components such as AWGs or even active components for reach extension are required depending on the NGOA architecture variant. Both these aspects could lead to more failures of the infrastructure. An evaluation of the total failure rates of the active and passive network components (presented in Chapter 4) will show the differences between the NGOA architecture variants.

3.3.4 Impact of node consolidation on travel effort

Node consolidation will not change the distances from today's maintenance offices (MO) to the remote passive access nodes and to the users (if no optimization of staff location structure is considered), but may change the average distance to the remaining access nodes with active equipment. The change of travel time (increase or decrease) mainly depends on the node consolidation degree and the distribution of the staff locations. (Note: In a typical network scenario the staff locations, in most cases, are not identical with network locations.) Therefore, for maintenance and reparation purposes, the time required could change due to the changing traveling time to and from the equipment location. This change of time will impact on the operational expenditures of maintenance and fault management. However, this is not expected to be linear, since the traveling time will not affect all components in the same way (i.e. lower impact for the existing equipment) and the maintenance and reparation rates depend also on the equipment type. In this section, the traveling distance model, which is used for comparison of different NGOA architecture options, is presented as follows:

TRAVELING DISTANCE MODEL

The following traveling distance model is the basis of the architecture comparisons relating to the impact of node consolidation on traveling effort described in Chapter 4 for all the selected NGOA architectures.

The country-wide network of a network provider is typically subdivided into several maintenance districts (MDs). We can assume that the number of central access nodes with active equipment is at least one order of magnitude higher that the number of MDs. For a German wide network this means that the number of MDs should be assumed to be equal to, or less than, about 100. The number and the dimensions of the MDs depend on the number of end users. Each MD covers multiple service areas and includes one maintenance office (MO) where the technicians are located.

Figure 3-3 shows an example of a country-wide network provider network that is subdivided into 100 MDs. Each MD covers multiple NGOA service areas (with one CAN each) and includes one maintenance office (MO) where the technicians are located.

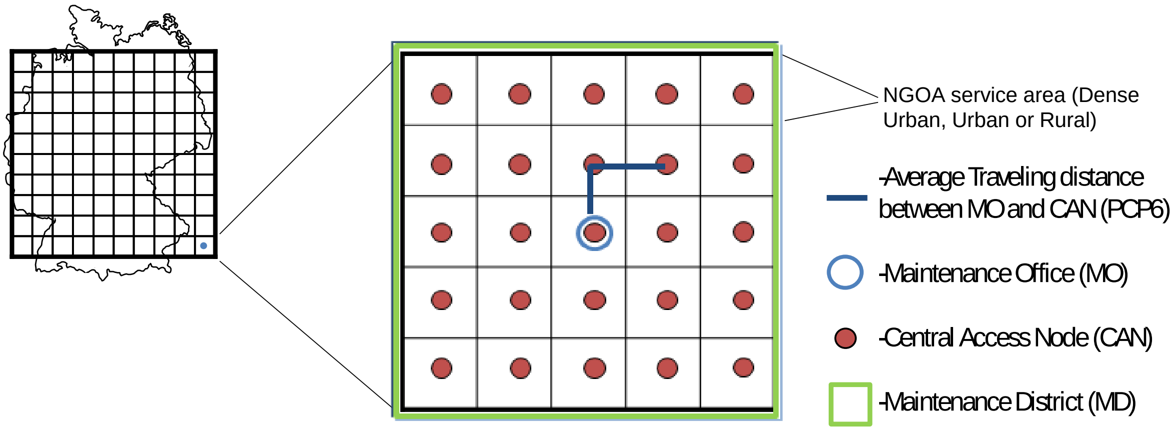


Figure 3-3: Maintenance district (Example)

It is assumed that the number and the dimensions of the MDs remain constant for all node consolidation scenarios and, therefore, the average traveling distance also remains constant as illustrated in Figure 3-4. The number of CAN locations does not influence the average traveling distance.

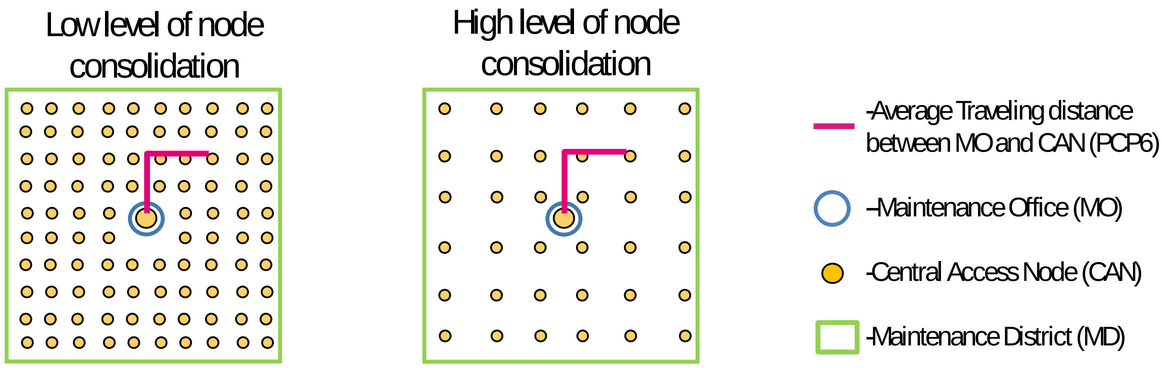


Figure 3-4: Average traveling distance in low and high level node consolidation scenarios

In addition, the average traveling distance to a failure location also depends on the NGOA services area type. As illustrated in Figure 3-5 the maintenance office is typically located near to areas with a high user density, with the result that the average traveling distance is relatively short for dense urban, medium for urban and high for rural service areas.

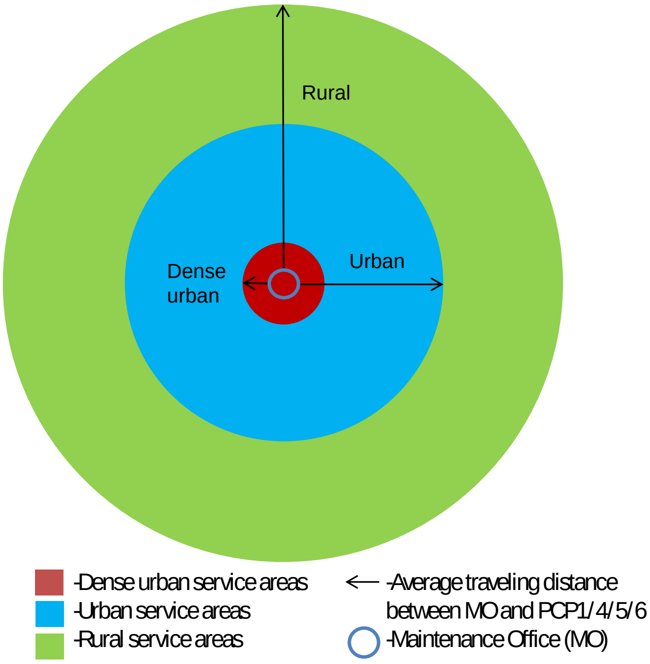


Figure 3-5: Average traveling distance also depends on the NGOA services area type

A maintenance office is typically co-located with a central office (PCP5) and a CAN (PCP6) network node. In this case the traveling distance between MO and PCP5/PCP6 = 0 km. Table 3-1 shows the assumption of the percentage of PCP5/PCP6 locations which are also MO nodes.

Table 3-1: Co-location percentage

	Node consolidation scenario	Dense Urban	Urban	Rural
Percentage of PCP5 locations which are also MO nodes	**All scenarios**	5%	4%	0%
Percentage PCP6 locations which are also MO nodes	**Scenario 2 (4000 CAN locations)**	6%	7%	0%
	Scenario 3 (1000 CAN locations)	14%	24%	0%

Table 3-2 shows the average traveling distance between the maintenance office and different failure locations. These values have been derived from the parameters of NGOA service area categories described in the OASE deliverable D5.1.

Table 3-2: Average traveling distance between maintenance office and different failure locations

	NGOA service area		
	Dense Urban [km]	**Urban [km]**	**Rural [km]**
Average traveling distance between MO and CAN (PCP6)	5.00*(1)*	20.00*(1)*	35.00*(1)*
Average traveling distance between MO and CO (PCP5)	6.00	23.00	40.00
Average traveling distance between MO and Cab (PCP4)	7.20	25.10	42.90
Average traveling distance between MO and User (PCP1)	7.50	25.50	43.50
Average traveling distance between MO and Feeder fiber failure	5.50	21.50	37.50
Average traveling distance between MO and Main cable failure	6.60	24.05	41.45

Average traveling distance between MO and Distribution cable failure	7.35	25.30	43.20
Average traveling distance between MO and Inhouse cable failure	7.50	25.50	43.50

(1) Assumption: Percentage of average traveling distance between MO and CO (PCP5); 83% (Dense urban); 87% (urban); 88% (rural)

In addition, the calculation of the travel effort described in Chapter 4 considers the following assumptions:

- Average travel speed per service area type:
  - Dense urban: 20 km/h
  - Urban: 40 km/h
  - Rural: 70 km/h
- Two technicians always travel to one failure event
- Travel time includes the trips there and back.

3.4 Control and Management

Most active network equipment has many configuration options and requirements, which in themselves may be straightforward and simple to set manually by a technician. But as the number of configuration points and more importantly the number of devices in the network increases, the need for a more automated and safe methods of C&M increases. This is where the control and management (C&M) systems come in, to simplify and improve the operation of the network. These systems can intelligently allocate resources, optimize and monitor the network, to name a few common capacities.

Today's trend in C&M system is to move to a common control plane for different transport technologies, with the goal to reduce operational complexity, enable more intelligent network allocations, and reduce costs. A current example of this trend is generalized multi-protocol label switching (GMPLS) from IETF where optical and electrical switches are controlled by a common distributed control plane. Another popular recent trend is software-defined networking, where the intelligent command and control are shifted to a central "controller", from which the network is configured and monitored. The currently most popular development in this field is the emergence of the OpenFlow protocol which has the support from many key players in the network field. This is also the focus of the FP7 project SPARC.

The NGOA networks must offer the ability to be controlled from a control plane, so as to be competitive with current solutions. In some cases the current and upcoming control systems can be used, for example AON networks can be controlled by both legacy systems, such as simple network management protocol (SNMP), but also by upcoming GMPLS and OpenFlow. The work is ongoing to provide the same integration with common C&M systems for the other NGOA architectures.

3.5 Resource Allocation

In this section, two types of resource allocation schemes are discussed. The first one is dynamic bandwidth allocation (DBA) which is mainly for TDM-based architecture, while the second one is for the architectures with reconfigurable components in the field, e.g., AON and some wavelength-selective switch (WSS)-enhanced system concepts (and variants).

3.5.1 Dynamic bandwidth allocation

To achieve high node consolidation in PON long reach is highly desired. Reach extension allows consolidation of multiple central offices to a single one, and hence has the high potential to reduce capital and operational expenditure. However, it introduces challenges to satisfy some performance requirements with respect to, e.g., delay, jitter, etc., in order to guarantee quality of service (QoS), as also explained in the OASE deliverable D3.1. Bandwidth allocation becomes an important aspect to be considered for NGOA architectures, in particular for those that are TDM based, i.e. hybrid WDM/TDM-PON. To achieve high efficiency in these kinds of networks, statistical multiplexing-based techniques are used, which can adapt to the changing traffic demand from ONTs in the upstream direction. This is because in TDM-based PONs (including EPON, GPON, XG-PON and hybrid WDM/TDM-PON) traffic in the upstream direction, only one ONT among all the ONTs connecting to the same splitter is allowed to transmit data at a given point in time because of the shared upstream channel. The start time and the length of a transmission time slot for each ONT are scheduled using a bandwidth allocation scheme. In order to achieve flexible sharing of bandwidth among users and high bandwidth utilization, a dynamic bandwidth allocation (DBA) algorithm that can adapt to the varied traffic load is used. A comprehensive survey of DBA algorithms has been included in the deliverable D3.1. In conventional DBA schemes for TDM-based PONs, performance depends on the round trip time (RTT) as it affects the delay of the DBA control loop. By extending the reach of the PON, the RTT may grow from today's 200 µs (20 km reach) to 600 µs (60 km reach) or potentially 1 ms (100 km reach) and beyond. With increased RTT, the DBA performance is ultimately degraded. Hence, developments of DBA schemes that can deliver adequate service, despite the increased RTT in future long-reach hybrid WDM/TDM-PONs, are highly desirable.

Furthermore, energy efficiency is a critical issue for the future as indicated in subsection 3.1. Devising energy-aware resource allocation algorithms is a promising approach to reduce power consumption. Here, the main objective of these approaches is to explore the possibility to schedule sleep (i.e., stand-by) mode cycles together with bandwidth allocation. The work related to energy-aware resource allocation schemes is presented in sections related to power efficiency.

3.5.2 Opportunities enabled by active elements within system concepts

While minimizing total cost of ownership (TCO) is a driving objective of the system concepts studied within OASE, the different solutions studied vary significantly in their approach to achieving this goal. The PON systems, as their name implies, include as-few active elements as possible in the network in an effort to reduce both their capital and operational costs. However, this can leave them rigid and with few opportunities for reconfiguration and adaptive management.

More-active solutions, which include the AON and some wavelength-selective switch (WSS) enhanced system concepts (and variants) offer opportunities for optimization and traffic reduction not available to the passive concepts. Within this section, such opportunities will be outlined including information on how they may be identified, and through what methods they may be acted upon.

OPTIMIZATION OPPORTUNITIES

There are two opportunities which may be employed, depending on the active elements which are utilized through the network. The first, in Figure 3-6 below, shows dynamic reconfiguration of the network in the optical domain.

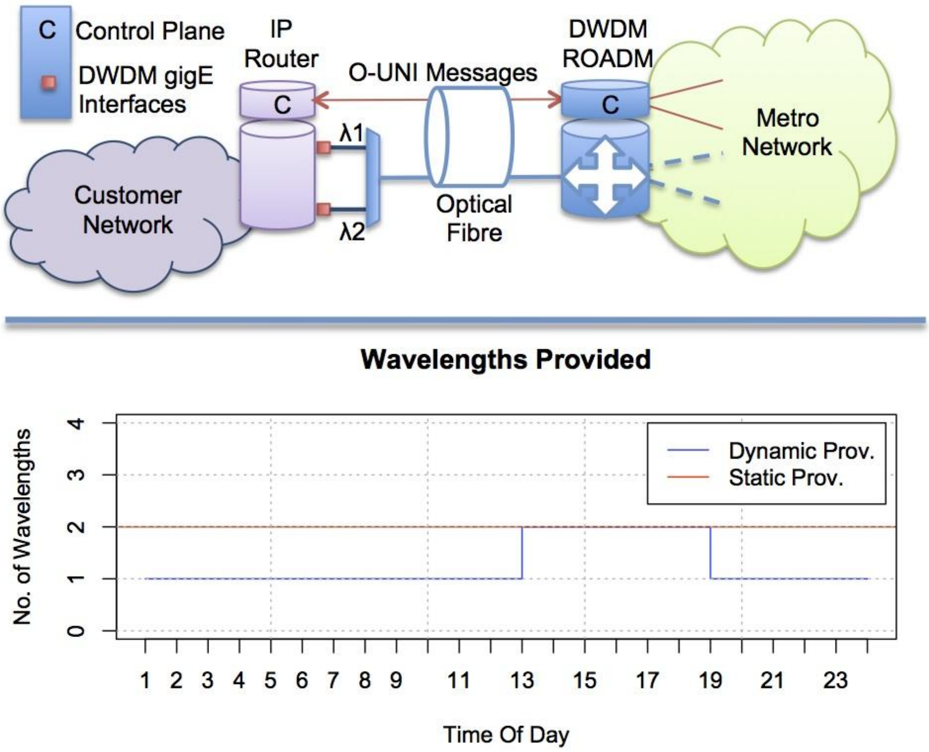


Figure 3-6: Dynamic allocation of wavelength channels

This shows a business customer connected to a transparent, reconfigurable optical access network which may be provided using a WSS. The customer in question is interconnecting two datacenters in different cities, and does so by leasing a wavelength service from the network provider (or physical infrastructure provider, depending on the unbundling/open access scenario), which is used to provide end-to-end gigabit Ethernet connectivity. This fixed connection is on λ1. However, this is a fast-reconfigurable optical network, and so the customer opts to make use of on-demand wavelength services to handle the peak in demand between 13:00 and 19:00. This wavelength is provisioned on-demand, and denoted λ2, by signaling between the customer and the control plane of the optical network.

This has some advantages, e.g. with a fixed network, two wavelengths would need to be supplied at all times in order to meet peak demand; but this is also clearly inefficient. By utilizing λ2 only when it is required, it is free for use by other customers at other times. This increases the utilization of each wavelength, resulting in economic advantages.

However, in this scenario the increase in utilization of the wavelengths comes at a cost: the utilization of client interfaces at the edge will fall. This may, at first, seem inefficient. However, compared to backbone equipment, which is high-bitrate (and therefore high-cost), the client interfaces are low-bitrate (and therefore low-cost) and (more importantly) high-manufacturing-volume which reduces price (consider the cost of Ethernet interfaces vs. SDH, for example). It may therefore be preferable to underutilize cheap, low-bitrate devices at the edge to save on costly upgrades to expensive, high-bitrate devices in the core, and this is an optimization made available through the use of active elements.

Another method of optimization available is to reconfigure bandwidth allocations in the electrical domain. This is shown in Figure 3-7 below.

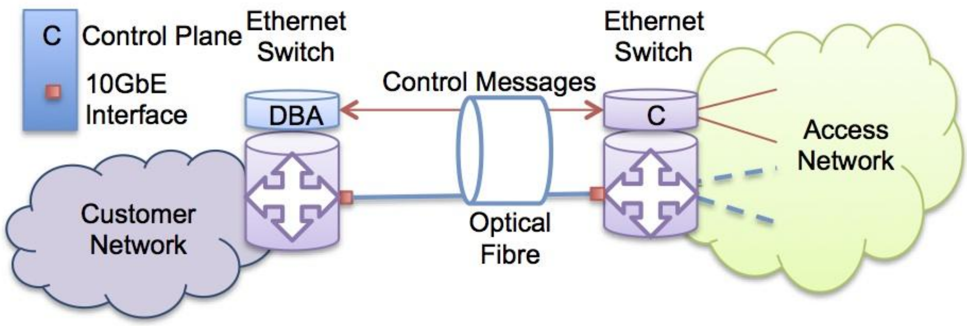


Figure 3-7 Reallocation of channel capacity in the electrical domain

In this example, a 10Gb Ethernet interface is shown; however this mechanism can as easily be used at lower bitrates which satisfy the OASE requirements. Here, customers at the edge can signal to the control plane to increase the capacity of their dedicated channel. Such allocations operating at extremely high speeds (and over single network links) are already utilized within PON systems, and the previous section has information as to the work within OASE on increasing the efficacy of such algorithms.

Active networks, such as AON, employ a larger number of shorter links in between their active elements. Therefore, changing the capacity of a channel, which may span the same distance as a PON solution, will involve the interaction of many nodes and is therefore not something to be undertaken frequently. It is therefore important to identify mechanisms which may be employed to predict future demand and make control plane requests in a timely (and accurate) manner.

METHODOLOGY

It has already been mentioned that DPI and SNMP provide network operators with considerable insight into the evolution and usage of services through analyzing traffic usage patterns. By employing similar technologies to determine the customers network usage, these devices will act on their information about the traffic, their information about themselves, and their information about the network to make decisions about the capacity required at any given time utilizing dynamic bandwidth allocation algorithms (DBAAs). These decisions will be subjective and potentially erroneous, dependent upon the quality of information that they receive, as well as the inherent flaws in the algorithms used for the decision-making process.

The traffic utilized here is an artificial traffic trace generated from a sinusoidal function. This was utilized because of its simplicity and its broad similarity to the traffic profiles observed in our analysis of ISP backbone network traffic. An example of this is shown in the figure below.

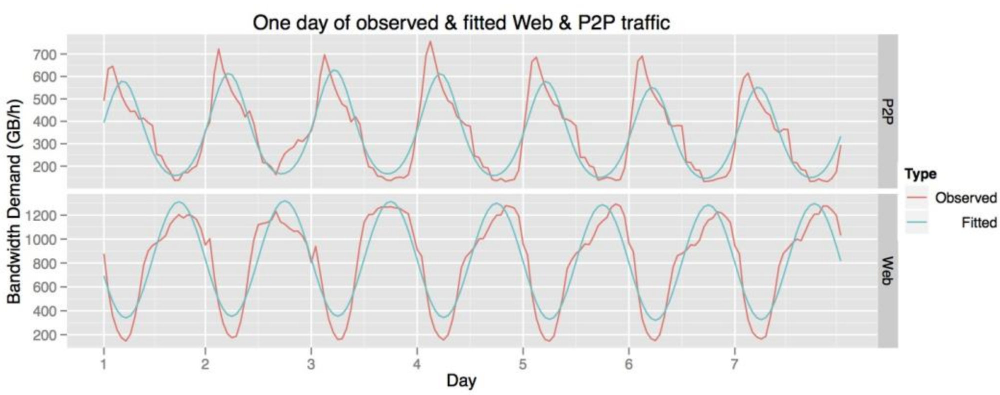


Figure 3-8: A fitted sinusoidal model

An algorithm that automates allocation of capacity must provide bandwidth in an accurate and timely fashion.

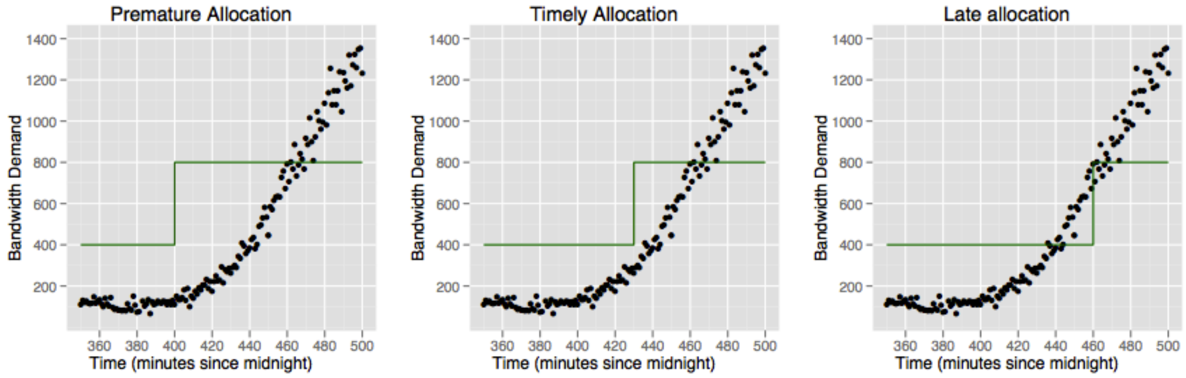


Figure 3-9: The importance of time in good allocation

The timeliness of bandwidth requests will have an enormous impact on the efficiency of any DBAA. In order to highlight why this is the case, the graphs in Figure 3-9 show a single change in the bandwidth provision by three different hypothetical DBAAs at a variety of different times. The green line indicates the bandwidth allocated, while the data points indicate the traffic usage.

The graph on the left indicates the result of a premature allocation by the DBAA, where bandwidth is requested (and received) before it is needed. While this ensures good quality of service, the bandwidth supplied is underutilized and may be better utilized elsewhere in the network. For this reason, this is considered to be an inefficient allocation.

The graph on the right shows the result of late allocation by the DBAA. Here, the bandwidth has been requested (or received) after it is needed. Performance such as this, rather than being merely inefficient as in the premature allocation example above, is unacceptable. As a direct result of the actions of the DBAA there is insufficient bandwidth available to satisfy the needs of the underlying traffic, which will lead to a degradation of the Quality of Service (QoS). This may manifest itself through packet loss or increased delay (which will have a more-adverse effect on interactive data, as well as streaming audio or video).

The center graph shows the perfect allocation: the bandwidth request is delayed until the last moment, while ensuring that there is sufficient bandwidth to satisfy the immediate demand. Such timeliness is the aim of the DBAAs under study.

It must be noted, however, that due to the definition of the control plane that has been adopted, the timing of bandwidth requests may not always be under the control of the DBAA. In such situations, it is vital that the amount requested be enough to cover the spectrum of possible demand over the period.

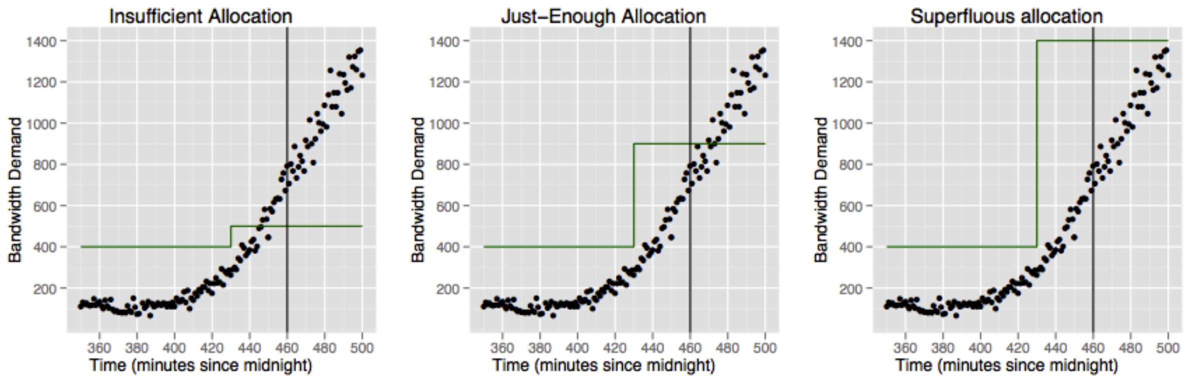


Figure 3-10: The importance of amount in good estimation

The amount requested at each bandwidth request is also important due to the complexities of how often a DBAA may be able to signal (limited by the control plane), and when it choses to do so. A careful balance must be found; sufficient bandwidth must be assigned to account for the bandwidth demands until signaling may occur again (or the algorithm chooses to do so), while simultaneously the assigned bandwidth must be kept as small as possible such that it may be re-assigned elsewhere in the network.

The graphs in Figure 3-10 show the importance of the accuracy of allocation; the allocation made in minute 430 must be sufficient to last until the next opportunity to signal arises (shown by the horizontal line at 460 minutes).

The graph on the right shows too-much bandwidth being provisioned. Similarly to the premature allocation above, this is an inefficient use of the bandwidth which may be better utilized elsewhere in the network.

The graph on the left demonstrates a scenario where the required traffic is un-determinated, leading to a shortfall in bandwidth. This shortfall may adversely affect QoS as in the late allocation scenario described above.

Finally, the graph in the middle shows the "optimum" allocation, where there is sufficient bandwidth requested to cover the usage profile until another opportunity to signal arises.

In order to quantify the performance of the algorithms, we define four key metrics: overprovisioning, under-provisioning, signaling and unstable determination

OVERPROVISIONING

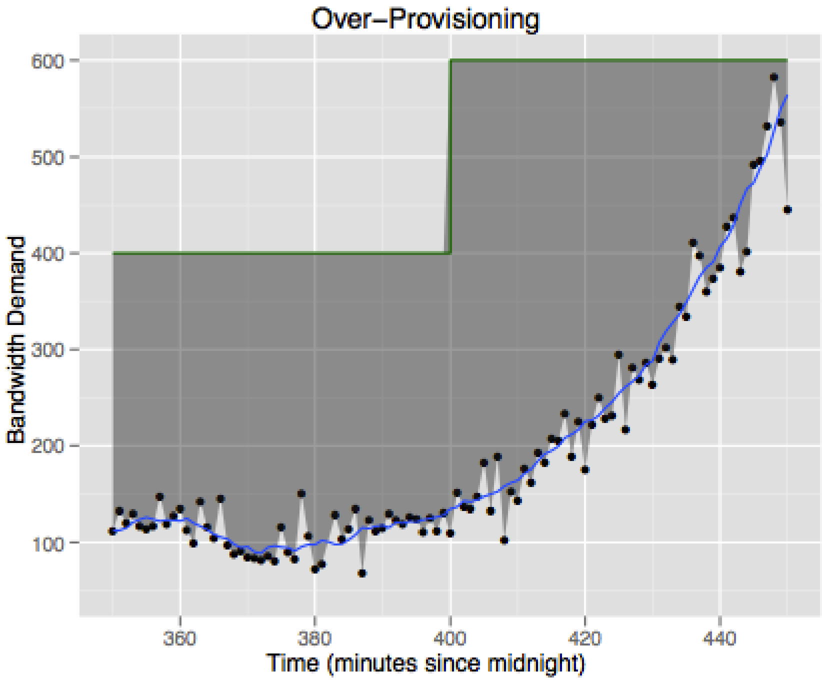


Figure 3-11: Defining Over-Provisioning

Overprovisioning indicates areas where optimization of bandwidth is possible, and is shown by the shaded area on the graph in Figure 3-11. The allocated bandwidth, which is under-utilized, may be better utilized elsewhere in the network, and therefore represents a failure of the algorithm to optimize for the observed traffic pattern.

UNDER-PROVISIONING

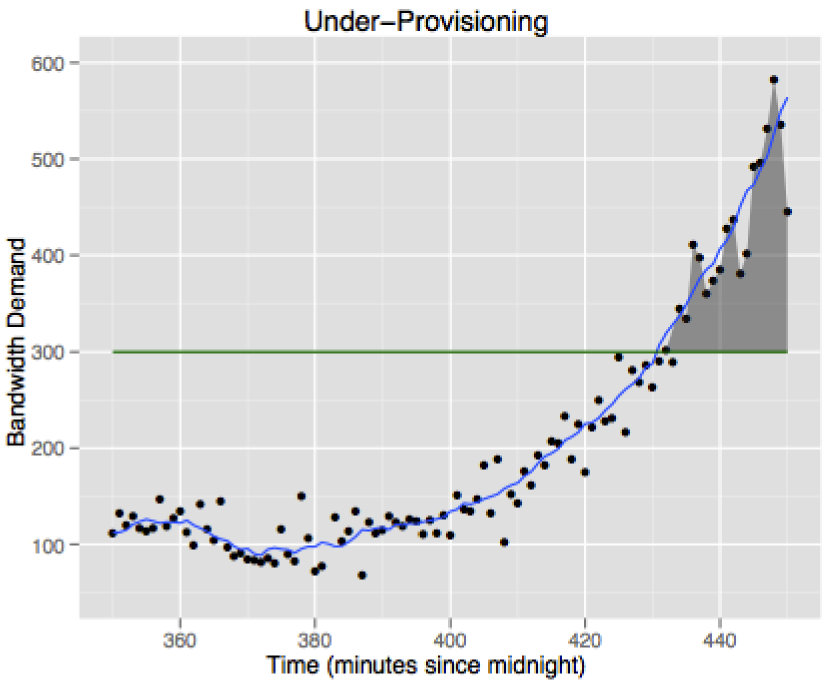


Figure 3-12: Defining Under-Provisioning

Under-provisioning is indicated by intervals during which the algorithm underestimates demand, and can be seen by the shaded shortfall in Figure 3-12. In a real network scenario, this may cause packet loss and unacceptable congestion on the link, as well as a violation of the service level agreement (SLA) between the client and the network provider. For this reason, it is the most important metric by which a DBAA is evaluated

SIGNALING

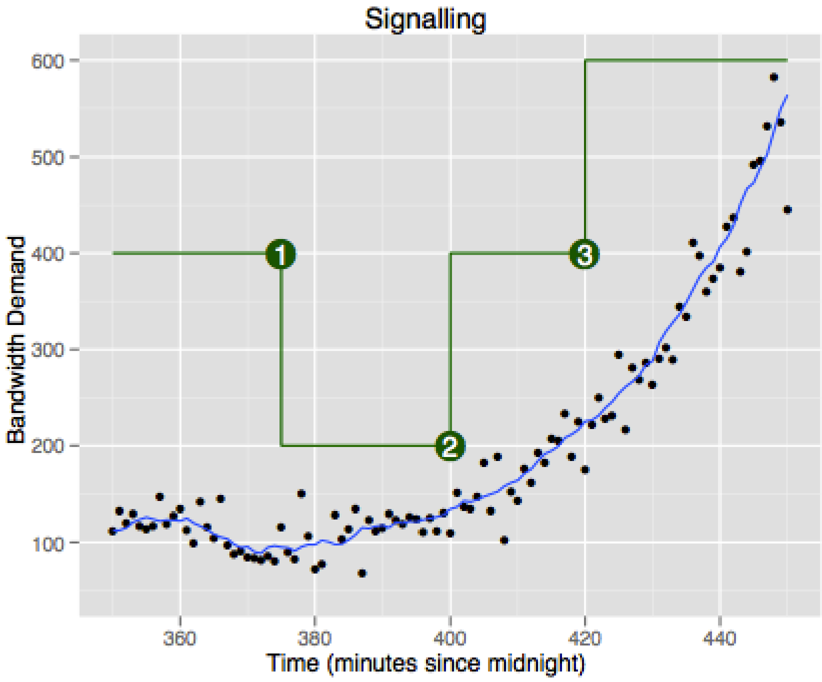


Figure 3-13: Defining Signaling

When a DBAA decides that a change in the provisioned bandwidth required, a request is sent to the network's control plane in order to actuate this change. This request is termed a signal. This can be seen in Figure 3-13 where the each signal has been highlighted and numbered. The number of times such signals must be sent will obviously have an effect on the control plane load. It may therefore be useful to minimize the number of times that such signals are sent, and the signaling rate should therefore should be part of the analysis of the performance of the DBAAs under study in later chapters.

UNSTABLE DETERMINATION

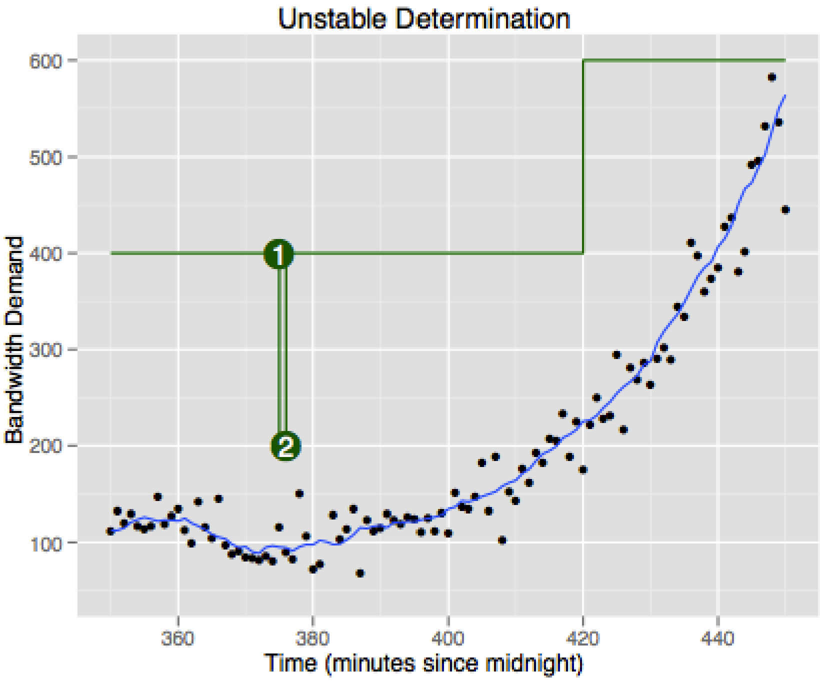


Figure 3-14: Defining Unstable Determination

The graph in Figure 3-14 above highlights an instance of unstable determination: the DBAA has made an error in predicting the bandwidth requirement, and thus sends a signal to decrease the provision. Unfortunately, this decision is immediately reversed by the DBAA, causing the bandwidth to increase once more, resulting in the waste of two signals. The benefit of decreasing provision is that it allows the bandwidth that was provisioned to be allocated elsewhere in the network. However, when considering this benefit, one must also take into account the load on the control plane. A signal to decrease bandwidth that results in a saving over a long timescale (much greater than the network delay) can be considered useful. However, one in which the decision is instantly reversed cannot; it is certain that bandwidth has been saved, but only for a very short time that does not justify the increased control plane load caused by the signaling. This makes unstable determination a very interesting object of study when considering the performance of the DBAAs presented.

ALGORITHMS

The goal of having dynamic bandwidth allocation (DBA) is realized through a combination of enabling technologies and the application of dynamic bandwidth allocation algorithms (DBAAs) The evaluation within OASE will focus on 6 algorithms. The ideas presented here originate from a wide variety of network backgrounds. The idea of utilizing algorithms to calculate the necessary bandwidth and then to assign such bandwidth automatically was first outlined during the introduction of asynchronous transfer mode (ATM) switching into networks. This enabled some fascinating early research into DBAAs [17][18][19][20][21][22][23][24].

This research developed the concept of equivalent bandwidth; the bandwidth that must be allocated to a connection in order for it to have the appearance of dedicated bandwidth that is unshared by other connections. Within this section an early algorithm for calculation of equivalent bandwidth provided by Guerin *et al.* has been implemented to show the performance of this early work in the field [25]. Although rooted in ATM, which saw only limited success, there still remains good research in the area of equivalent bandwidth. The concepts have matured and developed, leading to a recent new-look at equivalent bandwidth by Pras *et al.* [26], which has been implemented and analyzed.

Concurrently, other techniques for bandwidth allocation were being developed, such as the statistical decision mechanism by Yamamoto *et al.* [27] for next-generation synchronous digital hierarchy (NG-SDH) networks, which are also implemented and analyzed. This technique shows an evolution from a naive threshold-based capacity increment/decrement scheme to one that includes a justification through statistical analysis. This algorithm also differs in its desired outcome; clearly under-provisioning remains unacceptable, but one of the central aims of the work was to develop an algorithm which minimizes the frequency of unstable determination and thus attempts to reduce unnecessary control plane load. This may be of particular concern to legacy network technologies retrofitted to be more dynamic.

A different technique is provided by Roughan *et al.* [29][30], who significantly develop a statistical model first outlined by Norros [28] and apply it for use in wavelength-division multiplexing (WDM) networks. By enhancing the statistical model of Norros through a framework of traffic forecasting techniques, Roughan arrives at a simple algorithm with minimal parameters which can make reliable predictions about future bandwidth requirements for highly regular, periodic traffic. Its drawback is, however, that a much larger window of previous observations is required, compared to other algorithms. This algorithm is also implemented and analyzed.

In contrast to the algorithms above which, having been born out of a network analysis background, are quite specific to networking implementations, the dynamic linear bandwidth estimation through regression of traffic (DYLBERT) algorithm proposes the adoption of a simple technique that has been widely-used in many other research areas to understand trends in data-sets: linear regression.

Finally, a novel algorithm resulting from a hybridization of parts of multiple algorithms will be presented.

RESULTS

The results gathered here show the performance of the six algorithms when tasked with predicting (and requesting) bandwidth over a single point-to-point Ethernet link. In order to emulate systems where fine control of bandwidth is not possible (for example, in circuit switched systems), the minimum granularity of requests was altered in order to see how a higher granularity might affect the results. Intuitively, higher-granularity ought to be more forgiving of errors in provisioning, but achieve fewer benefits.

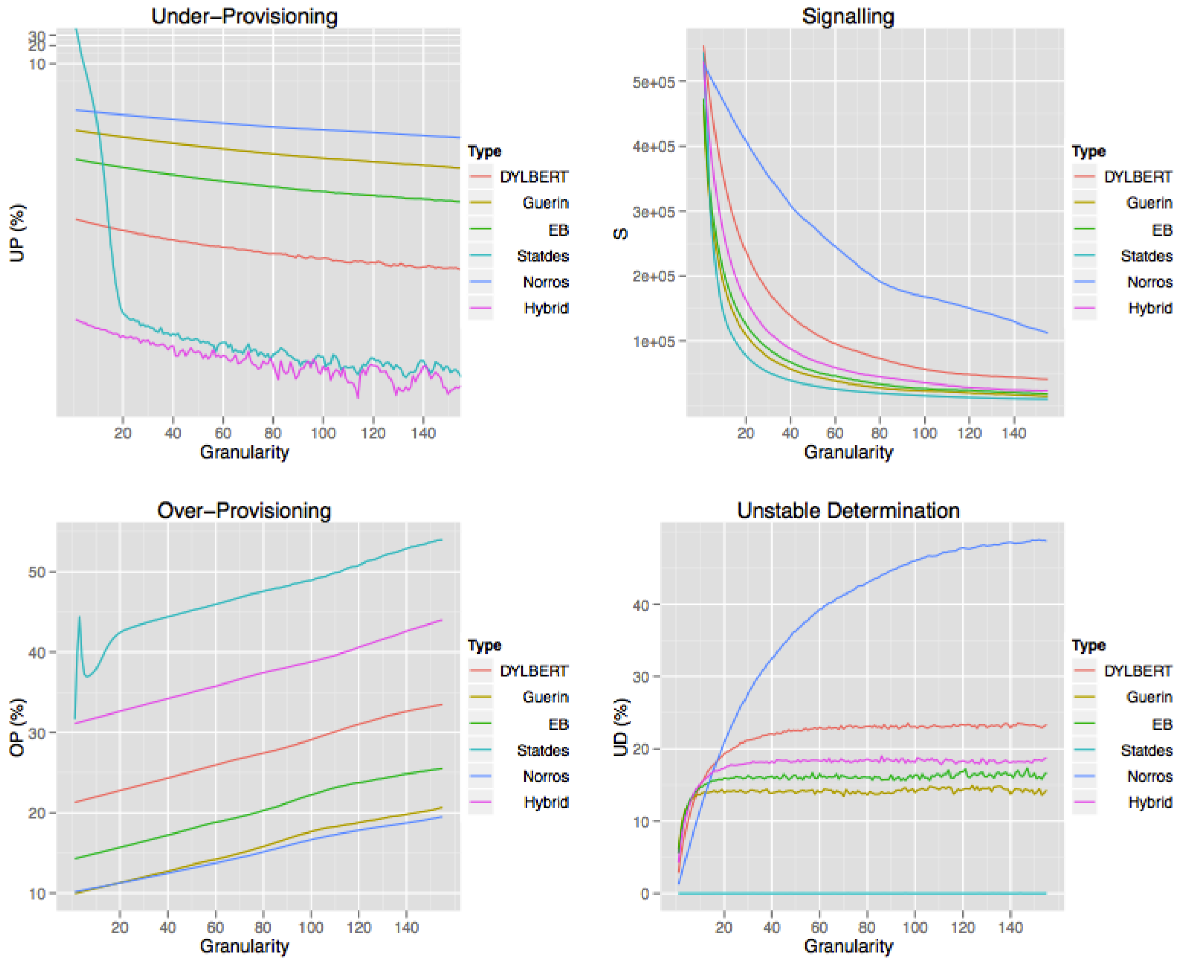


Figure 3-15: Comparative performance analysis of 6 different DBA algorithms

From the under-provisioning and over-provisioning it is clear that our thesis is correct under-provisioning falls with increased granularity, while over-provisioning rises. What is particularly of interest is the decrease in signaling associated with increased granularity. Taken together, this is a useful insight. Imposing a minimum granularity on requests, even when a significantly smaller granularity is imposed by the actual data plane, may result in better allocations and lower control plane load.

It is clear that a number of algorithms offer excellent performance, and may provide optimization potential. Utilizing the cost information and network scenarios of OASE provides the potential for an interesting economic analysis within other work packages, e.g. WP5 and WP6.

3.6 MIGRATION

When evaluating different NGOA architectures, migration is an important criterion for brownfield scenarios, where operators are upgrading their legacy networks. There is no single one-fits-all migration path to each of the NGOA architectures, but there are multiple starting points (depending on the current situation) and migration/coexistence scenarios (from only changing the OLT to a disruptive approach where the ODN is completely changed).

To deploy NGOA architectures, it is important to have a clear view on the migration challenges, when migrating from the legacy architectures, most probably in multiple steps, to the NGOA solutions targeted in OASE. We detected different challenges for reaching the final goal, and they can be classified in the following main categories:

- Coexistence with currently deployed architectures
- Reuse of infrastructure in the optical distribution network (ODN)
- Minimize disruption time at the user side during the migration phase
- Node consolidation to reduce the number of central offices
- Limit the required recourses and migration time
- Keep general performance

The migration steps can be classified into three main parts:

- Starting point: legacy architectures, corresponding to the current network of the operator.
- Intermediate point(s): migration and coexistence scenarios, ranging from only changing the OLT to a disruptive approach where the ODN is completely changed.
- End point: NGOA architectures, corresponding to the four selected architectures in OASE deliverable D3.1. At this point, unnecessary components which were used during the coexistence scenarios (e.g. additional couplers etc.) should also be removed.

It is clear that an enormous number of different migration paths can be followed. It is impossible to make a detailed evaluation of all possible migration options, but we can select a limited number of relevant paths that will serve as a general rule of thumb for any migration scenario. In OASE deliverable D3.4 (due date M36), the most relevant migration paths will be elaborated, and a comprehensive migration assessment of the different options will be made. This will consist of a qualitative evaluation with respect to the different migration challenges, with a detailed evaluation of technical parameters like used frequency spectrum, reach, availability and energy efficiency.

3.7 OPEN ACCESS (OA)

Open access (and unbundling) concerns the design and operation of a network or architecture such that it supports a degree of freedom in parts of the network. For example, an open access network may be utilized to offer a choice of services to the customer (for example, allowing them to choose between internet service providers). This is a benefit to customers as it promotes competition and market diversity. In addition, open access networks allow for a high degree of freedom to collaborate between companies in the undertaking of the deployment of a network, thereby mitigating risks. For example, the supply of an internet connection to a customer could be divided up into the civil works, network architecture design, deployment and operation and service provision tasks. By dividing these tasks between different companies in a collaborative arrangement the risks and investment (at each level) can be compartmentalized, potentially reducing the barrier to market entry to new market entrants outside the initial collaborative agreement. Open access is possible on two distinct levels, i.e. between physical infrastructure provider (PIP) and network provider (NP), or between NP and service provider (SP), utilizing three mechanisms (i.e. fiber, wavelength or bitstream). Open access represents a broad study area, and while some types of OA will not differentiate between the architectures under study, there remains a wide variety which will challenge them on many levels. These challenges and the assessment of architectures are therefore reported in OASE deliverable D3.3, which includes a detailed and structured open access evaluation.

4. Assessments of OASE Network Architecture Options

A preliminary assessment of the OASE architecture options has been presented in OASE milestone M3.1, where some weak points have also been identified. This section of the current document summarizes the results that have been included in OASE milestone M3.1, as well as the new evaluation done in Year 3 of the project by mapping NGOA architectures into different scenarios with consideration of node consolidation and types of populated areas. The assessed architecture aspects have been presented in the previous section, i.e., power consumption, resilience, operational aspects, control and management and resource allocation. It should be noted the evaluation results of open access and migration will be included in the OASE deliverables D3.3 and D3.4 which will be finalized soon after this deliverable.

4.1 WDM-PON

4.1.1 Power consumption

Table 4-1 shows energy consumption figures for the considered variants of WDM-PON architecture presented in Section 2.2.1. Cooling system and aggregation are not included.

Table 4-1: Energy Consumption in WDM-PON

Different Variants	ONT/OLT implementation option	Sustainable data rate (first mile & feeder) *Symmetric*	Client count (feeder)	*Total power consumption per client*	Power cons. at ONT	Power cons. per client at remote nodes	Power cons. per client at OLT
WR-WDM-PON with tunable lasers for *wavelength-routed WDM-PON*	APD & pre-amp	300/500Mb/s	80 (M=80)	***6.7/6.9 W***	4.7 W	0 W	2/2.2 W
	APD & pre-amp	300/500Mb/s	160 (M=160)	***6.7/6.9 W***			2/2.2 W
	APD & pre-amp	300/500Mb/s	320 (M=320)	***6.6/6.8 W***			1.9/2.1 W
	PIN	300/500Mb/s	80 (M=80)	***5.9/6.1 W***	4.2 W		1.7/1.9 W
	PIN	300/500Mb/s	160 (M=160)	***5.9/6.1 W***			1.7/1.9 W
WS-WDM-PON with tunable lasers for *power-splitting WDM-PON*	APD & pre-amp	300/500Mb/s	32 (M=32)	***7.2/7.3 W***	4.9 W		2.3/2.4 W
	APD & pre-amp & booster	300/500Mb/s	64 (M=64)	***7.2/7.3 W***			2.3/2.4 W
	APD & pre-amp & booster	300/500Mb/s	128 (M=320)	***7.2/7.3 W***			2.3/2.4 W
Seeded reflective WR-WDM-PON for *wavelength-routed WDM-PON*	*APD*	300/500Mb/s	80 (M=80)	**6.6/6.9W**	4.7 W		1.9/2.2W
	PIN	300/500Mb/s	80 (M=80)	**6.1/6.4W**	4.2 W		1.9/2.2W
Ultra dense WDM-PON *(hybrid wavelength-routed and power-splitting)*	*FEC*	300/500Mb/s	320 (M=40, N=8)	***7.8/8.4 W***	5.6 W		2.4/2.8 W
	FEC	300/500Mb/s	640 (M=80, N=8)	***7.9/8.3 W***			2.3/2.7 W
	FEC	300/500Mb/s	640 (M=20, N=32)	***7.9/8.3W***			2.3/2.7W

In order to identify the impact of node consolidation on the overall power consumption in the access network Figure 4-1 shows the power consumption per PCP layer of one urban service area for WR-/WS-WDM-PON versus UDWDM-PON and three node consolidation scenarios as described in Section 1.1.

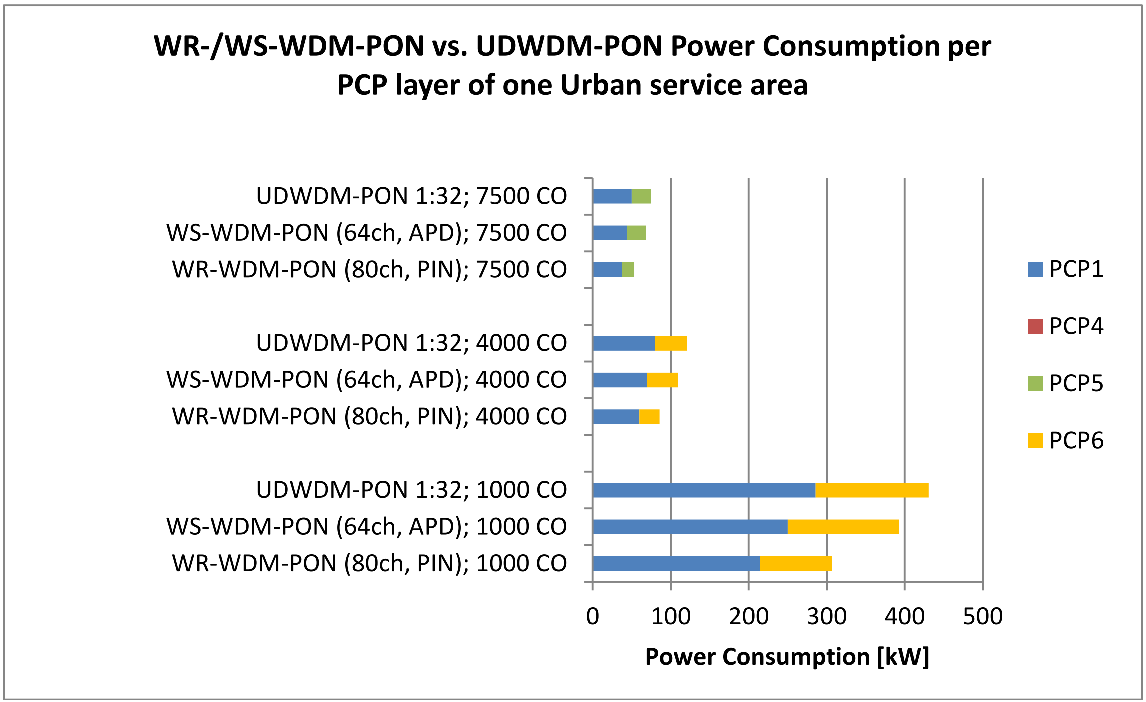


Figure 4-1: WR-/WS-WDM-PON vs. UDWDM-PON Power Consumption per PCP layer for one Urban Service area

The power consumption has been calculated for a guaranteed downstream data rate of 300 Mbit/s per ONT.

In general, the power consumption per service area increases with a higher level of node consolidation due to increasing number of users per consolidated service area. However, this does not mean that the countrywide power consumption increases in case of node consolidation as Figure 4-1 shows the power consumption of three node consolidation scenarios with different numbers of users per service area.

The power consumption per service area is clearly dominated by the ONT part at the PCP1 (user flat) in all scenarios, e.g.:

- UDWDM-PON: 49 kW (scenario 1) to 285 kW (scenario 3) for one urban service area
- WR-WDM-PON: 37 kW (scenario 1) to 214 kW (scenario 3) for one urban service area
- WS-WDM-PON: 43 kW (scenario 1) to 250 kW (scenario 3) for one urban service area

There is no power consumption at PCP4 in all three WDM-PON architectures. In scenario 1 the WDM-PON OLT equipment is located at PCP5 (local exchange) with a power consumption of 15.9 kW for WR-WDM-PON, 24.8 kW for WS-WDM-PON and 25.3 kW for UDWDM-PON.

In the case of scenario 2 and 3 the OLT equipment is located at PCP6 (CAN) with a power consumption of:

- 26 kW (scenario 2) and 93 kW (scenario 3) for WR-WDM-PON,
- 40 kW (scenario 2) and 143 kW (scenario 3) for WS-WDM-PON and
- 41 kW (scenario 2) and 145 kW (scenario 3) for UDWDM-PON.

The scenarios 2 and 3 require no power at PCP5.

Figure 4-2 shows the power consumption per line and PCP for different node consolidation scenarios and service area types. The WR-DWDM-PON solution requires about 75% of the UDWDM-PON power consumption. It also shows that node consolidation brings no significant benefit regarding the per-line power consumption.

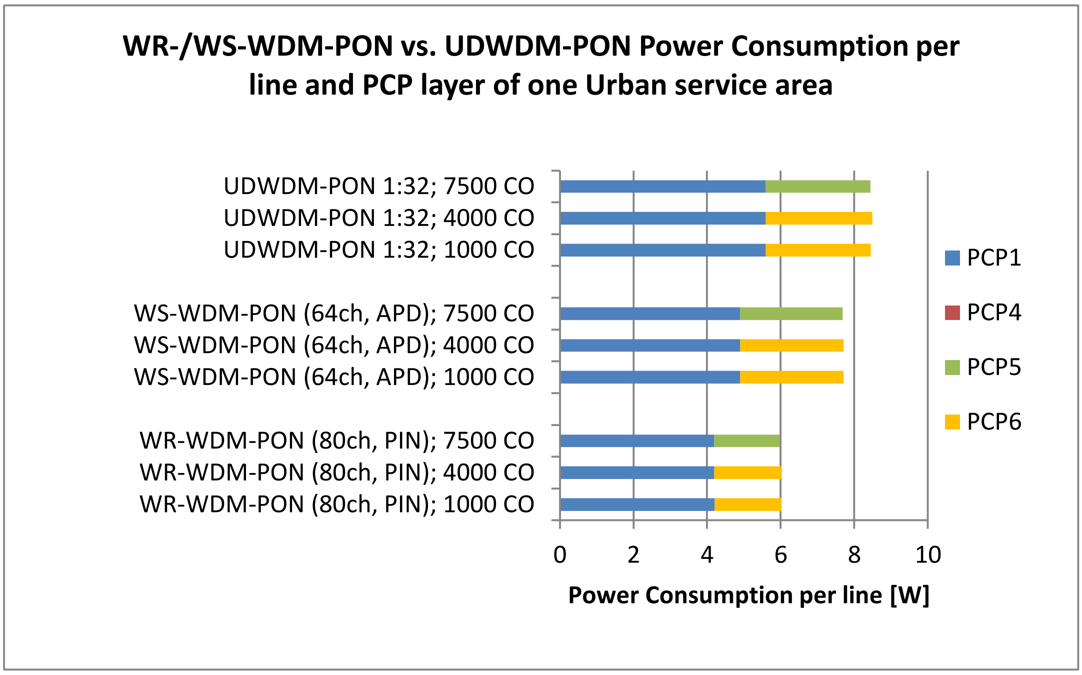


Figure 4-2: WR-/WS-WDM-PON vs. UDWDM-PON Power Consumption per line and PCP layer for one Urban Service area

WDM-PON probably presents the architecture (of the set of 4 candidate architectures) that offer the greatest possibilities for improved energy-efficiency performance compared to the-state-of-the-art optical access networks. In particular, because it represents a purely passive solution between the CAN at PCP5, and the ONT at PCP1, there is no power dissipation in between (apart from the passive attenuation of the optical fiber and components and their associated insertion losses.) There is also therefore no active equipment at the intermediate street level, which in itself would conventionally dissipate power and require air-conditioning (i.e. power usage effectiveness (PUE) tends to be always greater than unity, PUE>1, typically equal to 2.) Instead, active equipment is concentrated at the CAN and at the end-user premises. Concentration of active equipment at a single geographic location offers the best possible potential for: (a) economies of scale, (b) selective switching-on and -off of equipment according to traffic demand. Considering the first option, concentrating all electrical equipment together allows a single (unified) approach to reducing its carbon footprint. For example, a single air-conditioning plant can be deployed to provide the necessary cooling. In addition, by concentrating at a single CAN location, if the heat/power requirements are sufficiently high (i.e. >100 kW) then tri-generation solutions become possible, where the heat generated by the rack equipment can be used itself to help drive cooling equipment (e.g. absorption fridges) and also used to supply heat for external, municipal purposes. In addition, a centralized CAN location can be powered using renewable micro-generation plant, e.g. solar photovoltaic panels and/or wind turbines, which can adequately supply the modest (approx. 100 kW) power requirements of a central office. This is in addition to saving the 8% transmission line losses associated with long-distance high-voltage electricity transmission from conventional large-scale power generating stations. Clearly, the greater the node consolidation, the more applicable are the arguments with reference to option (a) presented here. With reference to the second option (b), where equipment is selectively switched on and off according to traffic demand, whilst being true for most architectures, the WDM-PON is also particularly suited, since wavelengths can be routed to a single optical switch, and/or groomed into a single higher line-rate wavelength for upstream transmission towards the core. Alternatively, wavelength conversion can be selectively employed to groom wavelengths onto a single band, or a contiguous set of wavelengths, which can be more easily dealt with. It should be emphasized that WDM-PON is likely to be experience a lower spectral efficiency (since each user has a dedicated wavelength channel) as compared with the other architectures being studied here, but that does not imply intrinsically inferior energy efficiency.

With regard to the power consumption at the ONT, it is clear that the CPE equipment associated with the WDM-PON architecture is the simplest, featuring a passive wavelength–filter for downstream traffic (e.g. if a passive splitter is employed at the RN), and a (tunable) laser for the upstream traffic (or a reflective electro-absorption modulator (REAM) device, for reflective-mode WDM-PON architectures.) Simple equipment tends to require less associated equipment (e.g. complex digital signal processing (DSP) and control/monitoring functionality) as well as associated cooling systems, so that the overall CPE/ONT power requirement is also likely to be lower. In which case, it is to be expected that CPE equipment for WDM-PON is also likely to be one of the more energy-efficient NGOA options.

4.1.2 Resilience

ITU-T recommendation G.984.1 lists protection and dual-parenting options for both the entire PON segment and the feeder fiber section for power-split ODN. Wavelength-selective WDM-PONs can support all of these resilience concepts and have similar reliability performance as wavelength-routed (-filtered) WDM-PON. Therefore, they are not further elaborated in this document. For wavelength-routed (-filtered) WDM-PON and UDWDM-PON which needs to run via a hybrid ODN (filters plus power splitters), three resilience options down to remote node have been described hereinafter and their reliability performance on connection availability has also been assessed accordingly. In addition, end-to-end resilience (which is also covered in G.984.1) can be applied to any (WDM-) PON, irrespective of the ODN type (filtered, power-split, hybrid). Such end-to-end resilience can be implemented by means of fiber switches or duplicated PON transceiver interfaces in conjunction with electronic switch-over. Fiber switches (in particular at the OLT) may lead to cheaper implementation, whereas duplicated interfaces will lead to better path availability.

FILTERED (AWG) ODN

AWG-based remote nodes support protection by the addition of a second AWG feeder port. This port has the same insertion loss as the first feeder port, without increasing total insertion loss (the latter follows from symmetry considerations). 2:N AWGs can be used for feeder protection or dual parenting.

The configuration for feeder fiber resilience in a filtered ODN is shown in Figure 4-3. Two PON line terminations (LTs) are connected to two feeder fibers in the OLT. Dual parenting can be similarly configured. In the RN, the two feeder fibers connect to the two AWG ports that carry the optical multiplex sections. Preferably, these two ports are adjacent ports in a generic M:N AWG. This is also an important aspect of WDM-PON standardization.

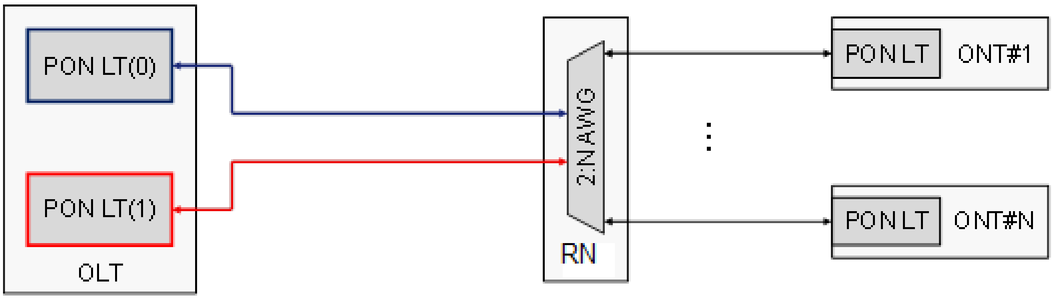


Figure 4-3: 2:*N* AWG-based protection of feeder fiber in filtered ODN.

When switching from one feeder fiber port of the 2:*N* AWG to the second (and given that these are adjacent ports of an *M*:*N* device), while keeping the OLT wavelengths the same, a wavelength shift by one channel occurs at all AWG fan-out ports in the downstream direction. By default, then, the downstream signals would be routed to the wrong ONTs. In the upstream direction, the second feeder fiber port would remain dark if the ONTs retained their original working wavelengths. The second feeder fiber can be lighted correctly and the downstream wavelength shift can be compensated by re-tuning both OLT and ONTs by one channel. In the seeded wavelength-routed WDM-PON, seed light, which includes broadband light sources or multi-frequency "comb" sources, is switched onto the respective feeder fiber in the OLT, and ONT re-tuning happens automatically.

The re-tuning requirement by one channel implies that a 41st channel be supported in a 40-port AWG, or that an 81st channel be supported in an 80-port device and likewise for other port counts. This is inherent in the AWG grids discussed herein.

HYBRID (FILTERED PLUS POWER-SPLIT) ODN

For UDWDM-PON, a hybrid (i.e. filtered plus power-split) ODN is required (see OASE deliverable D4.2.1). Protection / dual-parenting based on 2:*N* AWGs also applies to hybrid ODNs. A protection example is shown in Figure 4-4. In this configuration, the ODN part between the two RN stages is unprotected.

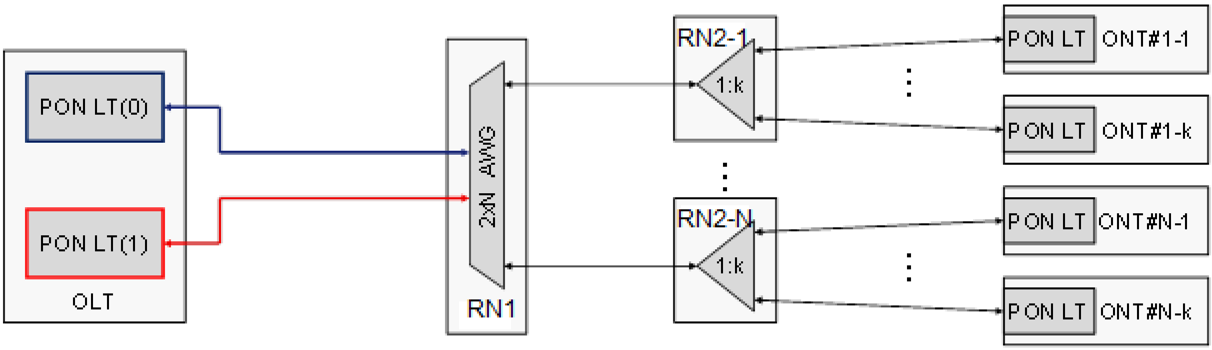


Figure 4-4: 2:*N* AWG protection of feeder fiber in hybrid ODN

The resiliency scheme shown in Figure 4-4 leads to the same wavelength-shift / re-tuning considerations as discussed in the filtered-ODN resilience section. It can be accounted for by tunable lasers and seeded reflective transmitters.

RING ODN (FILTERED OR HYBRID)

Resilience for WDM-PON can optionally be configured in rings that connect several RNs to a single OLT, or in open rings that dually parent several RNs to two OLTs. An example of ring protection is shown in Figure 4-5. It is based on adding/dropping single or groups of wavelengths in the respective RNs by means of group add/drop filters (G*n*). RNs are resiliently connected to the OLT(s), protecting the feeder fibers. Several RNs can be passively traversed. For rings with a large number of RNs, a subset of the RNs may have to be active nodes with lumped amplifiers, e.g., EDFAs. If the added/dropped wavelengths are directly assigned to dedicated ONTs, it is designated a filtered ring ODN. If the ring-RNs or subsequent RNs also accommodate power splitters/combiners, the recommended terminology is hybrid ring ODN. Legacy GPON/XG-PON can co-exist either through passive transparent transmission or wavelength conversion to the DWDM grid at the active branching nodes.

In the OLT, “all-groups” add/drop filters must de-/multiplex all wavelength groups used in the ring. Switchover is performed in the OLT by means of a switch matrix (one switch per group). It is triggered by upstream loss of signal (LoS).

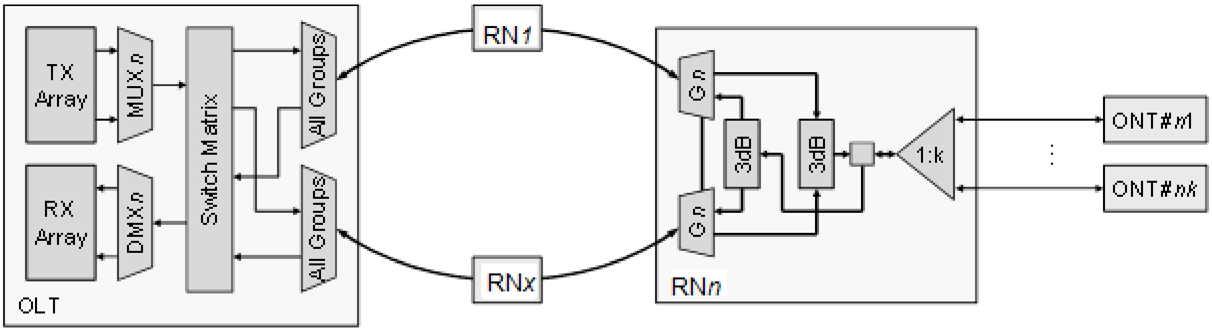


Figure 4-5: Ring protection (in hybrid ODN)

The ring protection shown in Figure 4-5 is suited for resiliently connecting several power splitters. Per power splitter, groups of densely-spaced wavelengths can be used in wavelength-selected “sub-PONs.” This facilitates the addition of resilience to existing infrastructure.

The ring protection can be extended to chains of branching nodes that are connected to two OLTs (dual parenting) in an “open ring” structure. Between the OLTs, signaling or centralized management must be established.

Comparing the three considered protection schemes for WDM-PON, it can be seen that the first two do not introduce extra power-loss and affect the wavelength utilization while the third one obviously needs higher power budget for the connection between the OLT and ONT if several RNs are cascaded. Moreover, each sub-PON should avoid using the same wavelength at the same time.

Figure 4-6 and Figure 4-7 show the connection availability and FOM values of the wavelength routed WDM-PON and the one with the first considered protection scheme (i.e. filtered ODN) for different node consolidation scenarios and populated areas. It can be clearly seen that with protection of feeder fiber and OLT, the resiliency performance is significantly increased.

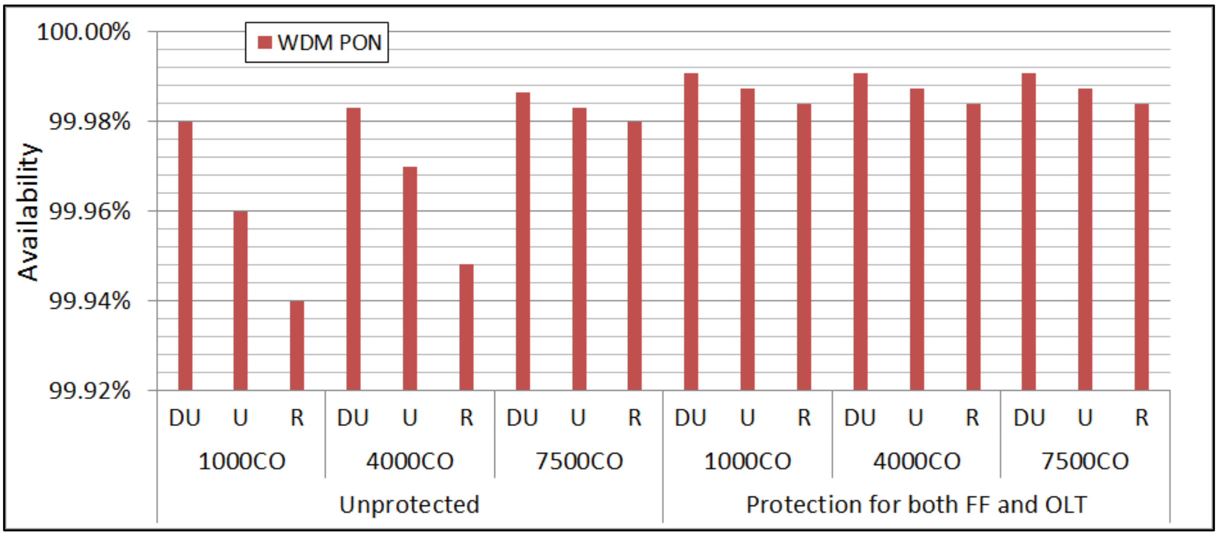


Figure 4-6: Connection availability of basic WDM-PON and the one with protection for both FF and OLT

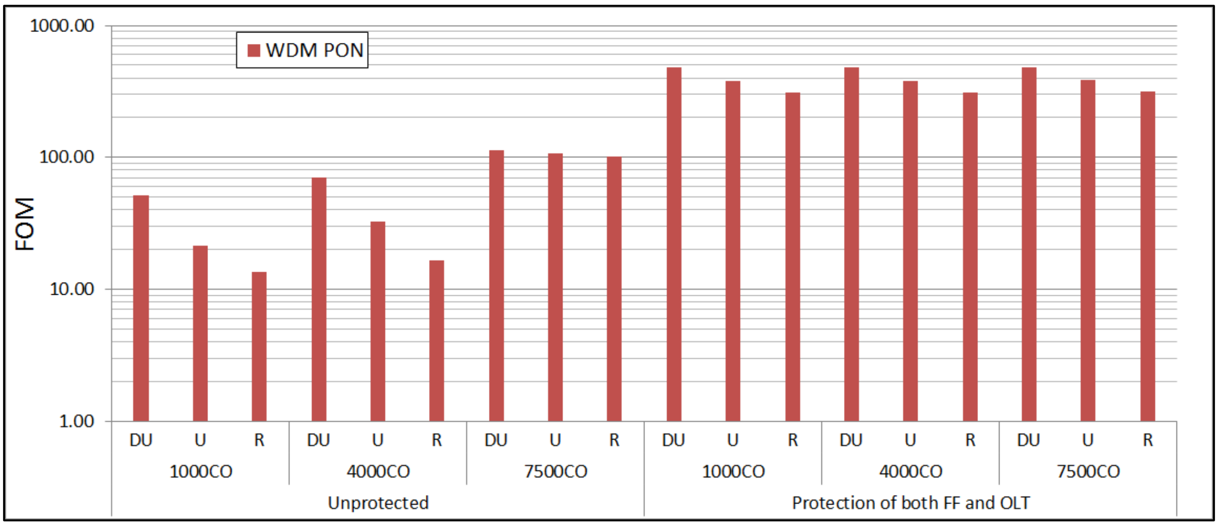


Figure 4-7: FOM of basic WDM-PON and the one with protection for both FF and OLT

Furthermore, UDWDM-PON which needs to run via a hybrid ODN (filters plus power splitters) are slightly less reliable than the wavelength-routed WDM-PON due to the introduction of the extra power splitters in the field. Besides, the resiliency performance of ring protection depends on the number of cascaded RNs. In the best case where only one RN is considered the ring protection is similar as the first two schemes. However, because there is no duplicated line terminal at the central office, both the connection availability and FOM in ring protection is worse than the ones with backup of both the feeder fiber and OLT.

4.1.3 Operational complexity

We evaluated the operational impact in terms of energy consumption and footprint in combination with the three node consolidation scenarios defined in Section 1.1.

OPERATOR RELATED ENERGY CONSUMPTION ASSESSMENT IN NODE CONSOLIDATION

Figure 4-8 shows the network operator related power consumption without the ONT part for WR-/WS-WDM-PON versus UDWDM-PON in one urban service area. It represents the operational expenditure (OpEx) cost related power consumption part of the WDM-PON architectures. Figure 4-8 shows that the WR-WDM-PON requires about two thirds of the UDWDM-PON power consumption independent of the node consolidation.

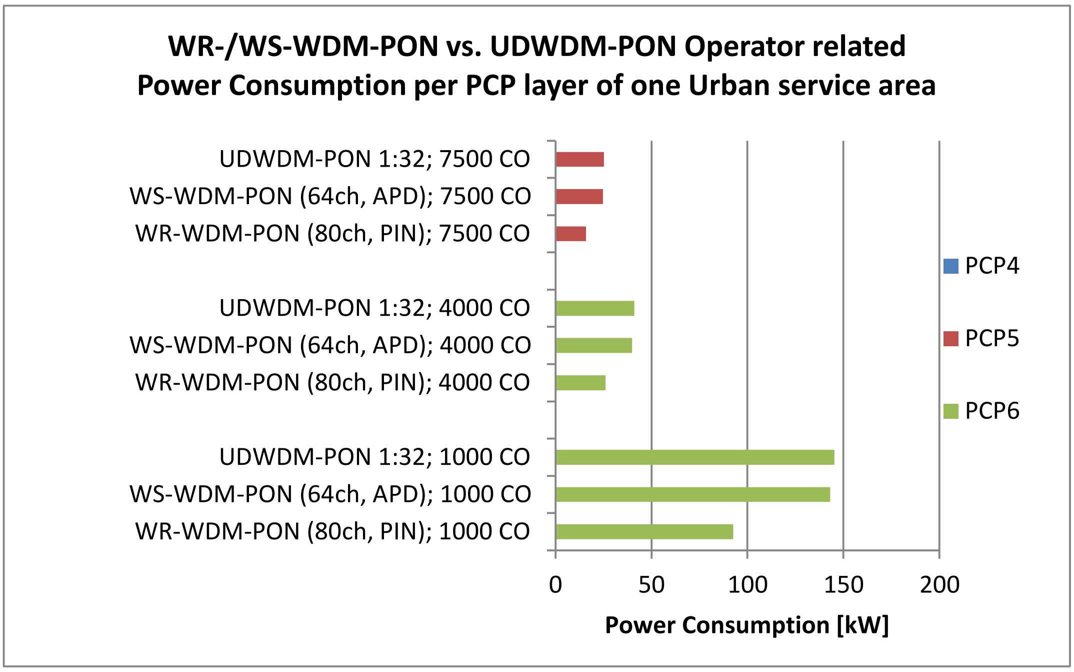


Figure 4-8: Network operator related power consumption for WR-/WS-WDM-PON vs. UDWDM-PON

In addition, Figure 4-8 shows that the power consumption per service area increases with a higher level of node consolidation due to increasing number of users per consolidated service area. However, this does not mean that the total power consumption per architecture increases in case of node consolidation.

Figure 4-9 shows the network operator related power consumption per line and PCP for different node consolidation scenarios and service area types. The WR-DWDM-PON solution requires less than 70% of the UDWDM-PON power consumption. It also shows that node consolidation brings no significant benefit regarding the network operator related power consumption.

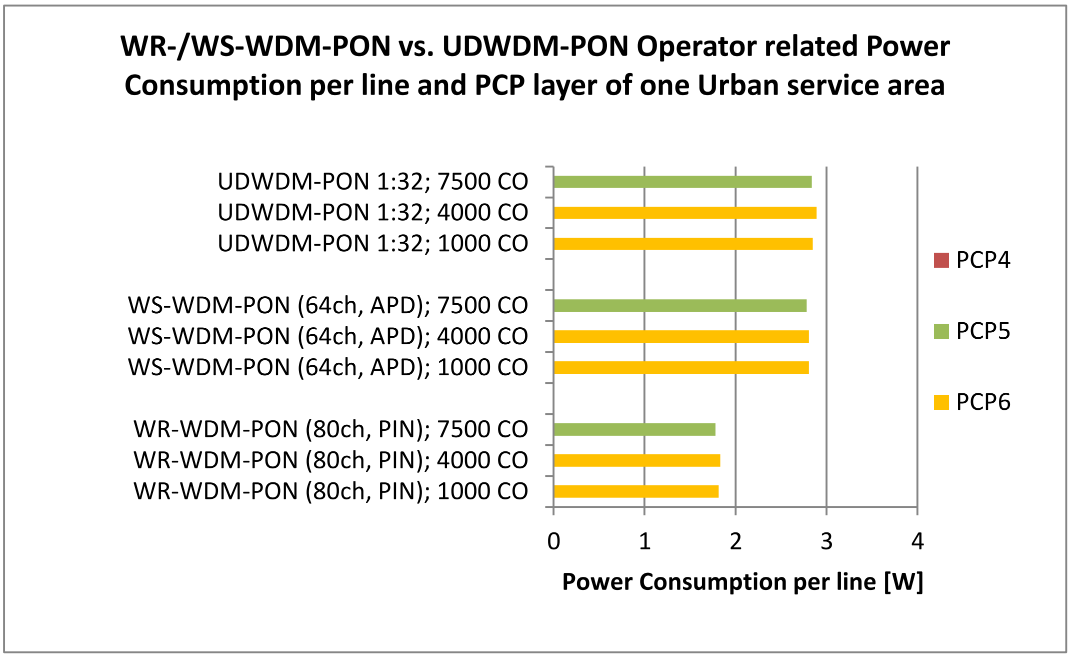


Figure 4-9: Network operator related power consumption per line for WR-/WS-WDM-PON vs. UDWDM-PON

FOOTPRINT ASSESSMENT IN NODE CONSOLIDATION

Figure 4-10 shows the footprint per PCP layer of WR-/WS-WDM-PON versus UDWDM-PON for the three node consolidation scenarios as described in Section 1.1. The footprint is shown for one dense urban (DU), one urban (U) and one rural (R) service area. This footprint calculation is based on the footprint model described in OASE deliverable D4.3.1. The model includes the footprint of the passive and active system technology and the optical distribution frame (ODF) at PCP4, PCP5 and PCP6. For the WDM-PON architectures there is no footprint for ODF, power splitter and AWG components at PCP4 because it was assumed that such equipment can be housed by closures in the field.

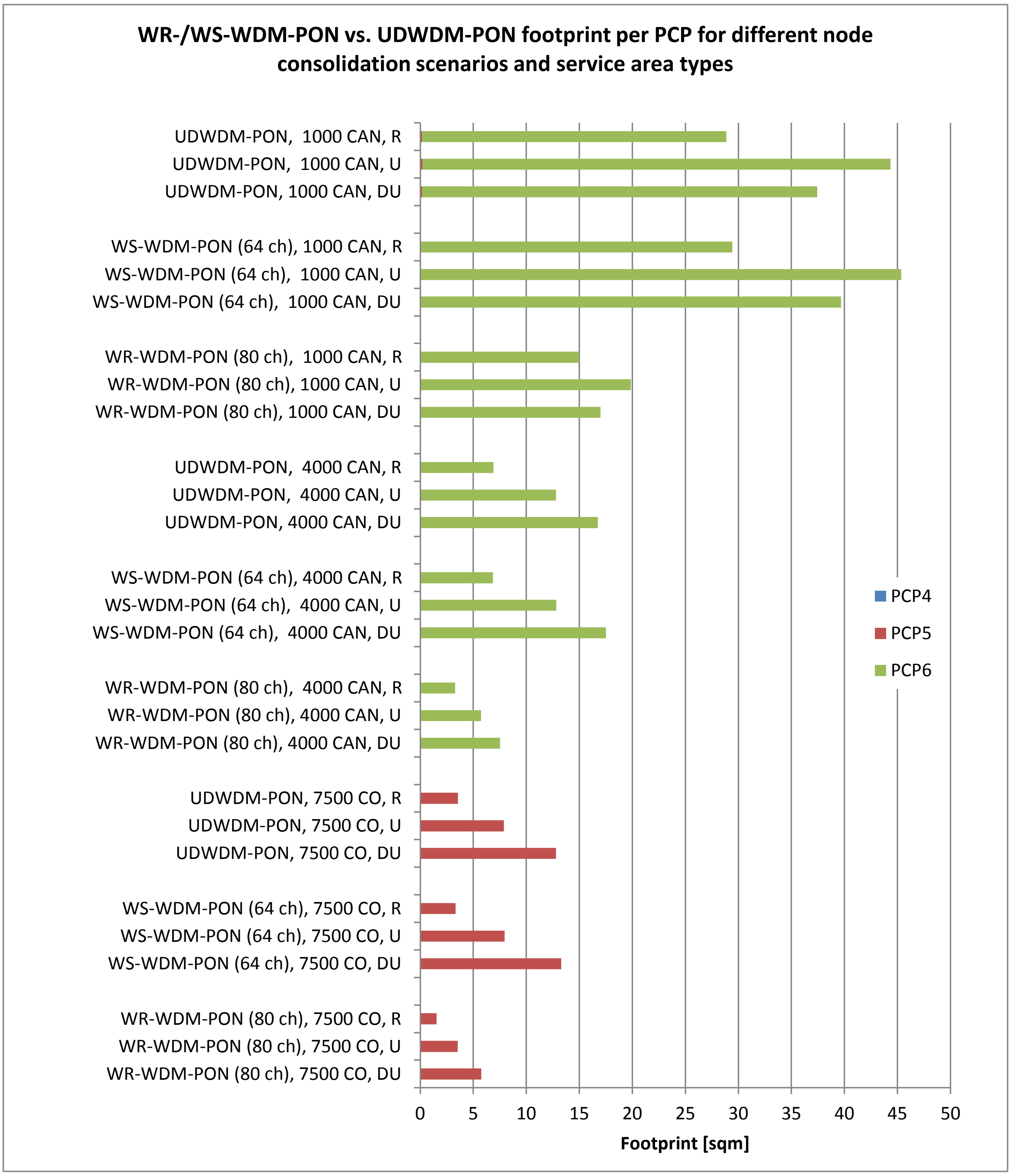


Figure 4-10: WR-/WS-WDM-PON vs. UDWDM-PON footprint per PCP layer in dense urban

In general, the footprint per service area increases with a higher level of node consolidation due to increasing number of users per consolidated service area. However, this does not mean that the countrywide footprint increases in case of node consolidation as Figure 4-10 shows the footprint of three node consolidation scenarios with different numbers of users per service area.

The WR- and WS-WDM-PON require no footprint at PCP5 in the scenarios 2 and 3 whereas in the case of UDWDM-PON the AWGs are located at PCP5. However, the AWG equipment requires a negligible footprint. This means that the AWG equipment could be housed by closures next to PCP5 in order to shut down the legacy local exchange (LEx) location. Figure

4-10 shows that the WR-WDM-PON requires about half of the UDWDM-PON footprint in all cases. In scenario 1 the WR-WDM-PON architecture requires a footprint of 3.5 m^2 at PCP5 compared to 7.9 m^2 in the case of UDWDM-PON for one urban service area. The node consolidation scenarios require a footprint of 5.7 m^2 (scenario 2) and 19.9 m^2 (scenario 3) at PCP6 for WR-WDM-PON and 12.7 m^2 (scenario 2) and 44.1 m^2 (scenario 3) for UDWDM-PON in one urban service area.

Figure 4-11 shows the footprint per line and PCP for different node consolidation scenarios and service area types. The WR-WDM-PON solution requires about half of the footprint of UDWDM-PON and WS-WDM-PON. The WS-WDM-PON and UDWDM-PON architectures have nearly the same footprint demand. It also shows that node consolidation brings no significant benefit regarding the footprint.

Figure 4-11: WR-/WS-WDM-PON vs. UDWDM-PON footprint per line and PCP layer in dense urban

FAILURE RATE IN NODE CONSOLIDATION

The WDM-PON failure rate analysis is based on the MTBF values shown in Table 4-2.

Table 4-2: MTBF values for WR-/WS-WDM and UDWDM

Components	MTBF (hour)	MTBF (year)
WR WDM-PON solution		
ONT (PIN)	257.143	29
ONT (APD)	236.842	27
Shelf / Backplane	1.500.000	171

Baseline card (Switch/Router, CPU, Control and Management Plane) (~500G)	420.000	48
Power Supply (redundant)	500.000	57
OLT Downlink line card DWDM-PON port card 80 channels (incl diplexer) (not incl pluggable)	750.000	86
OLT Downlink line card DWDM-PON port card 160 channels (incl 3 diplexers) (not incl pluggable)	363.636	42
OLT Downlink line card DWDM-PON port card 80 channels (incl diplexer, 1 EDFA preamp) (not incl pluggable)	428.571	49
OLT Downlink line card DWDM-PON port card 160 channels (incl 3 diplexers, 1 EDFA preamp, 1 TDFA preamp) (not incl pluggable)	210.526	24
OLT Downlink line card DWDM-PON port card 320 channels (incl 3 diplexers, 7 interleavers, 1 EDFA preamp, 1 TDFA preamp) (not incl pluggable)	118.310	14
OLT Pluggable 80x 1G Laser/Rx Array (C-band) - for 80 ch	300.000	34
RN AWG 80 channels + Diplexer+Interleaver	4.000.000	457
WS WDM-PON solution		
ONT (APD)	227.848	26
Shelf / Backplane	1.500.000	171
Baseline card (Switch/Router, CPU, Control and Management Plane) (~500G)	420.000	48
Power Supply (redundant)	500.000	57
OLT Basic Downlink line card DWDM-PON port card 64 channels (for use in 64 config) (incl 64x1G Laser/Rx Array C-band, 1 diplexer) incl EDFA preamp	176.471	20
Reach Extender device without optics	300.000	34
Reach Extender optics Pluggable	400.000	46
Optical power splitter (1:64)	6.000.000	685
UDWDM-PON solution		
ONT	204.545	23
Shelf / Backplane	1.500.000	171
Baseline card (Switch/Router, CPU, Control and Management Plane) (~500G)	430.000	49
Power Supply (redundant)	500.000	57
OLT Front end (TFF+Circulator+EDFA Booster) 340 ch	750.000	86
OLT Front end (TFF+Circulator+EDFA Booster) 640 ch	750.000	86
OLT Basic Downlink line card DWDM-PON port card 32 channels (for use in 640) - incl TRX, ASIC, but not TFF or circulators	173.911	20
RN TFF (20 x 4 ITU channels) for 1:32 splitt	2.000.000	228
RN Power splitter 1:32	6.000.000	685
Link Level		
Feeder Fiber 192 fibers	1.350.000	154
Feeder Fiber 1000 fibers	1.000.000	114
Main Cable	1.400.000	160
Distribution Cable	1.500.000	171

Inhouse Cable	525.000	60

Figure 4-12 shows the annual failure rate per PCP and link layer (LL) for WR-/WS-WDM-PON versus UDWDM-PON. The failure rates are shown for the node consolidation scenarios 1, 2 and 3 in one dense urban, one urban and one rural service area. The results show that the annual failure rate is clearly dominated by failures at PCP1 (ONT failures at user site) in all WDM-PON variants. The UDWDM-PON failure rate is about 28% higher compared to the WR-WDM-PON, which is mainly caused by the ONT equipment.

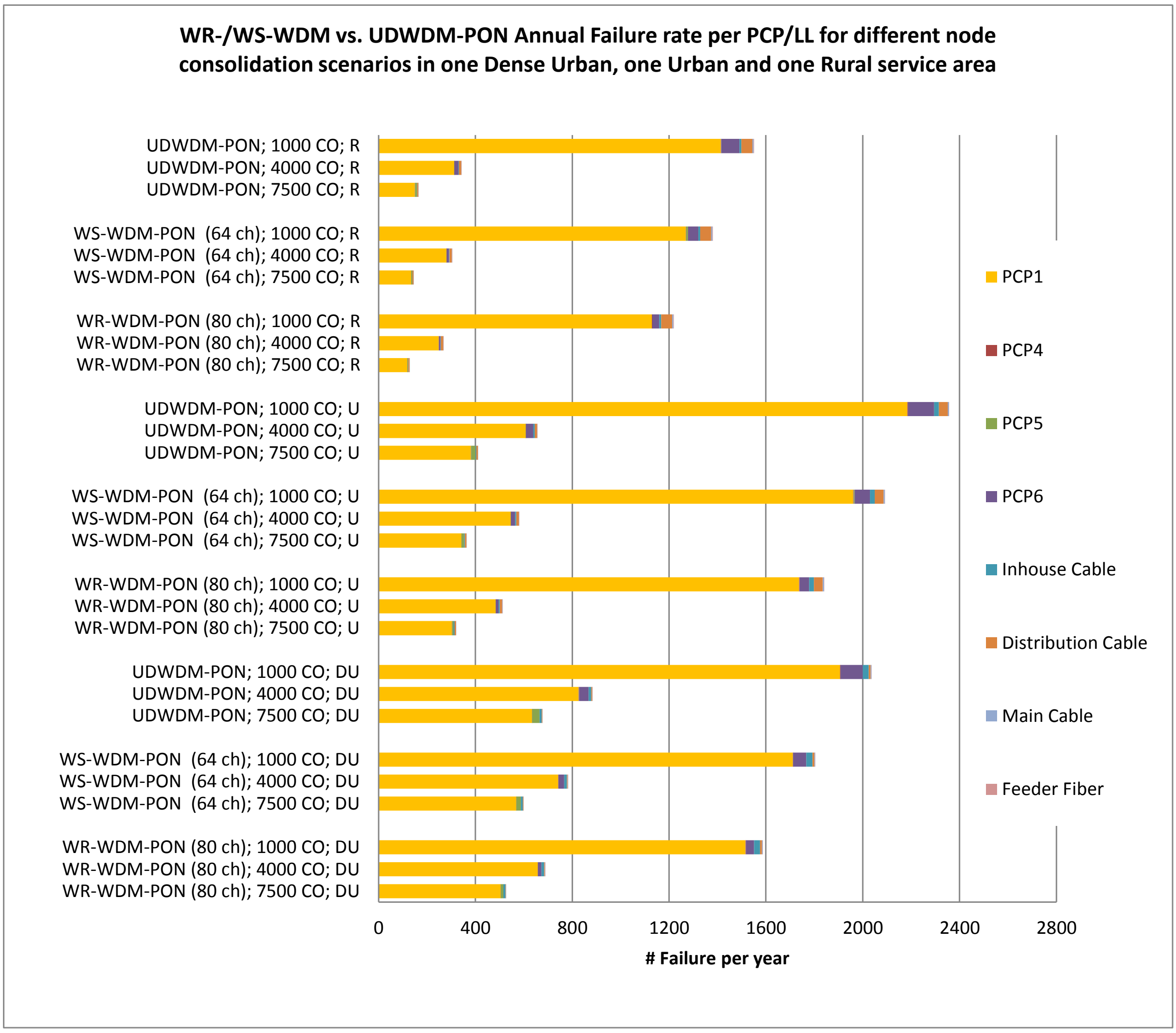


Figure 4-12: WR-/WS-WDM-PON vs. UDWDM-PON annual failure rate per PCP/LL

Figure 4-13 shows the annual failure rate per PCP/LL for WR-/WS-WDM-PON versus UDWDM-PON without the PCP1 part. It shows that the UDWDM-PON failure rate at the OLT location (PCP5 for scenario 1; PCP6 for scenario 2 & 3) is about 3 times higher compared to WR-WDM-PON. All WDM-PON variants have the same failure rate for the in-house cable and distribution cable due to similar fiber installations in these network sections. The failure rate of the PCP4, main cable and feeder fiber section is negligible for both WDM-PON architectures.

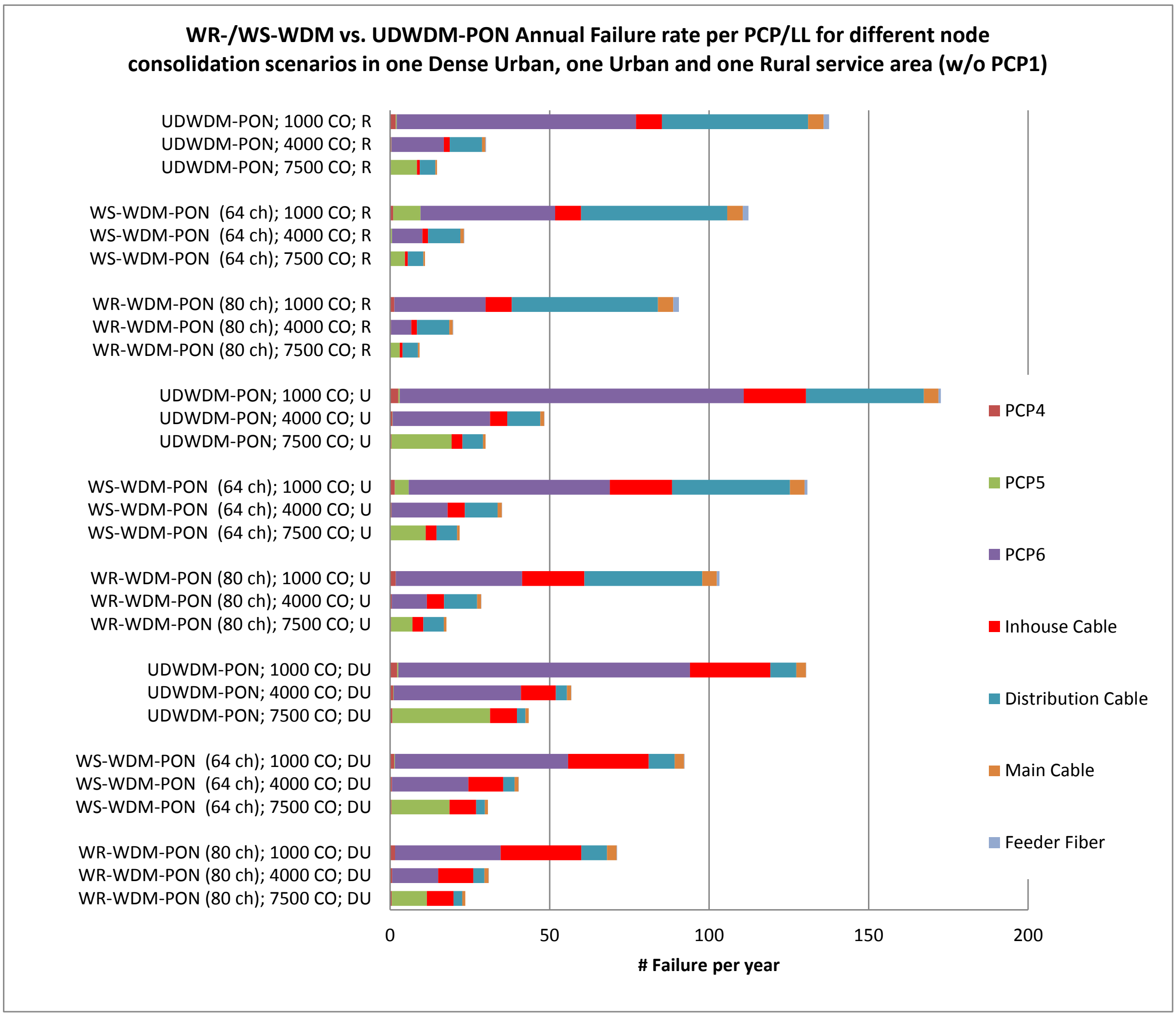


Figure 4-13: WR-/WS-WDM-PON vs. UDWDM-PON annual failure rate per PCP/LL (w/o PCP1)

Figure 4-14 shows the annual failure rate per line for WR-/WS-WDM-PON versus UDWDM-PON. The annual failure rate per line is more or less constant for all node consolidation scenarios. There is only a small increase of the WR-WDM-PON failure rate in rural service areas that is mainly caused by the increasing number of APD ONTs which have a lower MTBF value (Table 4-2). In addition, the WS-WDM-PON failure rate slightly increases in urban and rural service areas due to the increasing number of reach extenders at PCP5. In general, the impact of node consolidation on the failure rate is negligible for both WDM-PON architectures.

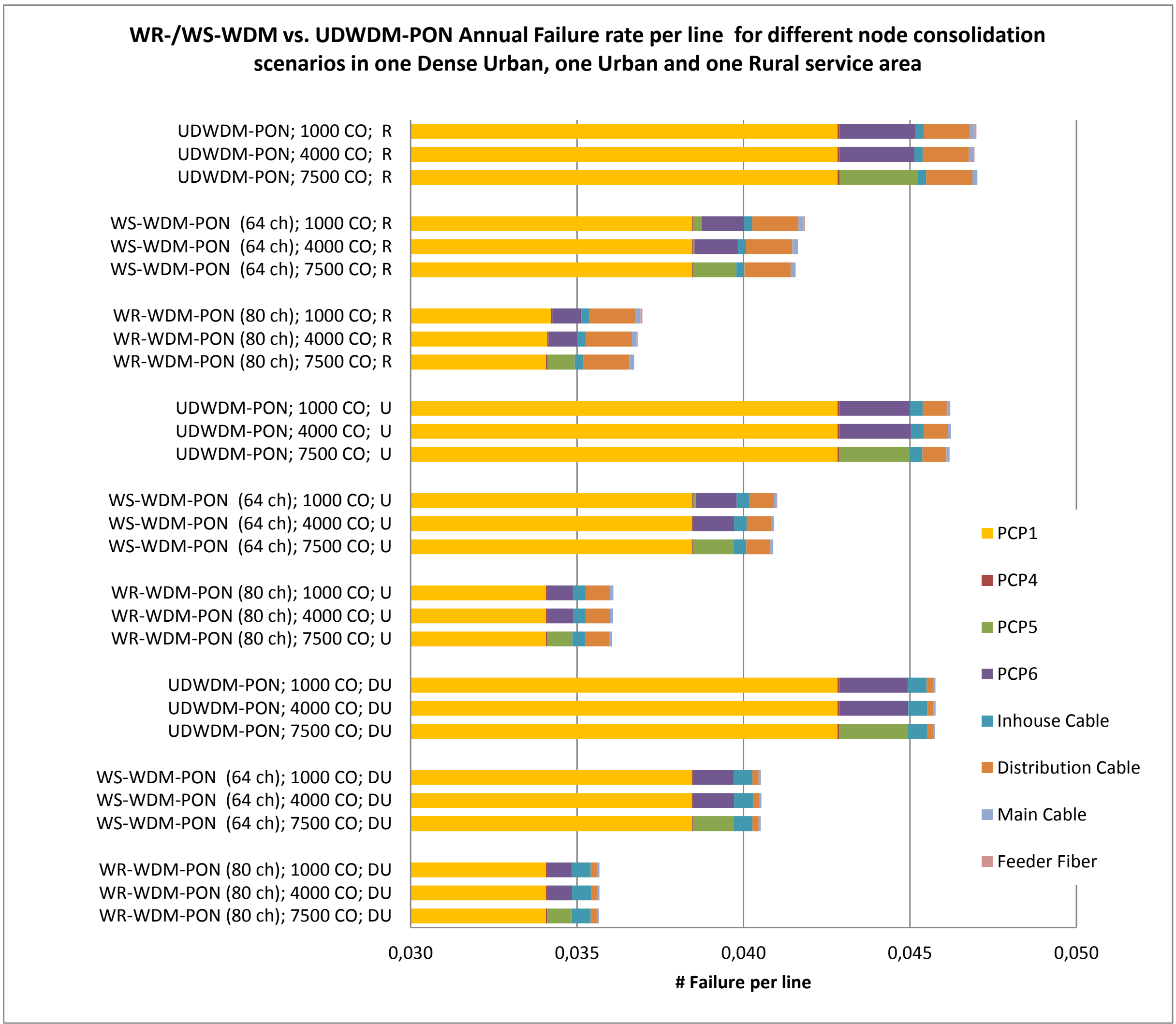


Figure 4-14: WR-/WS-WDM-PON vs. UDWDM-PON annual failure rate per line and PCP/LL

IMPACT OF NODE CONSOLIDATION ON TRAVEL EFFORT

The travel effort analysis is based on the annual failure rate and the travel distance model described in section 3.3.4. It is assumed that travel effort is not needed for ONT failures at PCP1. In the case of an ONT failure the user gets a new ONT device which will be installed by the user (plug-and-play).

Figure 4-15 shows the annual travel time per line for WR-/WS-WDM-PON versus UDWDM-PON. The annual travel times are shown for the node consolidation scenarios 1, 2 and 3 in dense urban, urban and rural service areas. The annual travel times are proportional to the annual failure rates. The most travel effort is caused by OLT failures at PCP6 (scenario 2 & 3) or PCP5 (scenario 1) and distribution cable failures followed by inhouse cable failures.

The results show that the impact of node consolidation on the travel effort is small for all WDM-PON variants due to the relatively low number of failures per day and PCP/LL. As shown in Figure 4-13 there is not more than one failure per day and PCP/LL assuming an uniform distribution of failure events over the time. This means that there is only a little chance to gain by fixing multiple failures with one travel activity. In general, there is no impact of node consolidation on the travel effort per line for in-house cable, distribution cable and main cable because these network sections have the same structure and failure ratio per service area cluster in all node consolidation scenarios.

The average travel time per line decreases for dense urban and urban service areas with higher level of node consolidation due to the increasing share of maintenance offices which are co-located with central offices (PCP5) and CANs (PCP6). In addition, the travel time per line is a little bit higher in scenario 1 compared to scenario 2 and 3 due to the longer distance between maintenance offices and OLT location (PCP5).

Figure 4-15 shows that the UDWDM-PON annual travel time per line is more than 50% higher compared to WR-WDM-PON.

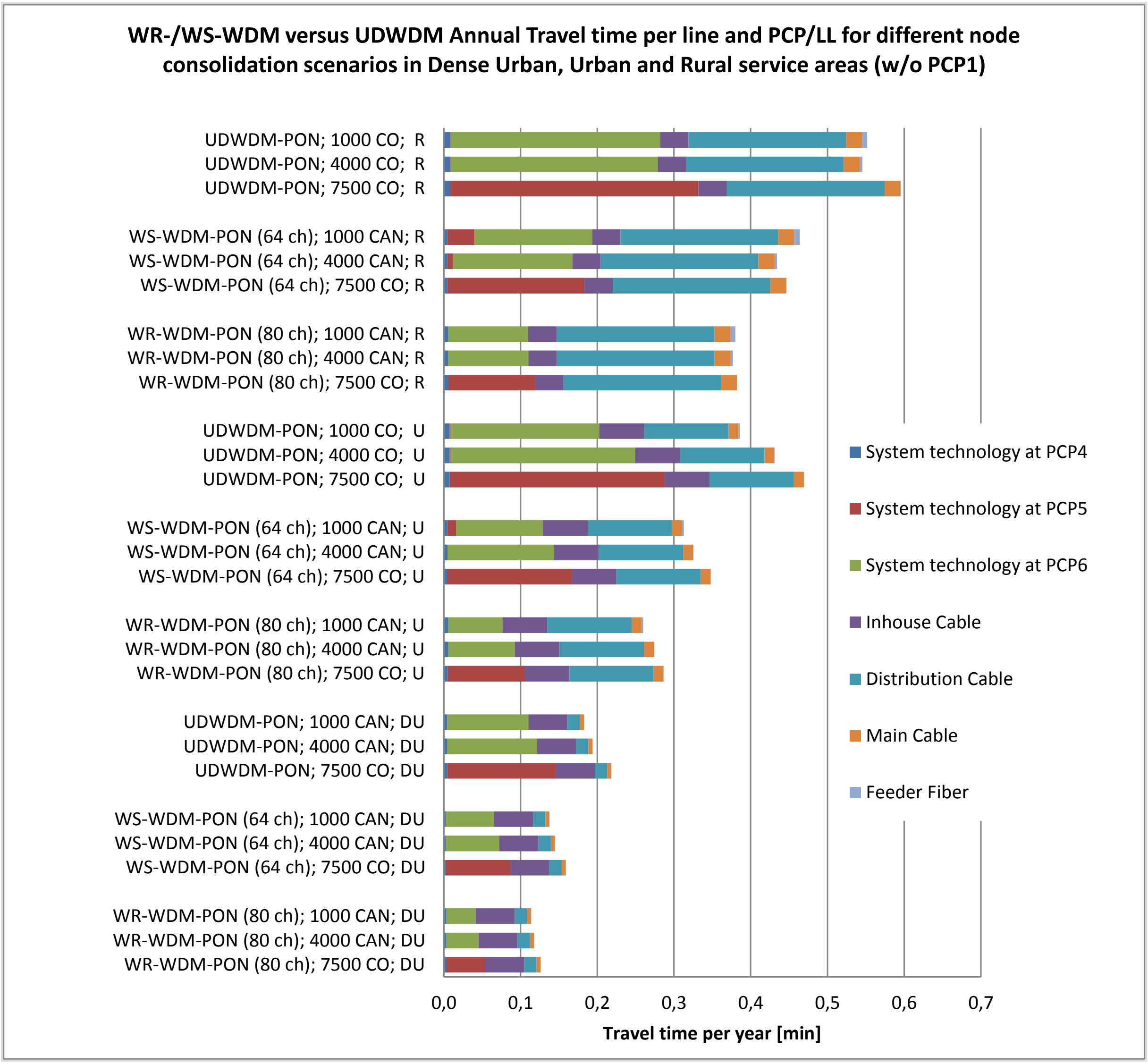


Figure 4-15: WR-/WS-WDM-PON vs. UDWDM-PON annual travel time per line (without PCP1)

4.1.4 Control and management

Two different aspect for control and management (C&M) need to be considered when evaluating WDM-PONs C&M potential and functionality, the interface between the ONT and OLT, and the interface between the OLT and the rest of the access/aggregation network.

The necessary C&M functions needed between the ONT and OLT depends heavily on what ONT technique is selected, since they differ in their configuration needs. For example an ONT using the seeded reflective variant of WDM-PON requires a limited amount of bootstrapping configuration since the selection of wavelength is done by the OLT and no active selection is taken by the ONT. An ONT using tunable laser on the other hand requires the ONT to actively select what wavelength to use, which could be accomplished in many ways. The ONT could for example be pre-configured before shipment to the customer or the wavelength to use could be found by actively scanning of the spectrum. A more advanced option, which could give additional benefits, is to use a dedicated control channel. Overall the configuration between the OLT and the ONT should be easy to solve but standard is needed to provide compatibility between vendors of ONTs and OLTs. On the L2 layer the connection to the OLT is a point-to-point link and the need for active management of the ONT should be limited, and high level management need could be accomplished via TR-069.

The configuration and management of OLT could be solved in a similar matter to existing L2 Ethernet switches, after some initial configuration of the OLT. Since the connection to the ONTs are in effect L2 point-to-point links, and could be managed and configured as such. This means that an OLT could act like a normal Ethernet based switch. But selecting which wavelength should be active and the mapping between the wavelengths and the L2 virtual port need to be performed, which is not covered by existing standards and needs to be addressed.

4.2 Hybrid WDM/TDM-PON

In this section, we consider two main variants of the hybrid WDM/TDM-PON architectures described in Section 2.2.3, i.e. passive and semi-passive.

A preliminary assessment of the hybrid WDM/TDM-PON has been presented in OASE milestone M3.1, where also some weak points have been identified. Here, we extend the results related to Hybrid WDM/TDM-PON that are included in OASE milestone M3.1 by mapping Hybrid PON into different considered scenarios and evaluate the associated performance in terms of power consumption, resilience, operational aspects, control and management, and resource allocation.

4.2.1 Power consumption

Power consumption on a per-user basis of the hybrid WDM/TDM-PON depends on the specific configuration, in particular on the required sustainable data rate per user. The detailed calculations have been performed in WP4 and presented in OASE deliverable D4.2.1. With the sustainable data rates of 625 Mb/s for downstream and 312 Mb/s for upstream, the power consumptions of 6.9 W and 7.3 W have been obtained for passive and semi-passive approaches, respectively. These numbers (not yet including any energy-efficiency techniques) are higher than most of the other OASE NGOA architectures. The main reason is the high power consumption at the ONT which needs a 10 Gb/s receiver and 5 Gb/s burst-mode transmitter. However, it should be mentioned that hybrid WDM/TDM-PONs have a potential to reduce the power consumption by applying energy-saving mechanisms.

Table 4-3 shows energy consumption figures for the considered variants of Hybrid WDM/TDM-PON architecture presented in Section 2.2.2. Cooling system and aggregation are not included.

Table 4-3: Energy consumption in Hybrid WDM/TDM-PON

Different Variants	Sustainable data rate (first mile & feeder)	Client count (feeder)	*Total power consumption per client*	Power cons. at ONT	Power cons. per client at remote nodes	Power cons. per client at OLT
Hybrid	1.25 Gb/s	320 (M=40, N=8)	***8.4 W***	5.5 W	0 W	2.9 W

WDM/TDM-PON (*Fully passive: AWG in the field)*	625 Mb/s	640 (M=40, N=16)	***6.9 W***			1.4 W
	312 Mb/s	1280 (M=40, N=32)	***6.2 W***			0.7 W
	625 Mb/s	1280 (M=80, N=16)	***6.9 W***			1.4 W
Hybrid WDM/TDM-PON (*Fully passive: only splitters in the field)*	1.25 Gb/s	320 (M=40, N=8)	***9.6 W***	6.7 W		2.9 W
	625 Mb/s	640 (M=40, N=16)	***8.1 W***			1.4 W
	312 Mb/s	1280 (M=40, N=32)	***7.4 W***			0.7 W
	625 Mb/s	1280 (M=80, N=16)	***8.1 W***			1.4 W
Wavelength-switched Hybrid WDM/TDM-PON (*semi passive: configurable optical switch in the field)*	1.25 Gb/s	640 (M=2, N=40, N'=8)	***6.9 W***	5.5W	0.016W	1.4W
	1.25 Gb/s	640 (M=4, N=20, N'=8)	***6.9 W***		0.017W	1.4W

In order to identify the impact of node consolidation on the overall power consumption in the access network Figure 4-16 shows the Hybrid WDM/TDM-PON power consumption per PCP layer of one dense urban and one urban service area for the three node consolidation scenarios described in Section 1.1. The power consumption has been calculated for a guaranteed downstream data rate of at least 300 Mbit/s per ONT.

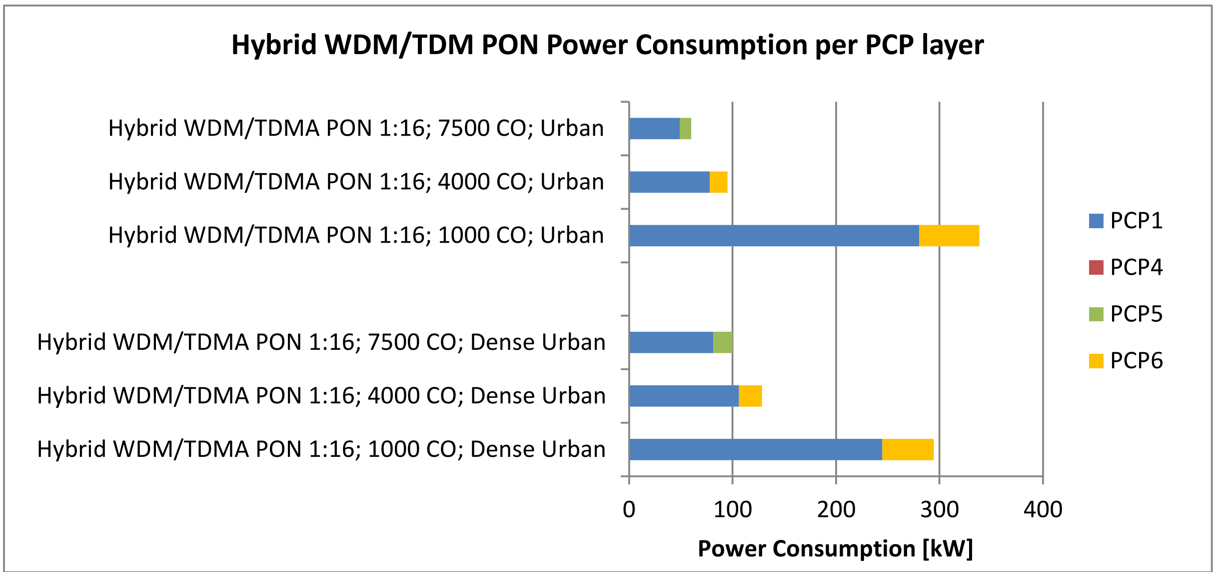


Figure 4-16: Hybrid WDM/TDM-PON power consumption per PCP layer for an urban and dense urban service area

Figure 4-16 shows that the power consumption per service area increases with a higher level of node consolidation due to increasing number of users per consolidated service area. However, this does not mean that the total power consumption per architecture increases in case of node consolidation. The power consumption per service area is clearly dominated by the ONT part at the PCP1 (user flat) in all scenarios, e.g. between 49 kW (scenario 1) to 275 kW (scenario 3) for one urban service area. There is no power consumption at PCP4 for

Hybrid WDM/TDM-PON. In the case of scenario 1 the Hybrid WDM/TDM-PON OLT equipment causes a power consumption between 11 kW (urban) and 19 kW (dense urban) at the PCP5 (LEx) location. In the case of scenario 2 and 3 the OLT equipment is located at PCP6 (CAN) with power consumption between 22 kW and 50 kW for one dense urban service area. The scenarios 2 and 3 require no power at PCP5. The power consumption of scenario 3 is 3 times (dense urban) and 5.5 times (urban) higher compared to scenario 1.

Figure 4-17 shows the power consumption per line and PCP for different node consolidation scenarios and service area types. It shows that node consolidation brings no significant benefit regarding the power consumption.

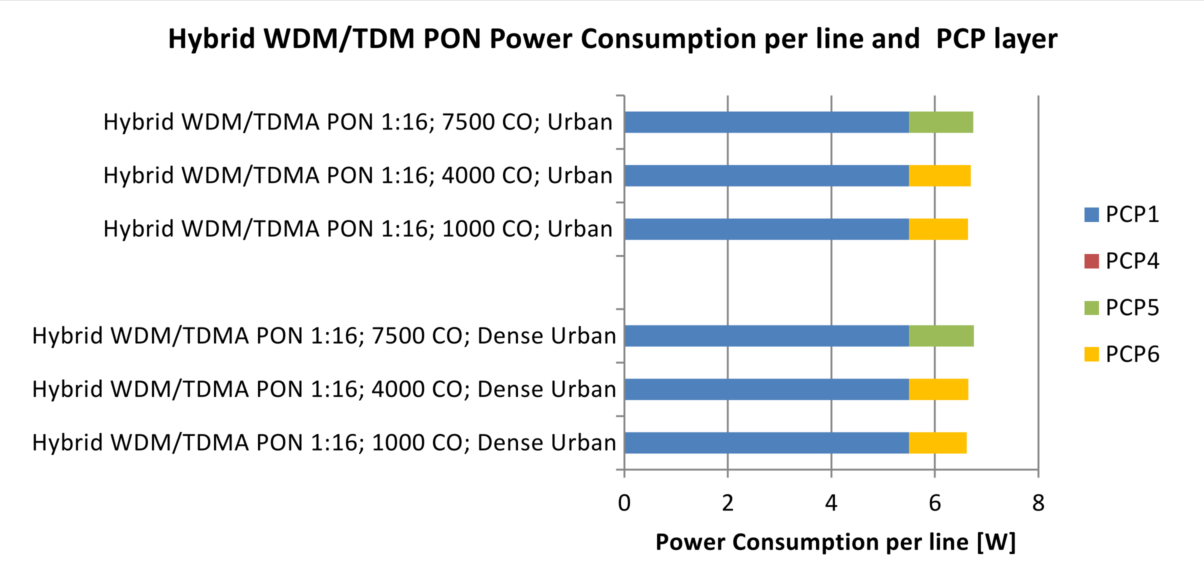


Figure 4-17: Hybrid WDM/TDM-PON power consumption per line and PCP layer for an urban and dense urban service area

With respect to energy efficiency, the hybrid WDM/TDM-PON architecture at first glance appears to exhibit the lowest efficiencies of the four architectures – however, this is based on the absolute power consumptions, and these power dissipations have been calculated without the introduction of any particular energy-saving techniques or approaches to improve the energy efficiency, as already highlighted above. In fact, the highly flexible nature of the hybrid WDM/TDM-PON means that there is greater scope for energy efficiency improvement techniques to be applied to the architecture. For example, the fact that there is a powered intermediate node (PCP5) at the LEx for the semi-passive version means that stochastic traffic management techniques can be introduced here to reduce both traffic volumes (itself a key factor in overall power consumption) as well as to apply intermediate statistical multiplexing and groom multiple end-user data streams onto a single wavelength. Such grooming tends to allow economies of scale at the higher aggregate bit-rate, with regard to the efficiency of operation of photonic equipment, so that there is a lower Joule/bit energy efficiency. The presence of active intermediate nodes also enables the introduction of content delivery (distribution) network (CDN) servers to store frequently accessed data sets, e.g. video streams of popular movies or TV programmes. Although requiring their own powering and adding to the capital expenditure (CapEx) (and OpEx) of the nodes, the CDN approach allows overall traffic volumes to be reduced throughout the network (both in the head-end of the PON, as well as in the metro and core networks), so that the overall carbon footprint of the complete network infrastructure is reduced, and hence the overall energy efficiency improved. It should be noted that the hybrid WDM/TDM-PON architecture allows a hierarchical CDN approach, with larger servers located at the CAN (PCP6) and a sub-set of smaller (identical) servers located at the LEx/CP (PCP5) active nodes. This again illustrates the additional flexibility afforded by having an active intermediate node. The WDM aspect to the hybrid architecture also allows the techniques described earlier in Section 5.1.1 to be applied here, as a means to increase the overall energy efficiency.

4.2.2 Resilience

In order to satisfy reliability requirement and reduce the risk that a large number of end users are affected by a single failure (as discussed in Section 3.2), protection at the OLT and the feeder fiber should be provided in the first place. Moreover, it should be noted that when introducing protection for hybrid WDM/TDM-PON, the performance degradation of other aspects, such as reach, supported number of end users per feeder fiber, and flexibility of resource allocation, should be avoided. With this in mind, we consider the architecture protected down to RN1 while minimizing the degradation of the other performance parameters. The considered protection schemes are illustrated in Figure 4-18.

The approach in Figure 4-18 has a protection scheme down to PCP5, where the OLT and FF are duplicated. In the protected architecture shown in Figure 4-18 the working and protection FFs are directly connected to one 2:*M* device at PCP5. As described in Section 2.3.2, in basic hybrid WDM/TDM-PON architectures, the device(s) at PCP5 can be: splitter, AWG, or a combination of WSSs and AWGs according to the type of the hybrid WDM/TDM-PON. If needed, two reach extenders (REs) can be placed at the end of each FF, right before any other component at PCP5. Two considered protection schemes do not affect the maximal number of supported users per feeder, flexibility on resource allocation and power budget for the connection between the OLT and ONT.

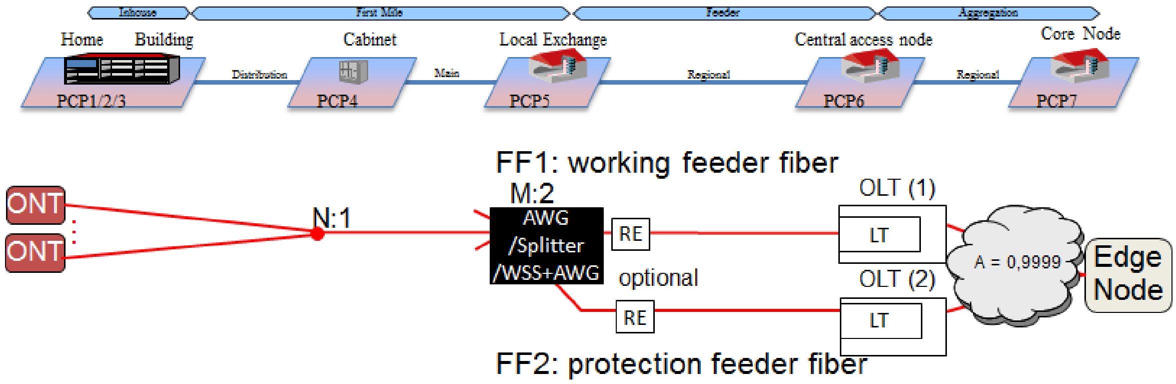


Figure 4-18: Two considered reliable architectures for all types of hybrid WDM/TDM-PON.

The connection availabilities for hybrid WDM/TDM-PON with FF protection are similar as for the other NGOA architecture options. For passive case both considered schemes (with protection down to PCP5) connection availability of 0.9997 can be achieved while semi-passive hybrid PON has slightly lower availability due to unprotected active components at PCP5. The connection availability can be further increased by providing protection for the distribution fiber and ONT.

Figure 4-19 and Figure 4-20 show the connection availability and FOM values of the passive and semi-passive hybrid WDM/TDM-PON with and without the considered protection scheme for different node consolidation scenarios and populated areas. For the passive concept of hybrid WDM/TDM-PON, here we only present the results of the wavelength-routed case since the wavelength-selective scheme has a similar (i.e. only slightly better) connection availability and FOM than the wavelength-routed one. It can be clearly seen that with protection of feeder fiber and OLT, the resiliency performance is significantly increased.

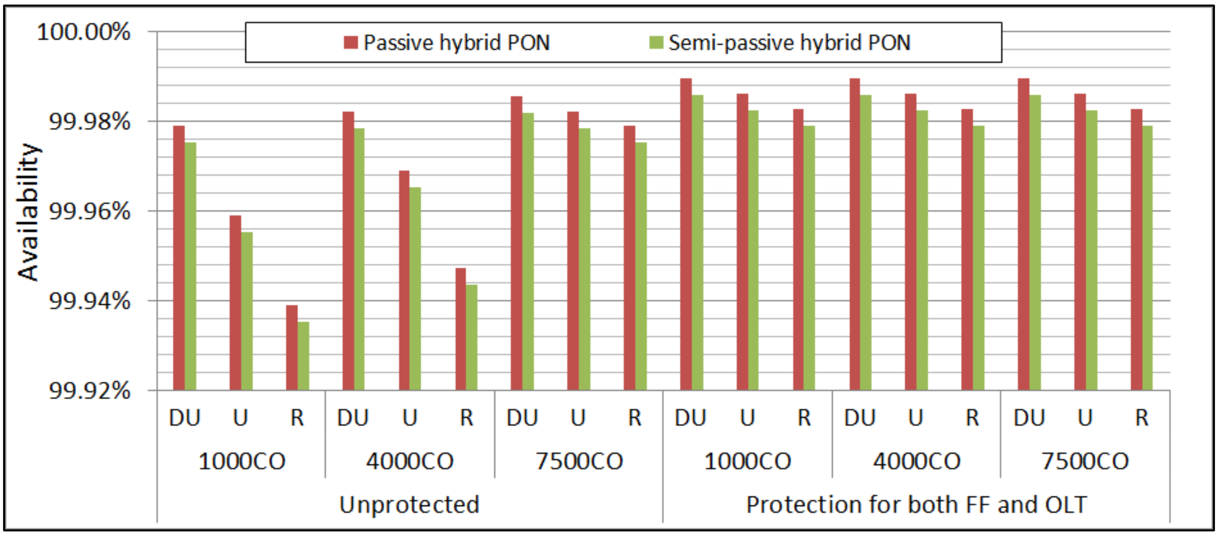


Figure 4-19: Connection availability of Hybrid WDM/TDM-PON and the one with protection for both FF and OLT

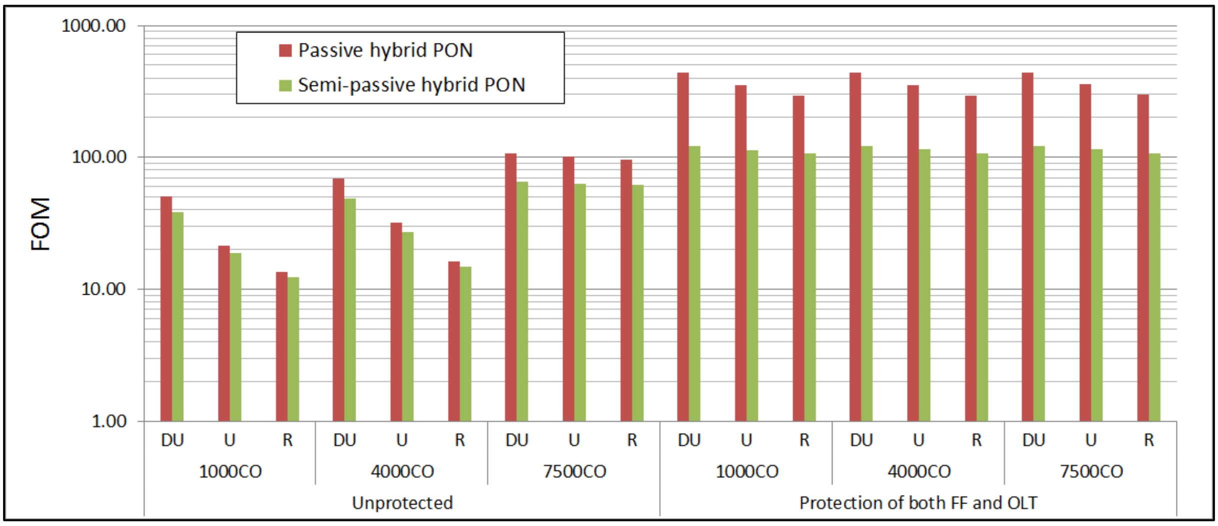


Figure 4-20: FOM of hybrid WDM/TDM-PON and the one with protection for both FF and OLT

4.2.3 *Operational complexity*

Operational impact on the hybrid WDM/TDM-PON system has been addressed in OASE deliverable D4.3.1. From the architecture point of view, due to its compatibility of legacy infrastructure, hybrid PON is more convenient to achieve zero-touch during network upgrade staring from current TDM-PON (e.g. GPON) compared with all the other OASE NGOA architectures. Furthermore, high flexibility of resource allocation in hybrid PON makes migration from residential to business user (which typically requires higher guaranteed bandwidth and quality of service) relatively easy. On the other hand, due to the broadcast nature of splitters the precise location of failures, which occur in the distribution fibers connecting splitters with end users, cannot be directly determined by traditional optical time domain reflectometry (OTDR) techniques. This limitation introduces some additional cost for fault management in the first mile network.

We have also performed a detailed assessment on the impact in terms of energy consumption footprint, failure rate and travel distance, which are tightly related to operational aspects, in combination with the three node consolidation scenarios as defined in Section 1.1.

Operator related energy consumption assessment in node consolidation

Figure 4-21 shows the network operator related power consumption without the ONT part for hybrid WDM/TDM-PON in one urban and one dense urban service area. The network operator related power consumption is relatively small compared with the other NGOA architectures. In the case of node consolidation the network operator related power consumption lies in the range of 17 kW (scenario 2) to 58 kW (scenario 3) for one urban service area and 22 kW (scenario 2) to 50 kW (scenario 3) for one dense urban service area (based on the three scenarios defined in section 1.1).

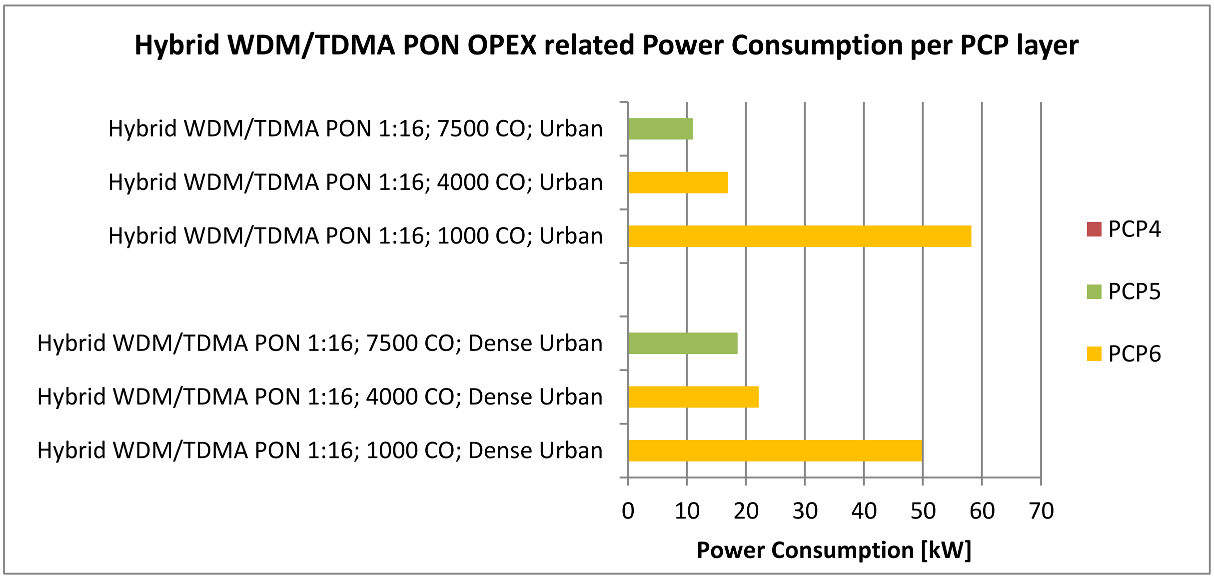


Figure 4-21: Network operator related power consumption for Hybrid WDM/TDM-PON

Figure 4-22 shows the network operator related power consumption per line and PCP for different node consolidation scenarios and service area types. It shows that node consolidation brings no significant benefit regarding the network operator related power consumption.

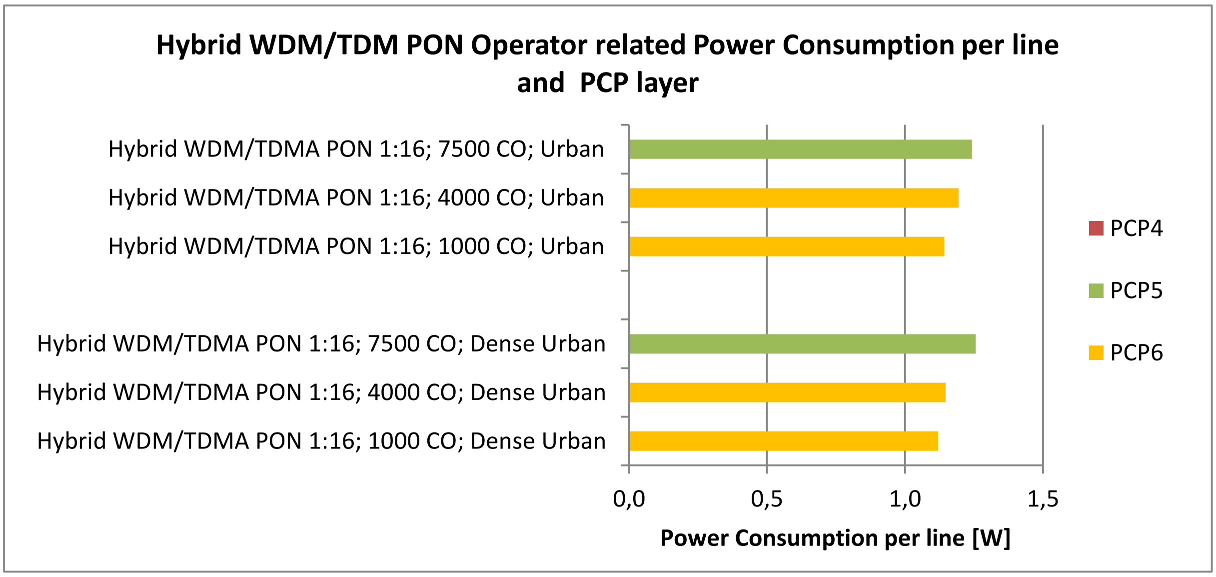


Figure 4-22: Network operator related power consumption per line for Hybrid WDM/TDM-PON

Footprint assessment in node consolidation

Figure 4-23 shows the footprint per PCP layer of the Hybrid WDM/TDM-PON architecture for the three node consolidation scenarios as described in section 1.1. The footprint is shown for one dense urban (DU), one urban (U) and one rural (R) service area. This footprint calculation is based on the footprint model described in OASE deliverable D4.3.1.

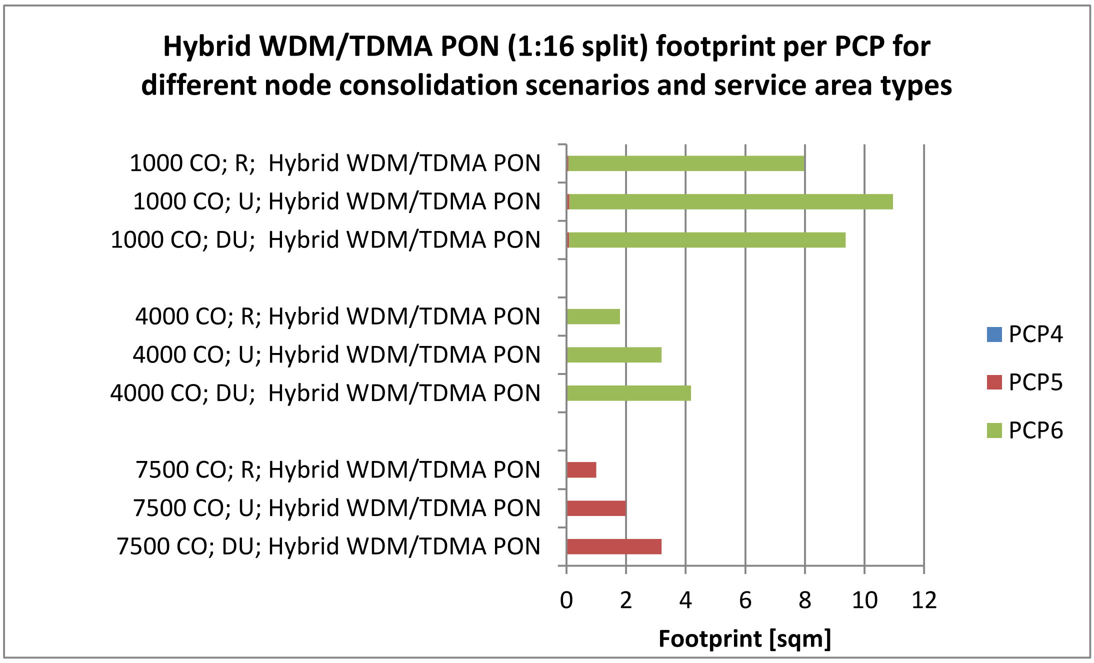


Figure 4-23: Hybrid WDM/TDM-PON footprint per PCP layer in dense urban

Figure 4-23 shows that the footprint per service area increases with a higher level of node consolidation due to the increasing number of users per consolidated service area. However, this does not mean that the total footprint per architecture increases in case of node consolidation. There is no footprint for ODF and passive power splitter components at PCP4 because it was assumed that such equipment can be housed by closures in the field.

In scenario 1 the hybrid WDM/TDM-PON OLT is located at PCP5 together with the AWGs which are used to combine multiple PONs to one feeder fiber. This scenario requires a footprint of 2.0 m^2 at PCP5 for one urban service area. In scenario 2 and 3 the OLT is located at PCP6. A footprint of 3.2 m^2 is needed for scenario 2 and 10.8 m^2 for scenario 3 at PCP6 in one urban service area. In scenarios 2 and 3 the AWGs are located at PCP5. However, the AWG equipment requires a negligible footprint. This means that the AWG equipment could be housed by closures next to PCP5 in order to shut down the legacy LEx location.

Figure 4-24 shows the footprint per line and PCP for different node consolidation scenarios and service area types. It shows that node consolidation brings no significant benefit regarding the footprint. In rural service areas the footprint per line is about 15% higher in scenario 1 as compared to scenarios 2 and 3, which is mainly caused by an adverse OLT occupancy rate.

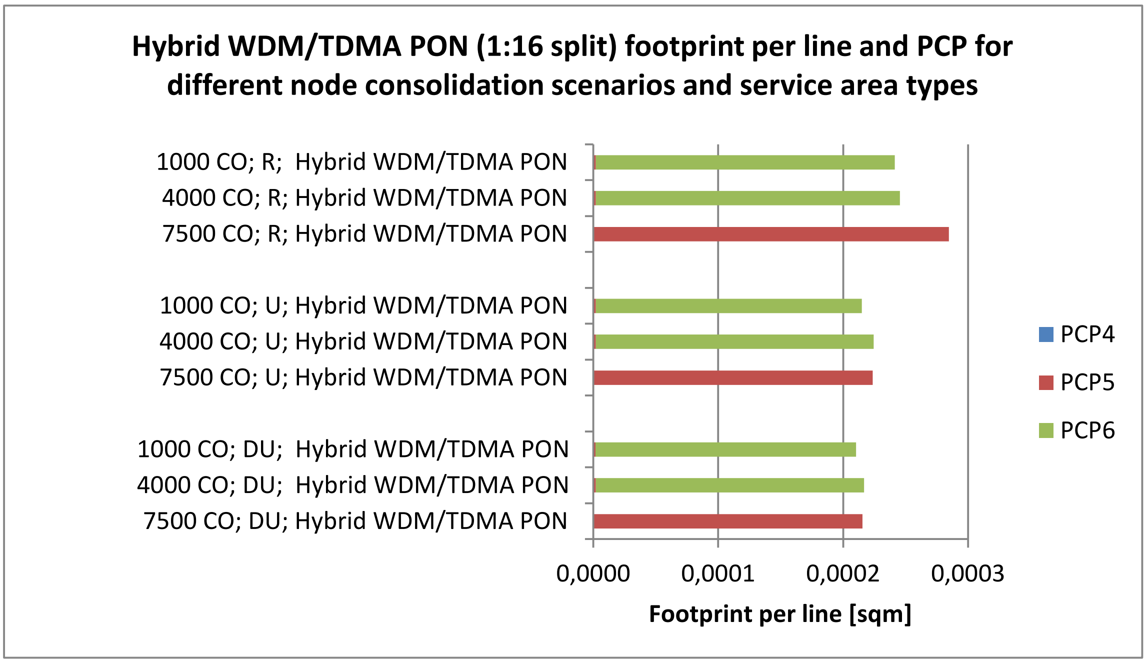


Figure 4-24: Hybrid WDM/TDM-PON footprint per PCP layer in dense urban

FAILURE RATE IN NODE CONSOLIDATION

The Hybrid WDM/TDM-PON failure rate analysis is based on the MTBF values shown in Table 4-4.

Table 4-4: MTBF values for Hybrid WDM/TDM-PON

Components	MTBF (hour)	MTBF(year)
Hybrid WDM/TDM-PON system technology		
ONT	204.545	23
Shelf / Backplane	1.500.000	171,23
Baseline card (Switch/Router, CPU, Control and Management Plane) (~500G)	430.000	49,09
Power Supply (redundant)	500.000	57,08
OLT Diplexer card (7)+Booster+Preamp	387.097	44,19
OLT Diplexer card (15)+Booster+Preamp	307.692	35,12
OLT Downlink line card Hybrid-PON (10 x 10G)	440.000	50,23
RN AWG 80 channels	4.000.000	456,62
EDFA based reach extender	1.000.000	114,16
RN Power splitter 1:16	7.500.000	856,16
Link Level		
Feeder Fiber 192 fibers	1.350.000	154,11
Feeder Fiber 1000 fibers	1.000.000	114,16
Main Cable	1.400.000	159,82
Distribution Cable	1.500.000	171,23
Inhouse Cable	525.000	59,93

Figure 4-25 shows the annual failure rate per PCP and LL for Hybrid WDM/TDM-PON. The failure rates are shown for the node consolidation scenarios 1, 2 and 3 in one dense urban, one urban and one rural service area. The result shows that the annual failure rate is clearly dominated by failures at PCP1 (ONT failures at the user site).

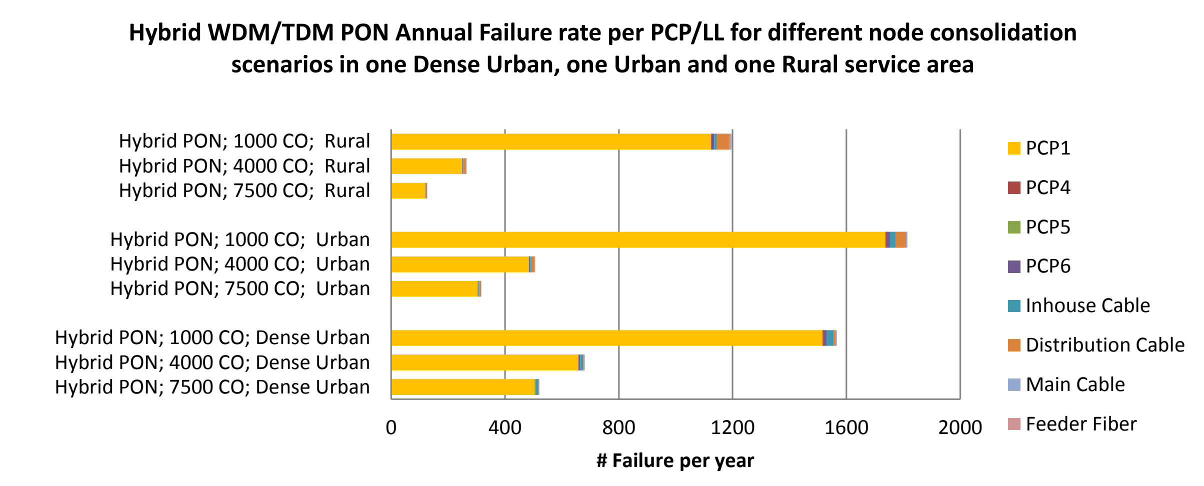


Figure 4-25: Annual failure rate per PCP and LL for Hybrid WDM/TDM-PON

Figure 4-26 shows the annual failure rate per PCP/LL for Hybrid WDM/TDM-PON without the PCP1 part. Apart from ONT failures at PCP1, most of the failures are caused by the distribution cable in urban and rural service areas and by the in-house cable in dense urban service areas. The PCP6 failure rate is quite low due to the small number of OLT components at PCP6 which is based on the high sharing ratio.

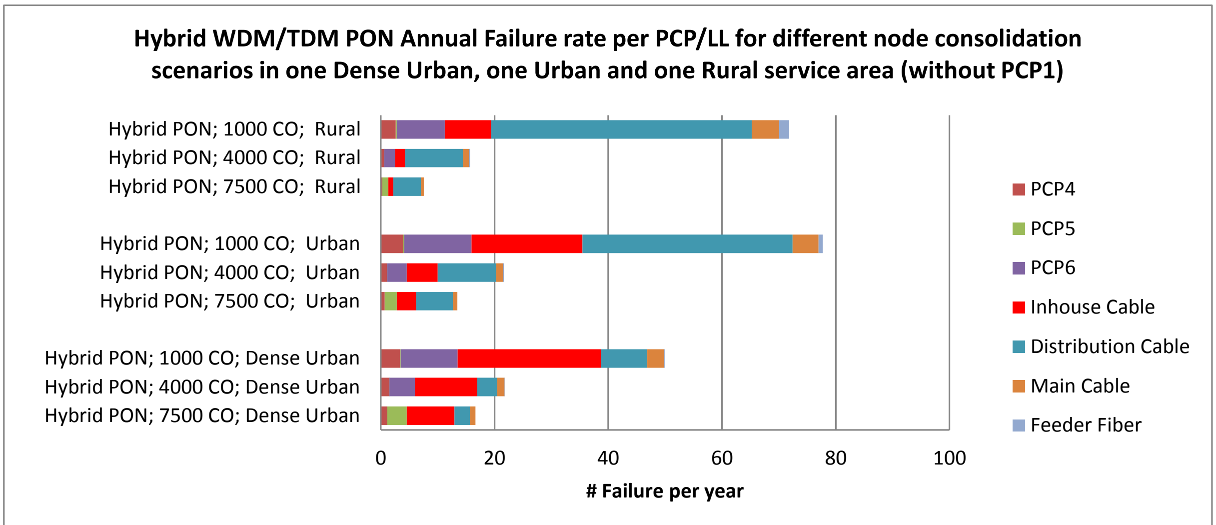


Figure 4-26: Annual failure rate per PCP/LL for Hybrid WDM/TDM-PON (w/o PCP1 part)

Figure 4-25 shows that the annual failure rate per service area increases with a higher level of node consolidation due to increasing number of users per consolidated service area. However, this does not mean that the failure rate per line increases in case of node consolidation as shown in Figure 4-27. The annual failure rate per line is more or less constant for all node consolidation scenarios.

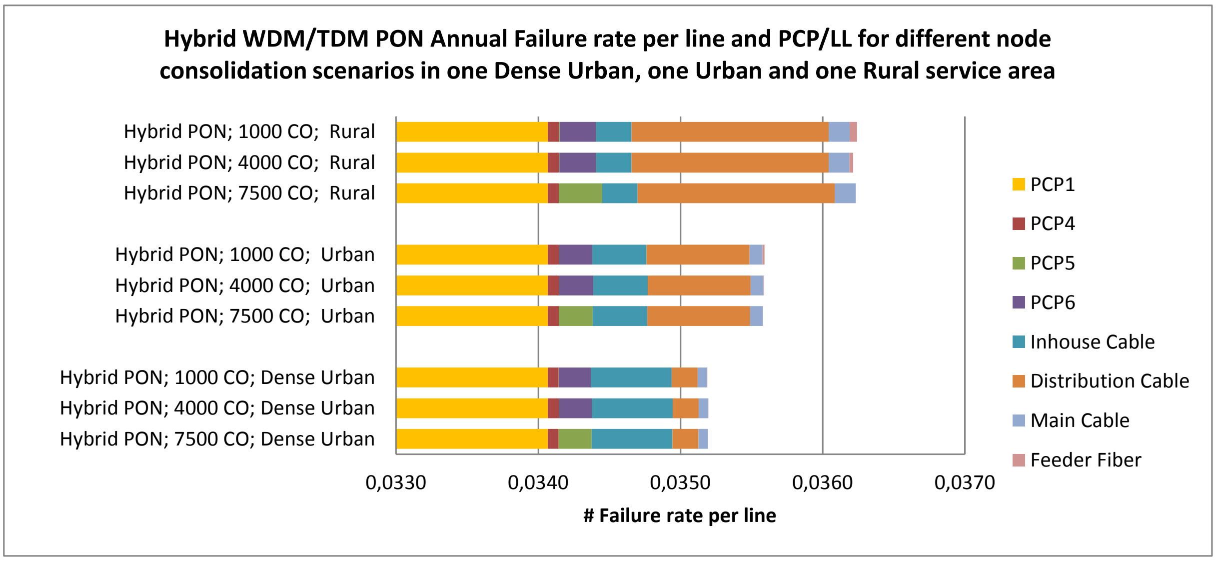


Figure 4-27: Annual failure rate per line and PCP/LL for Hybrid WDM/TDM-PON (w/o PCP1 part)

IMPACT OF NODE CONSOLIDATION ON TRAVEL EFFORT

The travel effort analysis is based on the annual failure rate and the travel distance model described in Section 3.3.4. It is assumed that travel effort is not needed for ONT failures at PCP1. In the case of an ONT failure the user gets a new ONT device which is installed by the user (plug-and-play).

Figure 4-28 shows the average annual travel time per line for Hybrid WDM/TDM-PON. The annual travel times are shown for the node consolidation scenarios 1, 2 and 3 in dense urban, urban and rural service areas.

The annual travel times are proportional to the annual failure rates. Most of the travel effort is caused by the distribution cable in urban and rural service areas, and the in-house cable in dense urban service areas. The result shows that the impact of node consolidation on travel time is more or less negligible due to the relatively low number of failures per day and PCP/LL. As shown in Figure 4-26 there is not more than one failure per day and PCP/LL assuming a uniform distribution of failure events over the time. This means that there is only a little chance to save travel time by fixing multiple failures with one travel activity.

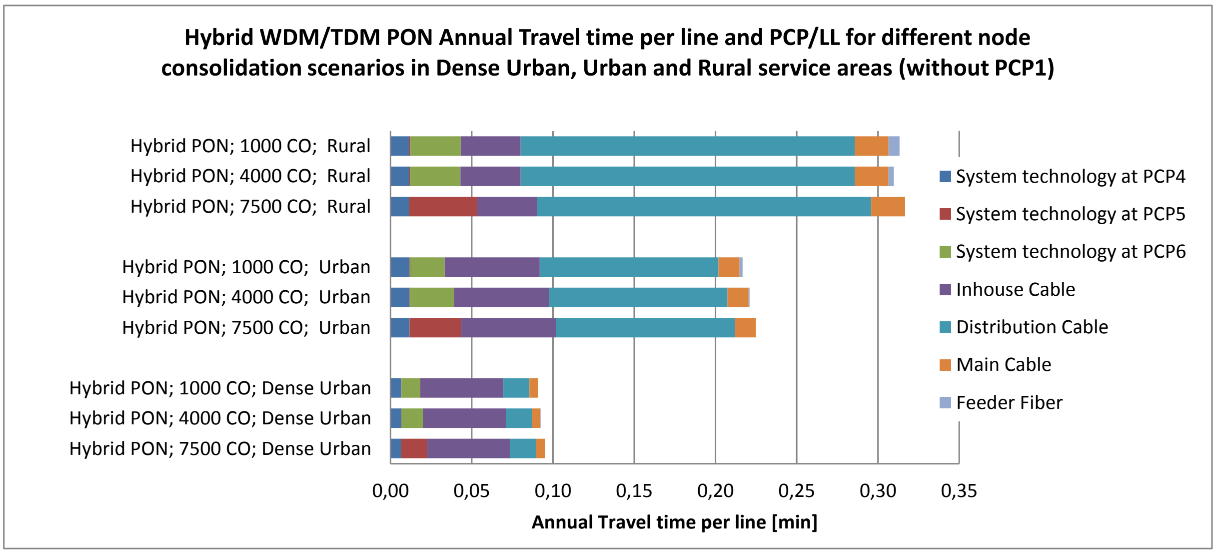


Figure 4-28: Annual travel time per line for Hybrid WDM/TDM-PON

4.2.4 Control and management

The control and management of WDM/TDM-PON can be separated into two separate parts, the interface between ONTs and OLT, and between the OLT and the rest of the access/aggregation network.

Two issues need to be addressed between the ONT and the OLT, bootstrapping of the connection between the two, and the management of the TDM layer when the initial data connection is established. The ONT needs to select which wavelength to use before the C&M function of TDM layer can be activated. How this can be performed, and what steps are needed, depend on the variant of WDM/TDM-PON considered. In variants where several usable wavelengths exist, the selection of wavelengths could be performed via a dedicated control channel which the ONT initially tunes to, and then receives the correct wavelength to operate. This approach would also provide functionality needed for open-access as well as potentially other useful functionalities. The ONT could scan the spectrum to find the correct wavelength, at least in cases where only one usable wavelength exists. Semi-passive hybrid WDM/TDM-PON requires control of the WSS which has to be re-configured on the basis of users' demand. This configuration could potentially reuse the same kind of control channel as used for bootstrapping the ONTs.

After the wavelength has been selected the TDM layer needs to be configured and managed. It can be assumed that the C&M function for the TDM layer will be based on existing established G-PON technologies, since WDM/TDM-PON is partly based on G-PON. G-PON offers a comprehensive standard for C&M of its TDM layer via the "ONT management and control interface specification" (OMCI) in the ITU-T G.984.4 recommendation. This recommendation specifies a C&M interface between the OLT and the ONT, both for low layer and high layer configurations via SNMP. The C&M of the TDM layer of future WDM/TDM-PON solutions should therefore be easy to solve in a standardized way. Configuration of the higher layer functions, such as Layer-2 aspects, could be performed via the well-known TR-069 specification from Broadband Forum.

The C&M integration between the OLT and rest of the access/aggregation network represents a more problematic aspect of WDM/TDM-PON because of the technology differences between the two. The C&M standard used in the rest of network, consisting mostly of Ethernet and MPLS based technology, cannot be used since a WDM/TDM-PON is inherently different. This issue exists also in G-PON, which lacks a standard for configuration of the G-PON OLT, for example via SNMP, and is therefore vendor specific. It is therefore unlikely that a standard for configuration and management of the WDM/TDM-PON OLT will be developed.

The integration between the OLTs and the rest of the network will therefore probably be performed in a vendor specific way, which imposes additional cost both in technical training and network management system (NMS) used. Some aspect of the OLT could still be preformed via well-known protocols, such as the Layer-2 functionality of the OLT. A long term approach could be to implement a C&M framework which integrates with existing solutions, such as the GMPLS integration proposed in [31].

4.2.5 Resource allocation

In this section, we consider static wavelength assignment and dynamic bandwidth allocation. This type of resource allocation can be freely applied to any type of hybrid WDM/TDM-PON. On the other hand, due to the lack of dynamic wavelength assignment, the flexibility of this type of resource allocation may be limited. Assuming that the hybrid WDM/TDM-PON based architecture is deployed in a long-reach PON, it will require some enhancements to the traditional DBA algorithms [11] for TDM-PON. If the TDM-PON based DBA algorithms are applied as it is in a long reach scenario (without taking in to consideration the increased RTT delays that might be experienced by the DBA control packets) they will suffer degraded performance (i.e., delay, jitter and throughput) [12].

To address the performance shortcomings, a multi-thread polling DBA schemes for long-reach PON can be used. The aim of a multi-thread DBA scheme is to minimize the effects of a long propagation delay by introducing multiple polling processes per cycle. But on the other hand, the "over-granting problem" which is inherent in several DBA algorithms becomes a much more prominent issue when they are applied to long-reach PONs using multi-thread techniques. The over-granting problem occurs when the DBA algorithm allocates a larger timeslot size than actually needed by the ONT. One of the sources of over-granting is related to overlapping polling cycles in multi-threaded DBA applied in long-reach PON. When using multiple threads, the same queued data may be reported more than once to the OLT. This overlap of information, if not handled properly, can result in granting twice (or more) the required bandwidth. As reviewed in the deliverable D3.1, DBA can be categorized into two groups, i.e. on-line and off-line schemes. Accordingly, there are also two different methods to efficiently mitigate the over-granting problem occurred in on-line and offline DBA schemes, respectively.

ON-LINE SCHEME

To explain how to overcome the over-granting problem in multi-thread DBA for on-line scheme, we take as an example the Interleaved Polling with Adaptive Cycle Time (IPACT) with limited service, which is a very popular algorithm for resource allocation. For all the other on-line DBAs, the similar method can be applied. In IPACT with limited service, the OLT assigns a requested bandwidth to each ONT up to some predefined maximum limit. Adopting this scheme to the conventional (single-thread) DBA facilitates efficient bandwidth sharing while maintaining fairness among ONTs. However, it might be inefficient to directly implement IPACT with limited service in a multi-thread DBA where bandwidth scheduling for different threads is done in parallel. To overcome this problem a modification to enhance IPACT (which is referred to as enhanced IPACT (E-IPACT)) with limited service for multi-thread DBA in long-reach (i.e., reach > 20 km) environment can be used [13].

In E-IPACT with limited service for multi-thread DBA, the over-granting problem due to lack of frame fragmentation is reduced by allowing the ONTs to participate more actively in the DBA process, i.e., performing an adaptive report. If the ONTs can get the information on the value of the maximum timeslot threshold, they would only need to report the frames in their queues that completely fit this threshold. This information can be sent by the OLT to the ONTs using a reserved field of the Gate message. In the case of IPACT, the maximum timeslot threshold is a constant value per ONT. Given this fact, the information can be sent once, or just configured in the ONTs. As for the over-granting problem due to multi-threading, it is avoided by keeping track of the already reported data at the ONT. Since the ONTs are always reporting up to the maximum timeslot allowed (solution to the first cause of over-granting), the reports will be always fully granted by the OLT. Frames remaining in any ONT's queue after multiple DBA threads in the current cycle will be reported in the next cycle.

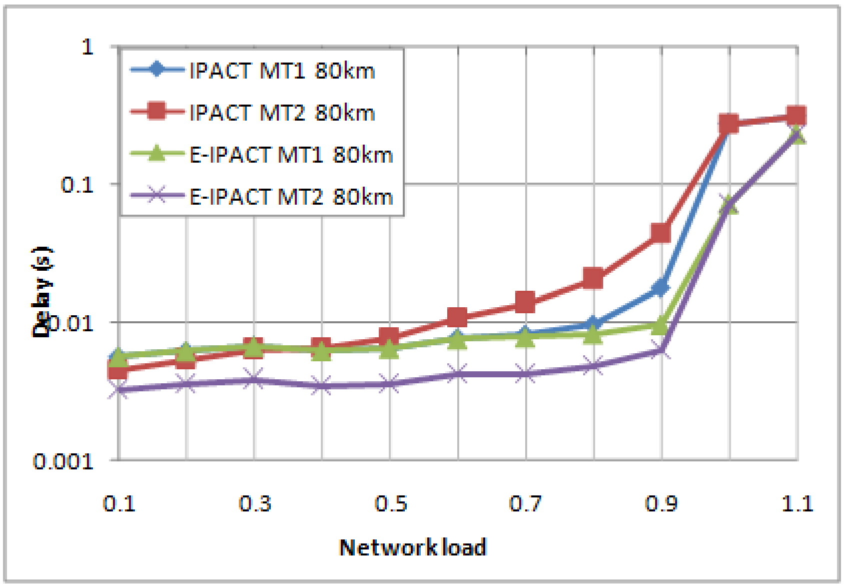


Figure 4-29: Average delay for IPACT and E-IPACT schemes versus network load, at 80 km distance between ONTs and OLT.

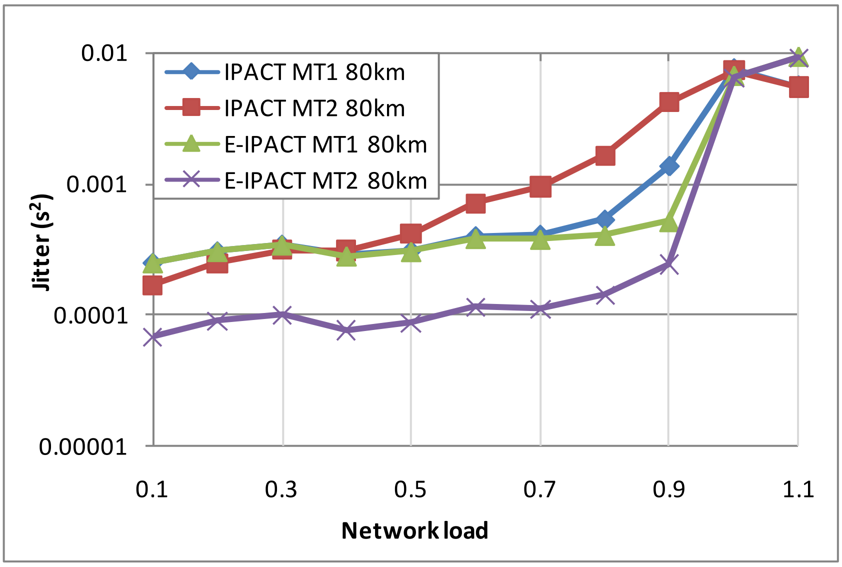


Figure 4-30: Jitter for IPACT and E-IPACT schemes versus network load, at 80 km distance between ONTs and OLT.

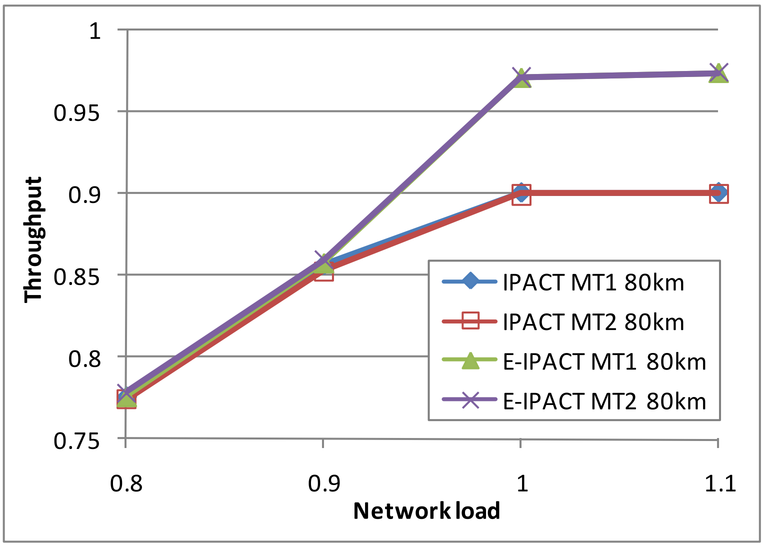


Figure 4-31: Normalized throughput for IPACT and E-IPACT schemes versus network load, at 80 km distance separation between ONTs and OLT.

Figure 4-29 shows average delay (sec) and Figure 4-30 shows jitter (sec^2) as a function of network load for 80 km distance (long-reach) between the OLT and ONTs. We observe that, due to the longer propagation time, the average delay and jitter increase with the distance. For both the single-thread and double-thread cases, E-IPACT outperforms IPACT with limited service, achieving both lower delay and jitter. This result is a direct consequence of avoiding unused bandwidth caused by over-granting. E-IPACT reduces the waiting time at the ONTs' internal queues, which affect both delay and jitter performance. The results obtained using double-thread (marked as MT2 in result figures) in E-IPACT are better than using single-thread (marked as MT1 in result figures) because with two Report-Gate processes in a cycle we can speed up the granting process for the ONTs, which are reporting the exact amount of bytes to be transmitted (less or equal to the maximum allowed). On the other hand, we note that the conventional IPACT with MT2 results in increased average delay and jitter compared to the MT1 case. This is because the algorithm generates more over-grants with multiple threads than it does with a single thread. Therefore, using multi-thread with the conventional IPACT algorithm does not seem useful.

In Figure 4-31, results are presented for normalized throughput versus network load for the IPACT and E-IPACT schemes. Results for network loads lower than 0.8 are not presented since the curves overlap and do not offer meaningful information for comparison. We notice that for network loads higher than 0.9, the E-IPACT scheme offers a higher throughput than the IPACT scheme, regardless of the number of threads per cycle. When the network is highly congested, the IPACT algorithm has higher probability of allocating the maximum timeslot size to the ONTs and, therefore, the over-granting problem is present. At high loads, an important reason for improved E-IPACT performance is the fact that the ONTs have information on the maximum timeslot size, so over-granting is avoided. On the other hand, the multi-thread scheme does not improve the performance when the system is overloaded. For low network loads, the data frames can be transmitted successfully using any of the schemes, but differences are evident in delay and jitter performance as presented in Figure 4-29 and Figure 4-30, respectively.

OFF-LINE SCHEME

As presented in the previous section, in the online scheme the OLT does not have to wait for the Report messages to arrive from all ONTs in the current cycle to schedule a grant.

However, it cannot achieve the optimized allocation of the bandwidth as well as the fairness in bandwidth allocation among ONTs. Thus, an off-line DBA scheme is usually preferred where the DBA algorithm is executed when the bandwidth reports from all ONTs are collected by the OLT in the current cycle. Two off-line schemes are presented in this section:

1) NEWLY ARRIVED FRAMES PLUS (NA+)

A scheme named 'newly arrived frames plus' (NA+) [12] can be used for coordinating between multiple threads in off-line DBA. The general idea of the NA+ scheme is that each DBA process is primarily responsible for allocating bandwidth to newly arrived frames, i.e., frames that have arrived since the last previously initiated DBA process. The idea provides a way of partitioning the workload among overlapping DBA processes. The proposed scheme also caters for the backlogged traffic at the ONTs as well (in case DBA process may not be able to cater for the full bandwidth request of all newly arrived traffic). NA+ can be adapted for any TDM-based PON resource allocation scheme but some technology specific issues may arise and required to be resolved. For example, in EPON, frames cannot be fragmented, and unused time slots (UTS) may occur. Therefore, in case of PON where the Ethernet frame is used in the media access control (MAC) layer, NA+ should also cater for the presence of frame fragmentation.

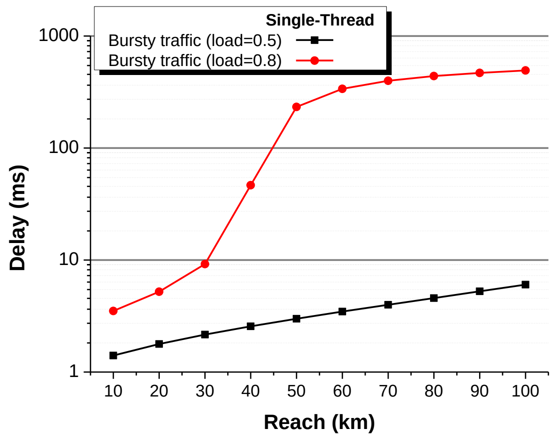


Figure 4-32: Degradation of average delay as a function of reach for different traffic patterns.

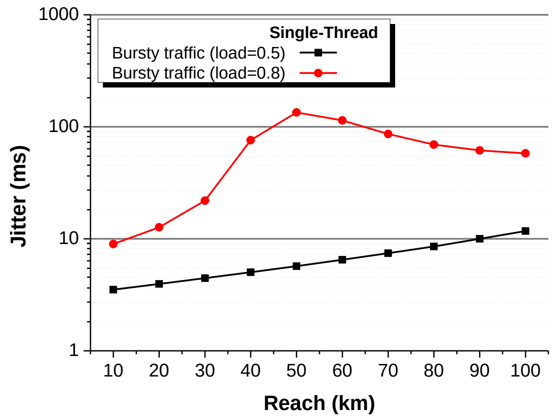


Figure 4-33: Degradation of average jitter as a function of reach for different traffic patterns.

The performance degradation for average delay and jitter due to extending the PON reach for traditional off-line DBA (single thread) is illustrated in Figure 4-32 and Figure 4-33 respectively as a function of reach. The exact nature and extent of the performance degradation depends on the details of the employed DBA. The increased propagation delay leads to an increased DBA response time resulting in increased average delay. The average delay is increased by approximately twice the increase in propagation delay. At heavy load (load = 0.8) there is a quite severe degradation of performance incurred by the reach extension. This is an effect of the increased propagation delay resulting in the requirement of a larger polling cycle in order for the DBA to remain efficient. If the variable polling cycle is smaller than twice the propagation delay, there will be a waiting time where the system waits for transmission of control messages to be completed. Note that there is an apparent improvement in jitter when the reach is extended to 50 km and beyond (Figure 4-33). But in this scenario, the results are affected by the limited buffer sizes used in the simulation which leads to packet loss and eventually results in an apparent improvement in jitter.

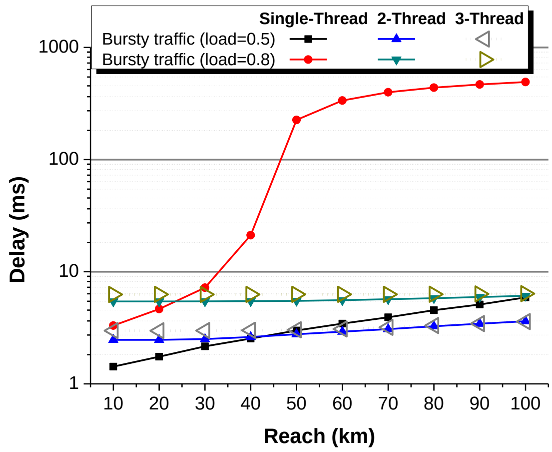


Figure 4-34: Average delay performance improvement for multi-threading.

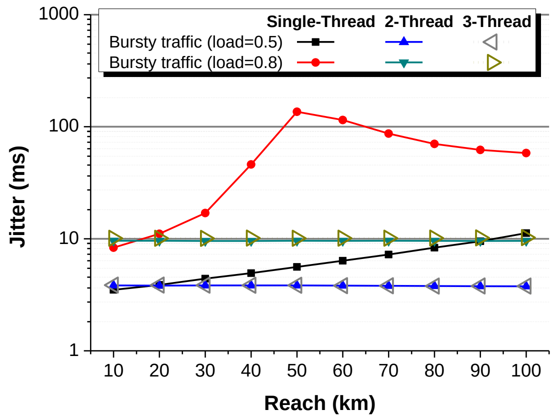


Figure 4-35: Average jitter performance improvement for multi-threading.

Here we show how the delay and jitter performance can improve when effective multi-threading is employed using NA+ for an offline DBA case (see Figure 4-34 and Figure 4-35 for delay and jitter, respectively). We see a general performance improvement by using multi-threading. The performance improvement is larger for longer reach. We see that multi-threading can compensate to large extent for the performance degradation of average delay. For non-infinite buffers and high load traffic, one may expect a reduced average delay to translate into higher throughput. From the results shown in Figure 4-34 and Figure 4-35, it can also be observed that performance improvement is more tangible for longer reach. However, there is performance degradation due to multi-threading through the increased overhead associated with report and grant messages in TDM-PON. When the reach is relatively short (e.g., 10 km), the average delay and jitter for the multi-thread scheme is even worse than for the single-thread scheme. Furthermore, we can observe that there is a trade-off between the number of threads employed to increase the DBA performance and extra message exchange overhead generated by them. According to the results shown in Figure 4-34 and Figure 4-35, we find that two is the optimal number of threads for this scheme in order to obtain the best delay and proper jitter. However, this value is sensitive to system characteristics (number of ONTs, line rate, etc.) and traffic characteristics (load, burstiness, etc.).

2) ADAPTIVE MULTI-GATE POLLING WITH VOID FILLING

Another method proposed to mitigate long-reach effects is the Adaptive Multi-Gate polling with Void filling (AMGAV) algorithm. Paper [14] proposed AMGAV to mitigate some problems with the multi-thread (MT) polling algorithm and NA+.

Problem Statement and Motivation

Although the MT polling algorithm improves the delay performance for long-reach PON (LR-PON) compared with the single-thread (ST, e.g., IPACT) polling algorithm, we identify the following problems with the MT polling algorithm:

Static number of threads (Issue 1) — We see that as the number of threads or Gate messages increases, the ONTs are polled more frequently leading to reduced delays but it may lead to a large number of Gate and Request messages and thus it will waste bandwidth in control message transmission and guard band overhead. Obviously if the load is very high, the penalty of bandwidth wastage in control message transmission and guard band overhead is more severe. This motivates us to make the number of threads transmitted in one cycle adaptive to the instantaneous network load and not static as in the MT polling algorithm.

Thread spread and convergence (Issue 2) — The MT polling algorithm suffers from the problem of thread spread and convergence. Thread spread occurs whenever a thread data cycle (i.e. the time period of data transmission of all ONTs in one thread) becomes larger than the round trip time (RTT) of the most distant ONT, i.e. larger than Max(RTT). In this case, the MT polling algorithm reduces to the ST polling algorithm as the new Gate message will be transmitted only after reception of the previous Request message. On the other hand, whenever a thread data cycle becomes large compared to the other threads, there is a problem of thread convergence. Also, due to thread convergence, the performance of the MT polling algorithm degrades to that of the ST polling algorithm. To prevent thread convergence in the MT polling algorithm, the threads are to be continuously tuned by shifting the load from some threads to the other threads. This leads to the complexity in the MT polling algorithm. Moreover, the packets in the moved bandwidth may encounter an increased delay. This motivates us to make the cycle time fixed to overcome the problem of thread spread and convergence.

Void formation (Issue 3) — The increase in the differential distances between ONTs and Max(RTT) in a LR-PON poses a problem of void formation. A void is the period in which the upstream channel is left unutilized. The MT polling algorithm is based on IPACT and thus the thread scheduling cycle (i.e. the time period between issuing the same thread to an ONT) cannot be less than Max(RTT) of the PON. Thus, if the aggregation of all thread data cycles is less than Max(RTT), then it will lead to void formation. This motivates us to determine the number of threads according to the network load which will minimize void formation to a large extent, and to over-grant an ONT whenever the number of used threads is smaller than the number of required threads.

Computational Complexity (Issue 4) — In addition to the complexity added by thread tuning in the MT polling algorithm, the bandwidth reporting (BR) scheme also makes the algorithm complex. The traditional queue size reporting will lead to the problem of over-reporting and thus an ONT has to report its bandwidth according to the thread number on which the grant has come. Thus, there is more computational power needed at both the OLT and ONT as there is an added dimension associated with the thread number on which the Gate and Request message depend. The computational complexity of the protocol is increased by n times the complexity of IPACT, where n is the number of threads. Inter-thread scheduling will further increase the complexity of the protocol. This motivates us to propose a bandwidth reporting scheme which solves the problem of over-reporting and in which the OLT and ONT do not have to keep track of the number of threads.

Adaptive Multi-Gate Polling with Void-Filling Algorithm

In our proposed AMGAV algorithm, we do adaptive multi-threading as more than one Gate may be issued to an ONT before the receipt of the acknowledgement of the previous Gate message and the number of Gate messages depends on the instantaneous network load.

Fixed cycle time (solves issue 2): The number of Gate messages is determined after a time interval referred to as a cycle. The time interval of a cycle depends on Max(RTT) and the number of Gate messages issued in the cycle. Generally,

$$T_{CYCLE}(I) = S_F \, \mathrm{MAX}(RTT) + N_O \, N_G(I) \, B \qquad (7)$$

where $T_{cycle}(i)$ is the time period of the i^{th} cycle, S_f is the scaling factor, N_o is the number of active ONTs, $N_g(i)$ is the number of Gate messages per ONT in the i^{th} cycle, and B is the guard time between two adjacent time-slots. The scaling factor (S_f) depends on the reach of the PON and is a key parameter of the AMGAV algorithm. In a 20 km reach PON, where Max(RTT) is very small, the gain of threading is much reduced as compared to the longer reach scenario. Thus, with the reach of the PON, both the cycle time and the number of threads have to be properly scaled. For a given PON reach, S_f is fixed leading to the fixed cycle time independent of the load.

Void-filling and adaptive number of threads (solves issue 3 and 1, respectively): The algorithm adopts the void filling approach in which the size of the grants issued to the ONTs is such that the transmission slot of a complete cycle is utilized. For simplicity, we first consider a single-thread process between an ONT and OLT. Let us consider an example of how voids are created in traditional ST DBAs like IPACT. In Figure 4-37 (a), two ONTs are considered for clarity. Let us assume that ONT_2 is having a RTT of 1 ms and ONT_1 and ONT_2 have requested for a transmission window of 200 µs each in the previous cycle. Since the next grant message for ONT_2 can only be issued after the receipt of the acknowledgement of the previous one, this leads to a void period of around 800 µs. In the first method of void-filling (cf. Figure 4-37 (b)), we distribute the unrequested bandwidth between all ONTs (using constant or linear credit schemes [15]). Here, we try to utilize the otherwise wasted bandwidth and this gives us a significant improvement in the average packet delay. First, the report from the ONT is transmitted at the beginning of the transmission slot, already reducing the void formation with 200 µs in this example. The OLT then calculates the bandwidth wastage and allocates the unutilized bandwidth to both ONTs. Instead of only granting a 200 µs transmission window to each ONT, an extra transmission window of 300 µs will be allocated to each ONT so that the bandwidth wastage is minimized. However due to the bursty nature of the traffic, the bandwidth demand of each ONT may be entirely different. A better method of void-filling is to poll ONTs multiple times in a cycle. Thus, on receipt of a Request for a transmission window of 200 µs from both ONT_1 and ONT_2, the OLT will divide the cycle into smaller time-slots, called sub-cycles. E.g. in the present case, the cycle will be divided in three sub-cycles where each sub-cycle will be equal to a time-slot of 333 µs. The OLT will poll each ONT once in a sub-cycle. The number of Gate messages (or threads) issued to each ONT is equal to the number of sub-cycles and is formulated by (3),

$$N_G(I) = \mathrm{Min}\left[\left\lceil \frac{S_f \ \mathrm{Max}(RTT) R_u}{B_l(i)} \right\rceil , \mathrm{Max}(N_g) \right] \quad (8)$$

where R_u is the upstream channel data rate, $B_l(i)$ is the sum of the Requests (in bytes) of all ONTs, and $\mathrm{Max}(N_g)$ is the maximum value of $N_g(i)$ for all cycles. Especially note that the number of Gate messages depends on the instantaneous network load which makes the algorithm adaptive. As at low load, however, the number of Gate messages may become very high, adversely affecting the downstream traffic, $\mathrm{Max}(N_g)$ is introduced. In a cycle, the time-slot for a sub-cycle is fixed. As illustrated in Figure 4-37 (c), three sub-cycles are initiated at time t_o, t_1 and t_2, respectively. The time t_o denotes both the beginning of the new cycle and the first sub-cycle. At time-interval t_1, the second sub-cycle will be distributed fairly according to the latest demands of the ONT. In the present case, since there is no new arrival of a Request message between t_o and t_1, the time-slots are distributed as in the previous sub-cycle. During the start of the third sub-cycle, the Request message from ONT_2 has already arrived and now the OLT will distribute the time-slots window of the third sub-cycle according to the new Request statistics. With this algorithm, there is no void formation and at all time the upstream channel is better utilized. Moreover, by using multiple Gates in a cycle we achieve fairer statistical multiplexing.

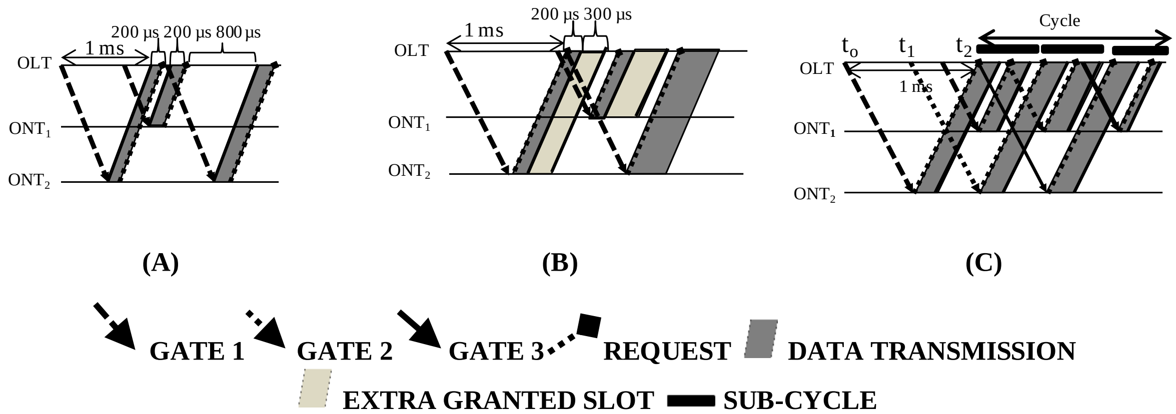


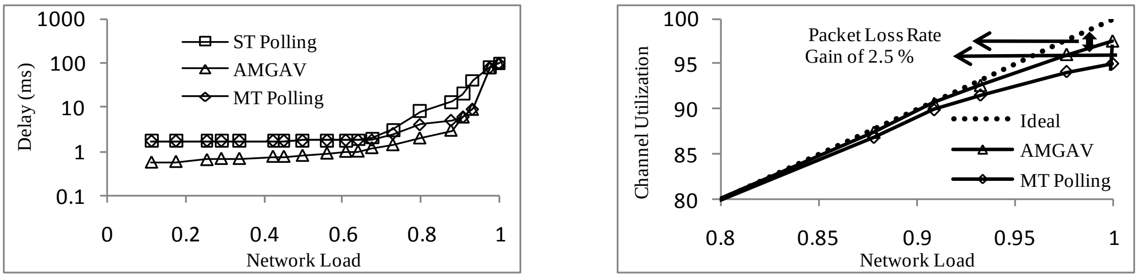
Figure 4-36: (a) Void formation in the ST polling algorithm (b) Removal of void formation by applying a void-filling algorithm (c) An example of application of the AMGAV algorithm

Bandwidth reporting scheme (solves issue 4): In the AMGAV algorithm, an ONT generates a Request message with multiple Requests to report the sum of the untransmitted bytes in the present cycle and the size (in bytes) of multiple fractions of newly arrived packets. The OLT will grant the window size choosing one of the multiple Requests such that it almost completely fills the transmission slot and there are no Request truncations (allocating smaller transmission slots than Requests). The use of multiple Requests is important for the AMGAV algorithm because the transmission slot of all ONTs has to be adjusted in a sub-cycle and thus otherwise there may be large Request truncations leading to bandwidth wastage in unused slot remainders (USRs). On the other hand, the OLT maintains a request variable (RV) for each ONT. The OLT increments the RV by the number of requested bytes in each thread and thus maintains track of all requested bytes. Similarly, on the issue of every Gate message, the OLT decrement the corresponding RV by the number of granted bytes. The proposed bandwidth reporting scheme requires the OLT to inform an ONT about any lost Request message.

Simulation Results

We simulate an LR-PON with 16 ONTs where the distance between the OLT and ONTs varies from 10 to 100 km. We have chosen R_u as 1 Gb/s, the maximum user data rate at an ONT as 100 Mb/s, S_f as 2, $\mathrm{Max}(N_g)$ as 8, and B as 1 µs. We generate packets in the form of Ethernet frames (64 to1518 bytes). The synthetic user traffic is self-similar with a Hurst Parameter of

0.8 [16]. The buffer size at each ONT is limited to 1 MB. In Figure 4-37 (a) and (b), the load is normalized to the upstream channel rate R_u (1 Gb/s). When the load is not very high, such as 0-0.9, our algorithm shows a much better delay performance than ST or MT polling as shown in Figure 4-37 (a). At high load, the delay is comparable to that of the MT polling algorithm. Figure 4-37 (b) shows the channel utilization vs. network load. The improved channel utilization is due to the reduced USR. At a network load of 1, the channel utilization is 97.5% compared to 95% in the MT polling algorithm. 0.8% of bandwidth wastage is due to guard band overhead, about 0.4% due to USR. This is an improvement over the MT polling algorithm where the bandwidth wastage is about 2.9% due to USR formation.



(a) (b)

Figure 4-37: (a) Average packet delay for OLT-ONT distance of 100 km (b) Channel utilization vs. Network Load

In general from the above discussion we can conclude that multi-threading techniques can improve DBA performance significantly in a typical LR-PON scenario based on TDM or a hybrid WDM/TDM-PON architecture (as described in the start of this section). Furthermore, DBA algorithms suggested for improved performance are presented both for online and offline DBA.

4.3 Two-stage WDM-PON

Figure 4-38 shows two Two-stage WDM-PON architecture alternatives. In essence, it is a WDM-PON connected to a second WDM-PON, and the second OLT is used as a port aggregator.

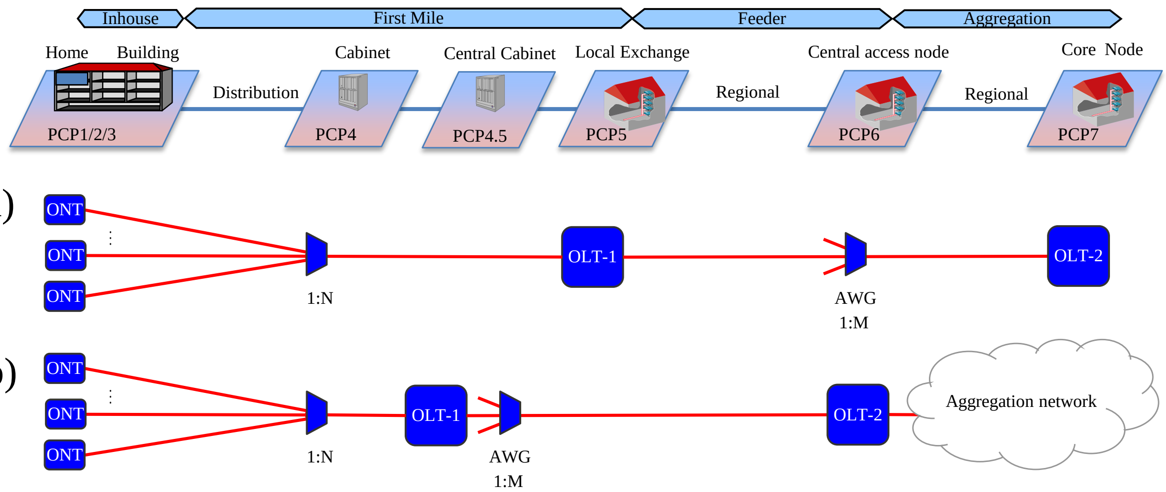


Figure 4-38: Two-stage WDM-PON architecture alternatives (Examples)

Figure 4-38a shows an architecture that integrates the aggregation network between PCP6 and PCP7. The OLT-1 is located at the legacy local exchange location whereas OLT-2 is located at PCP7.

Figure 4-38b shows a two-stage WDM-PON architecture alternative that enables shutting down the legacy local exchange location since the OLT-1 is located at a central street cabinet (PCP4.5). The OLT-2 is located at the CAN location (PCP6), which means that the aggregation network is not substituted.

The analysis of the two-stage WDM-PON has been made in OASE milestones M3.1 and M3.2. From there, we derive a summary for this section.

4.3.1 Power consumption

The power consumption of the two-stage WDM-PON depends on the specific configuration, in particular on the guaranteed per-client bit rate. For obvious reasons, significant differences exist for configurations which allow guaranteed 250 Mb/s as compared to those allowing for 500 Mb/s (and likewise for other bit rates). The detailed calculations have been performed in the OASE deliverable D4.2.1. From there, we derive total end-to-end per-client power consumptions of 5.8 W and 6.5 W for sustained bit rates of 250 Mb/s and 500 Mb/s, respectively. The results for a sustainable data rate of 500 Mb/s can be found in Table 4-5. These numbers (for which power-save modes are not yet considered) are within the lower half of the respective figures of all NGOA solutions which were considered within the OASE project. Power consumption can be further reduced by implementing power-save modes. Here, the second-stage (access) WDM-PON is more relevant because each wavelength carries dedicated per-client traffic. All the power-save modes for WDM-PON can be applied, as discussed in Section 5.1.1. Power-save modes for the backhaul WDM-PON are less likely to be implemented efficiently because the backhaul part already carries (highly) aggregated traffic. It also has to be noted that the two-stage WDM-PON, unlike some other approaches considered within the project, clearly covers the backhaul part and a first aggregation layer, i.e., no further power consumption has to be added for access, backhaul and aggregation up to PCP7. This makes the two-stage WDM-PON a relatively power-efficient solution.

Table 4-5: Energy consumption in Two-stage WDM-PON

Architecture options	Different Variants	Sustainable datarate (first mile & feeder)	Client count (feeder)	*Total power consumption per client*	Power cons. at ONT	Power cons. per client at remote nodes	Power cons. per client at OLT
Two-stage WDM-PON	Ethernet PtP in WDM-PON	500 Mb/s	800 (M=40, N=20)	***6.5 W***	3.5 W	2.2 W	0.8 W
	DWDM-PON in WDM-PON	500 Mb/s	800 (M=40, N=20)	***6.5 W***	4.2W	1.5W	0.8 W

In order to identify the impact of node consolidation on the overall power consumption in the access network Figure 4-39 shows the two-stage WDM-PON power consumption per PCP layer of one dense urban and one urban service area for the node consolidation scenarios 2 and 3 as described in 1.1. Scenario 1 has not been considered because the two-stage WDM-PON is explicitly designed for node consolidation applications which allow a shutdown of the legacy local exchange location (PCP5). The two-stage WDM-PON can be understood as an optimization of WR-WDM-PON architecture, since most of the ONTs are served by a WR-WDM-PON OLT at the PCP6 location. In the case of reach limitation a remote node WR-WDM-PON OLT is located at the PCP 4.5 (Figure 4-38b).

The power consumption has been calculated for a guaranteed downstream data rate of 250 Mbit/s per ONT.

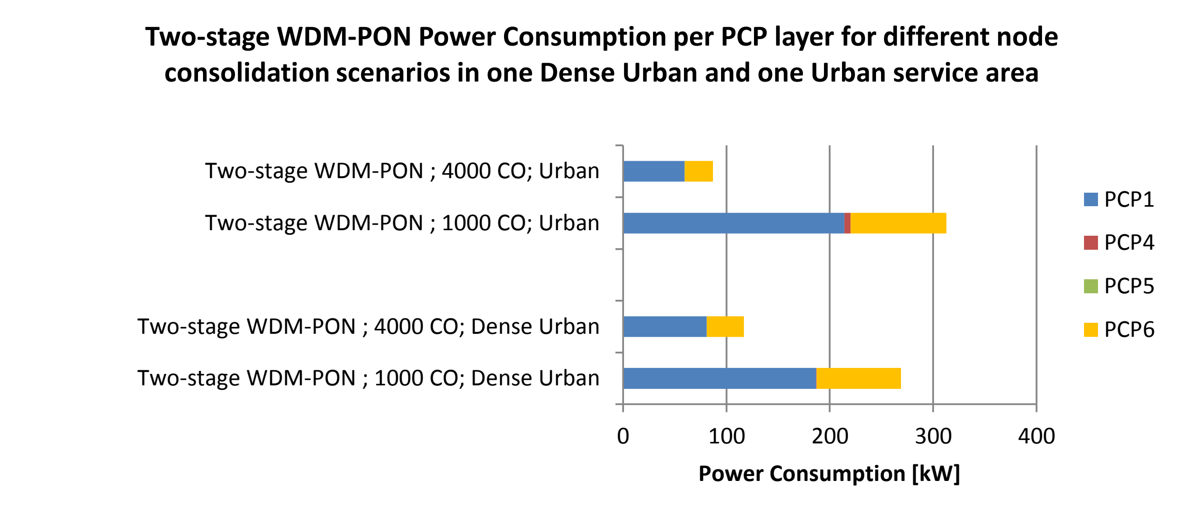


Figure 4-39: Two-stage WDM-PON power consumption per PCP layer in dense urban and urban

Figure 4-39 shows that the power consumption per service area increases with a higher level of node consolidation due to increasing number of users per consolidated service area. However, this does not mean that the total power consumption per architecture increases in the case of node consolidation. The power consumption per service area is clearly dominated by the ONT part at the PCP1 (user flat) in both scenarios, e.g. between 60 kW (scenario 2) to 214 kW (scenario 3) for one urban service area. In scenario 2 all ONTs can be served from the OLT at the PCP6. This means that there is no power consumption at PCP4. But in scenario 3 some ONTs are served by remote node OLTs at PCP4 that causes a power consumption of 0.5 kW (dense urban) and 6 kW (urban) per service area. It does not include the power consumption that would be caused by air-conditioning of the remote node in an outdoor cabinet. The PCP6 power consumption lies in the range of 27 kW to 93 kW for one urban service area.

Figure 4-40 shows the power consumption per line and PCP for different node consolidation scenarios and service area types. It shows that node consolidation brings no significant benefit regarding the power consumption.

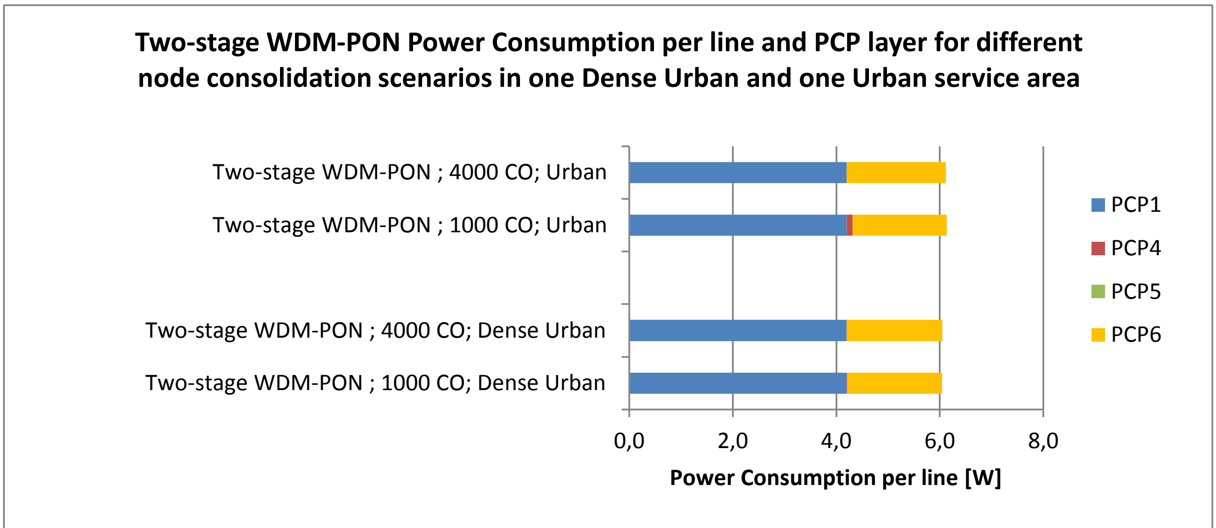


Figure 4-40: Two-stage WDM-PON power consumption per PCP layer in dense urban and urban

Similar to the hybrid WDM/TDM-PON architecture described in Section 5.2.1, the two-stage WDM-PON architecture offers particular flexibility in the application of energy-efficiency improvement techniques because of its two-stage approach featuring an active intermediate node. This means that traffic grooming techniques, i.e. statistical multiplexing, can be employed to increase the spectral efficiency (i.e. the line rate) of wavelength channels between PCP6 and PCP5, and so derive the economies of scale and enhanced energy efficiencies associated with higher data rates. In such a case, at the fundamental joule/bit level the energy dissipation of the two-stage WDM-PON can be reduced as compared to the single-stage WDM-PON architecture. In addition, as already described at length in the earlier Section 5.2.1, a hierarchical CDN approach can also be straightforwardly deployed at the active nodes PCP6 and PCP5, to reduce overall traffic volumes through the network, and hence reduce the overall power consumption requirements, thereby increasing the overall energy efficiency (i.e. reducing overall carbon footprint). Finally, the additional techniques already described in the pure WDM-PON context for increasing the energy-efficiency also remain valid for the two-stage WDM-PON architecture.

4.3.2 Resilience

Figure 4-41 shows the scheme with protection down to PCP5 for two-stage WDM-PON, which is recommended to be considered in the first place for operators. For this scheme, the OLT, FF, and part of remote node 1 (i.e. AWG and uplink line card at RN1) are protected.

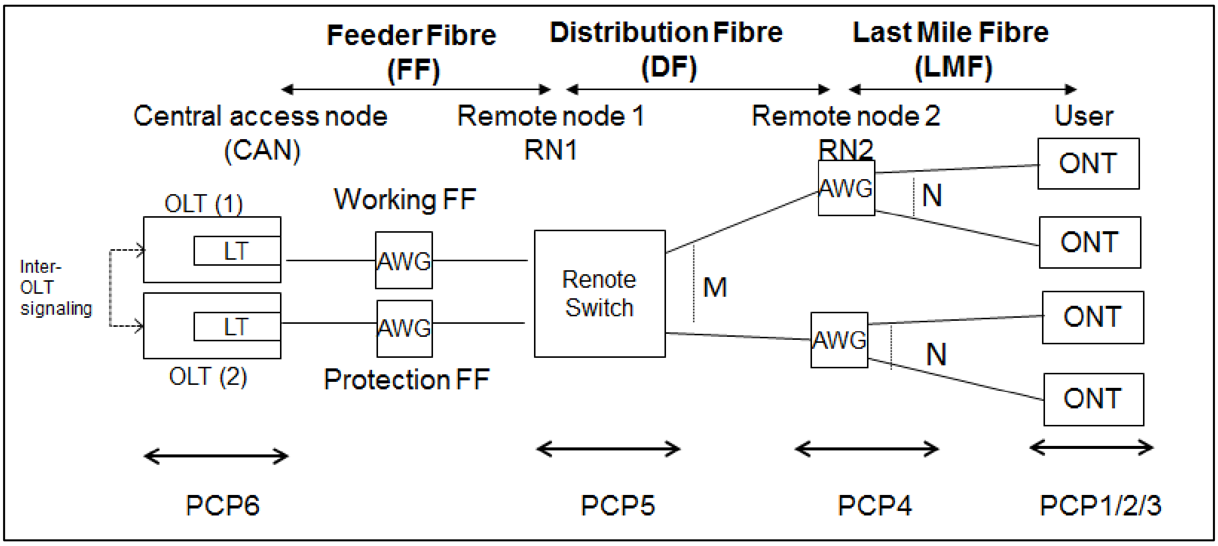


Figure 4-41: Scheme with protection of FF and OLT for Two-stage WDM-PON.

Figure 4-42 and Figure 4-43 show the connection availability and FOM values of the two-stage WDM-PON with and without the protection scheme presented in Figure 4-41. It can be clearly seen that with protection of feeder fiber and OLT, the resiliency performance is increased. However, as the active remote node has high unavailability and is not fully protected yet, the improvement on reliability by considering backup of FF and OLT is limited.

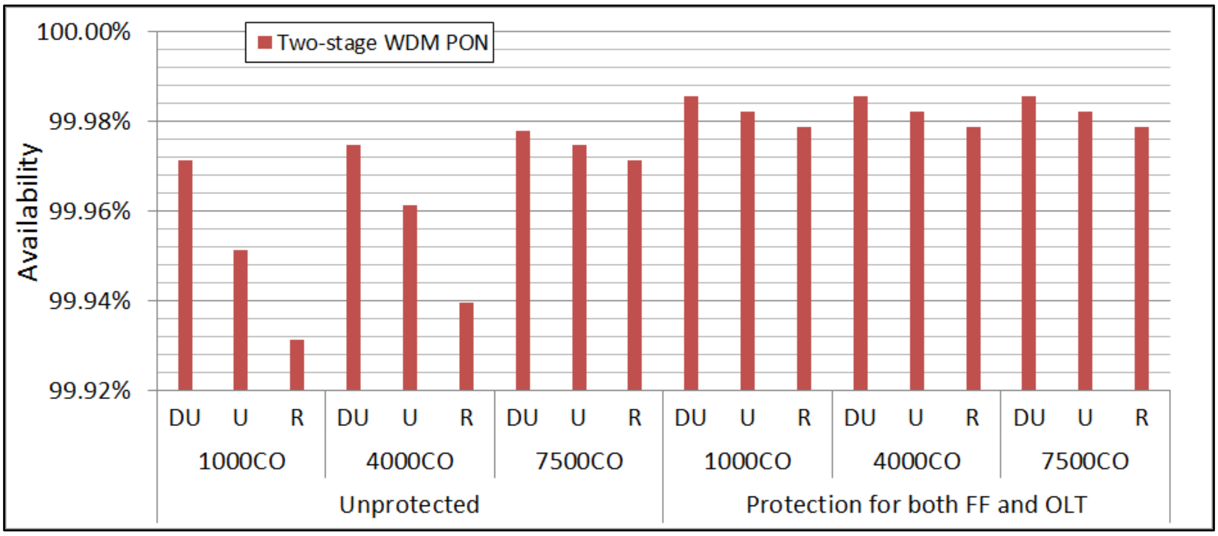


Figure 4-42: Connection availability of two-stage WDM-PON

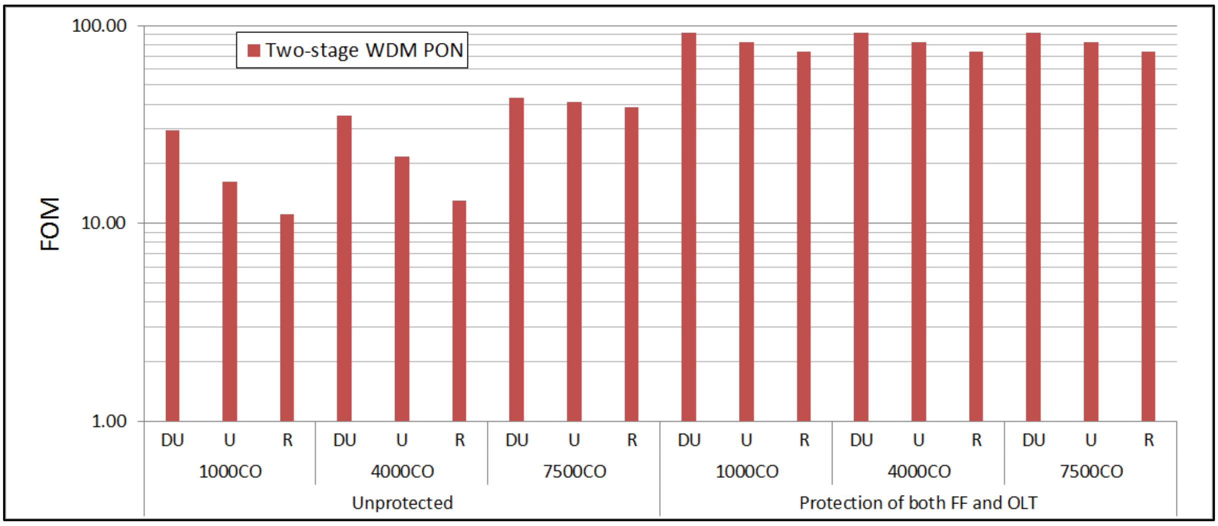


Figure 4-43: FOM of two-stage WDM-PON

To further improve the reliability of two-stage WDM-PON, a variety of resilience options can be considered, as indicated in Figure 4-44. Options include dual-parenting and protection, which consists of point-to-point and ring protection. Resilience can be provided, on demand, to the remote node 2 (PCP4), or to the client (PCP1/2/3). For protection (or dual-parenting) up to PCP4, path availability of 0.99989 can be always achieved regardless of node consolidation or population scenarios. This availability can be increased by approximately one order of magnitude by end-to-end protection. However, it should be noted that offering protection more towards to the end-users means that higher cost needs to be introduced. As distribution fibers and the remote node 2 are shared by a small number of end-users, the additional cost on a per-user based could therefore be significantly increased.

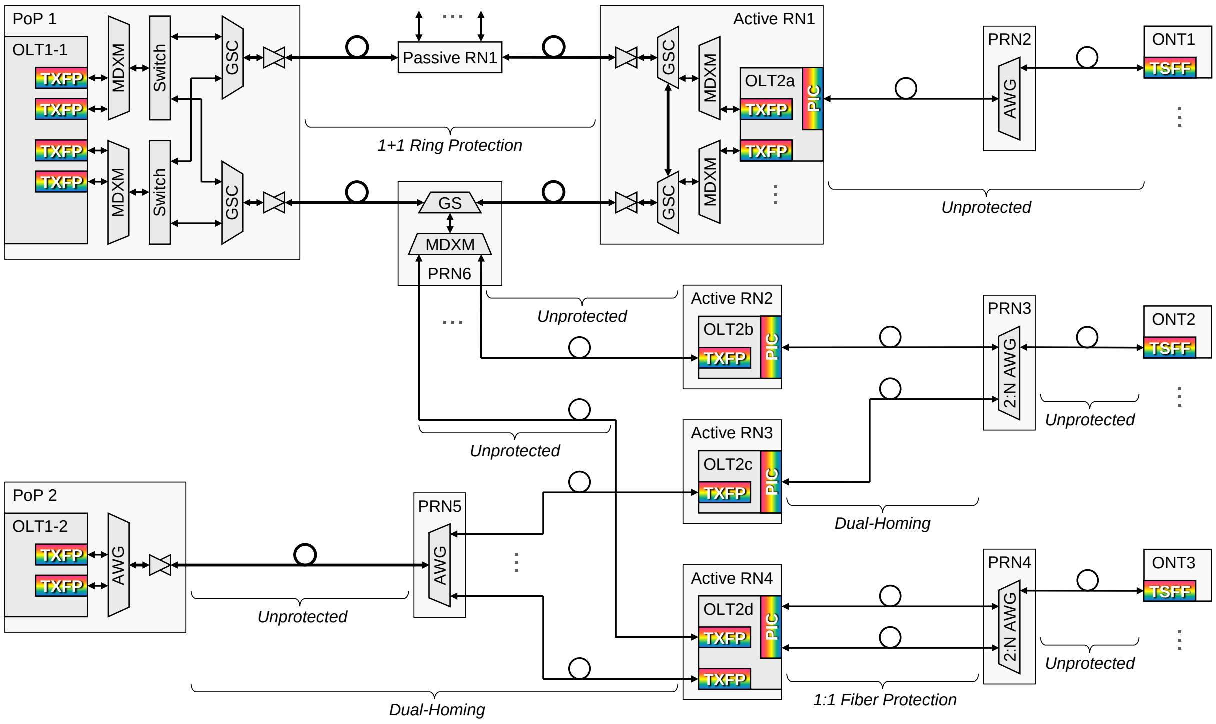


Figure 4-44: Two-stage WDM-PON resilience options.

4.3.3 *Operational complexity*

With regard to operational complexity, the two stages of two-stage WDM-PON should be considered separately. The backhaul part can support all OAM functions which were described for WDM-PON with tunable lasers in the OASE deliverable D4.3.1. In addition, the backhaul part can also be regarded a passive derivative of standard WDM backhaul systems. Again, the standardized OAM features of these systems apply. The access WDM-PON also supports standardized OAM and the related protocols.

Process automation is also inherently given for WDM-PON. All required configurations and management can be performed remotely via Layer-2. This can be automated via the respective management systems. Also, ONTs are self-installing (-tuning) and not wavelength-specific. Depending on the specifics of the ONT type, laser type and the tuning mechanism, installation may take several seconds.

Provisioning in hybrid active WDM-PON is relatively simple. Simplicity stems from the fact that the active remote node also performs regeneration, which eases network planning in particular for long-reach requirements.

Performance monitoring (PM), network supervision, and signaling are generally simpler or more feature-rich in a wavelength-routed WDM-PON than they are in a power-split approach. Hence, both WDM-PON stages can make use of all techniques mentioned in the OASE deliverable D4.3.1, including unambiguous OTDR measurements. In particular, the active remote node can be fully supervised in a similar way as in any WDM transport system. PM and signaling can be provided on a per-wavelength basis, using either in-band or out-band techniques, in WDM-PON (backhaul, access). In the OLT, this can be supported by fault correlation in order to identify failures of the feeder fiber (multiplex section) etc.

We have also evaluated the impact in terms of energy consumption and footprint, which are tightly related to the operational aspects, in combination with node consolidation.

OPERATOR RELATED ENERGY CONSUMPTION ASSESSMENT IN NODE CONSOLIDATION

Figure 4-45 shows the network operator related power consumption without the ONT part for two-stage WDM-PON in one urban and one dense urban service area. The results refer to the two-stage WDM-PON architecture illustrated in Figure 4-38b. As most of the ONTs can be served by WR-WDM-PON OLTs at the PCP6 location only a few active remote nodes are needed at PCP4/5 in scenario 3.

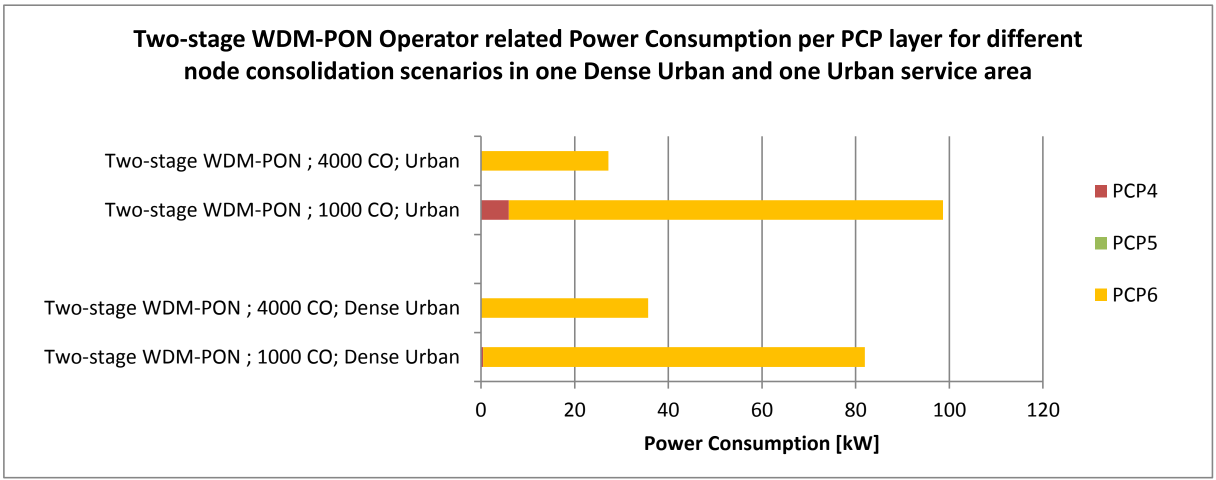


Figure 4-45: Network operator related power consumption for Two-stage WDM-PON

The network operator related power consumption lies in the range of 27 kW (scenario 2) to 99 kW (scenario 3) for one urban service area and 36 kW (scenario 2) to 82 kW (scenario 3) for one dense urban service area.

Figure 4-46 shows the network operator related power consumption per line and PCP for different node consolidation scenarios and service area types. It shows that node consolidation brings no significant benefit regarding the network operator related power consumption.

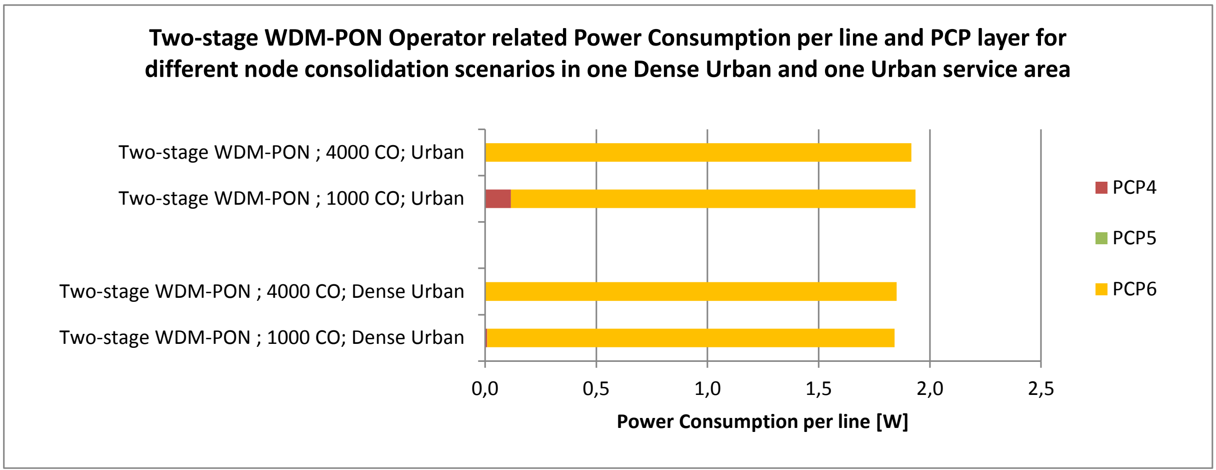


Figure 4-46: Network operator related power consumption for Two-stage WDM-PON

FOOTPRINT ASSESSMENT IN NODE CONSOLIDATION

Figure 4-47 shows the footprint per PCP layer of the two-stage WDM-PON architecture for the three node consolidation scenarios as described in Section 1.1. The footprint is shown for one dense urban (DU), one urban (U) and one rural (R) service area. This footprint calculation is based on the footprint model described in the OASE deliverable D4.3.1. The results refer to the two-stage WDM-PON architecture illustrated in Figure 4-38b.

The two-stage WDM-PON is characterized by remote node WR-WDM-PON OLTs located at the PCP 4/5 but the remote nodes are used only in the case of reach limitation. In scenario 2 all ONTs can be served by the WR-WDM-PON OLTs at the PCP6 location because the maximum distance is in the limit of the WR-WDM-PON system so that remote nodes are not required. Remote nodes are needed in scenario 3 but most of the ONTs can also be served by the OLTs at the PCP6 location.

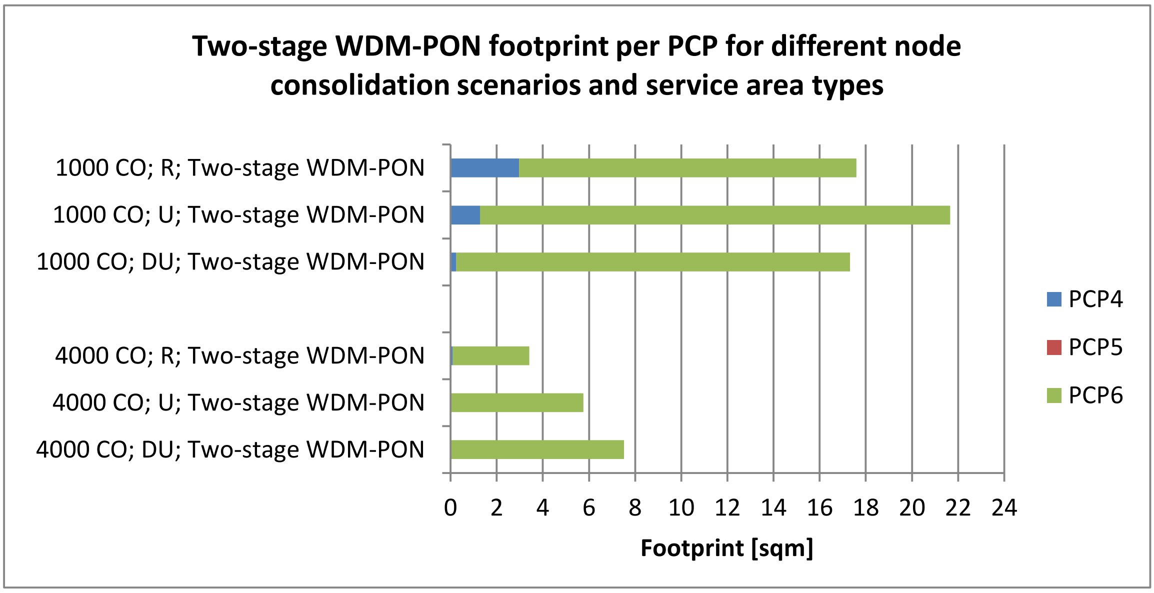


Figure 4-47: Two-stage WDM-PON footprint per PCP layer in dense urban

Figure 4-47 shows that the footprint per service area increases with a higher level of node consolidation due to increasing number of users per consolidated service area. However, this does not mean that the total footprint per architecture increases in the case of node consolidation.

The footprint of the active remote node equipment at PCP4/5 has been taken into account but the footprint of ODF and AWG components at PCP4 was not considered because it was assumed that such equipment can be housed by closures in the field.

In scenario 2 a footprint of 17.1 m^2 at PCP6 and 0.25 m^2 at PCP4 is required for one dense urban service area. One urban service area requires a footprint of 20.4 m^2 at PCP6 and 1.3 m^2 at PCP4 whereas a footprint of 14.6 m^2 at PCP6 and 3.0 m^2 at PCP4/5 is needed for one rural service area.

Figure 4-48 shows the footprint per line for different node consolidation scenarios and service area types. The footprint per line increases with higher level of node consolidation in particular in urban and rural service areas, which is mainly caused by the remote node equipment at PCP4.

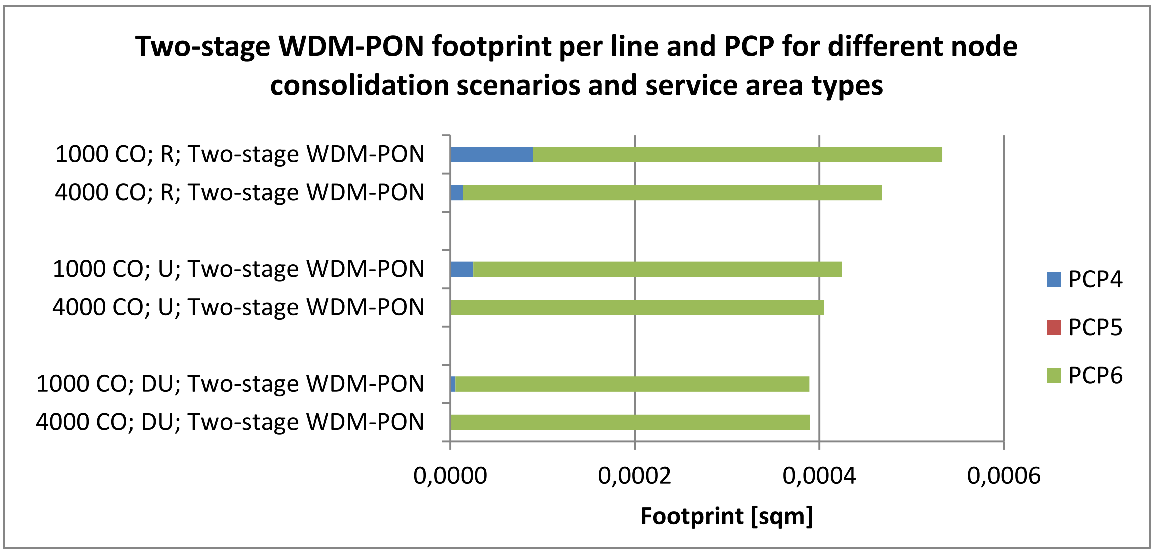


Figure 4-48: Two-stage WDM-PON footprint per PCP layer in dense urban

FAILURE RATE IN NODE CONSOLIDATION

The two-stage WDM-PON failure rate analysis is based on the MTBF values shown in Table 4-6.

Table 4-6: MTBF values for Two-stage WDM-PON

Components	MTBF (hour)	MTBF (year)
Two-stage WDM-PON system technology		
ONT	257.143	29,35
Shelf / Backplane	1.500.000	171,23
Baseline card (Switch/Router, CPU, Control and Management Plane) (~500G)	420.000	47,95
Power Supply (redundant)	500.000	57,08
OLT Downlink line card DWDM-PON port card 80 channels (incl diplexer) (not incl pluggable)	750.000	85,62
OLT Passive shelf incl 2xAWG (40:1)	1.000.000	114,16
OLT Pluggable 80x 1G Laser/Rx Array (C-band) - for 80 ch	300.000	34,25
OLT 10G TRX (colored)	500.000	57,08
OLT 8x10G port card	57.971	6,62
RNPluggable 80x 1G Laser/Rx Array (C-band) - for 80 ch	300.000	34,25
RN shelf	705.882	80,58
RN 10G TRX (colored)	500.000	57,08
RN2 2x40 channels (2x40:1 AWG)	4.000.000	456,62
RN AWG 80 channels + Diplexer+Interleaver	4.000.000	456,62
Link Level		
Feeder Fiber 192 fibers	1.350.000	154,11
Feeder Fiber 1000 fibers	1.000.000	114,16
Main Cable	1.400.000	159,82
Distribution Cable	1.500.000	171,23
Inhouse Cable	525.000	59,93

Figure 4-49 shows the annual failure rate per PCP and LL for two-stage WDM-PON. The results refer to the two-stage WDM-PON architecture illustrated in Figure 4-38b. The failure rates are shown for the node consolidation scenarios 1, 2 and 3 in one dense urban, one urban and one rural service area. The result shows that the annual failure rate is clearly dominated by failures at PCP1 (ONT failures at user site).

The annual failure rate per service area increases with a higher level of node consolidation due to increasing number of users per consolidated service area. However, this does not mean that the failure rate per architecture increases in case of node consolidation.

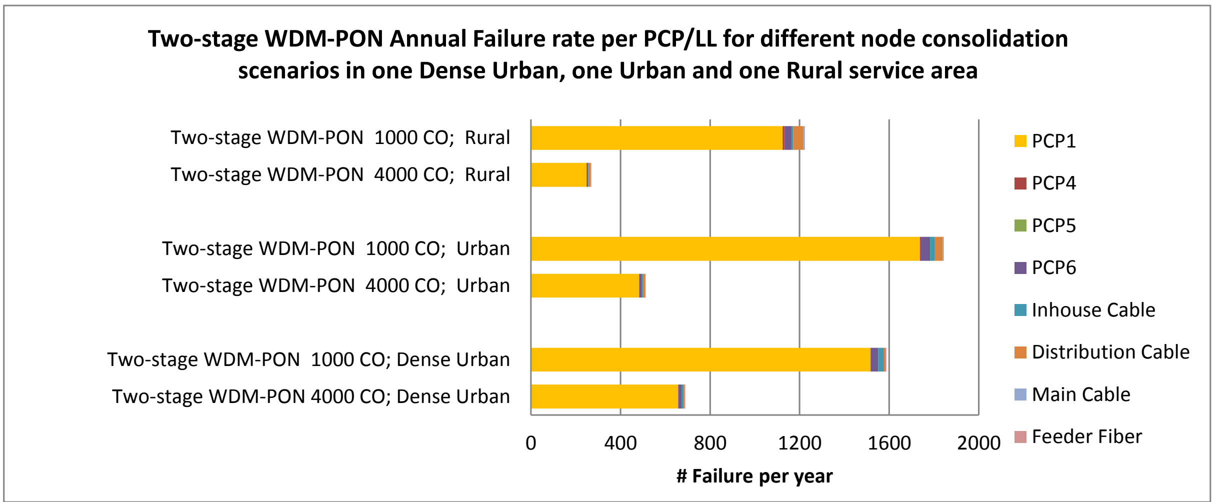


Figure 4-49: Annual failure rate per PCP and LL for two-stage WDM-PON

Figure 4-50 shows the annual failure rate per PCP/LL for two-stage WDM-PON without the PCP1 part. Apart from ONT failures at PCP1, most of the failures are caused by the OLT equipment at PCP6 in dense urban and urban service areas whereas in rural service areas the failure rate of the distribution cable is higher than the number of PCP6 failures.

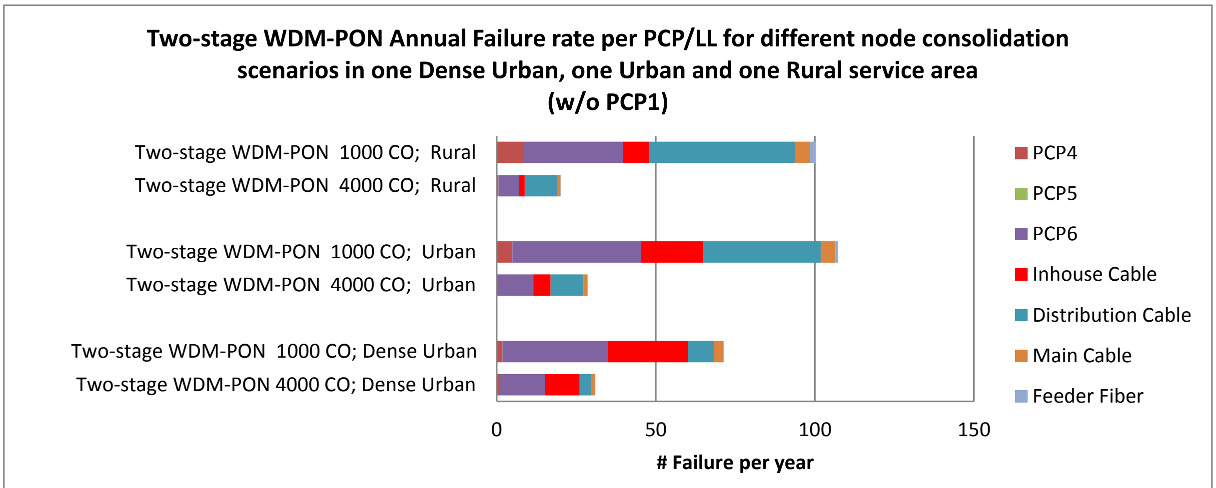


Figure 4-50: Annual failure rate per PCP/LL for two-stage WDM-PON w/o PCP1 part

Figure 4-49 and Figure 4-50 show that the annual failure rate per service area increases with a higher level of node consolidation due to increasing number of users per consolidated service area. However, this does not mean that the failure rate <u>per line</u> increases in a similar way. Figure 4-51 shows the annual failure rate per line that illustrates the impact of node consolidation on the failure rate. It shows a small increase of the failure rate in node consolidation scenario 3 (1000 CAN locations) that is mainly caused by the active remote node equipment at PCP4. In general, the impact of node consolidation (scenarios 2 & 3) on the failure rate is negligible for two-stage WDM-PON.

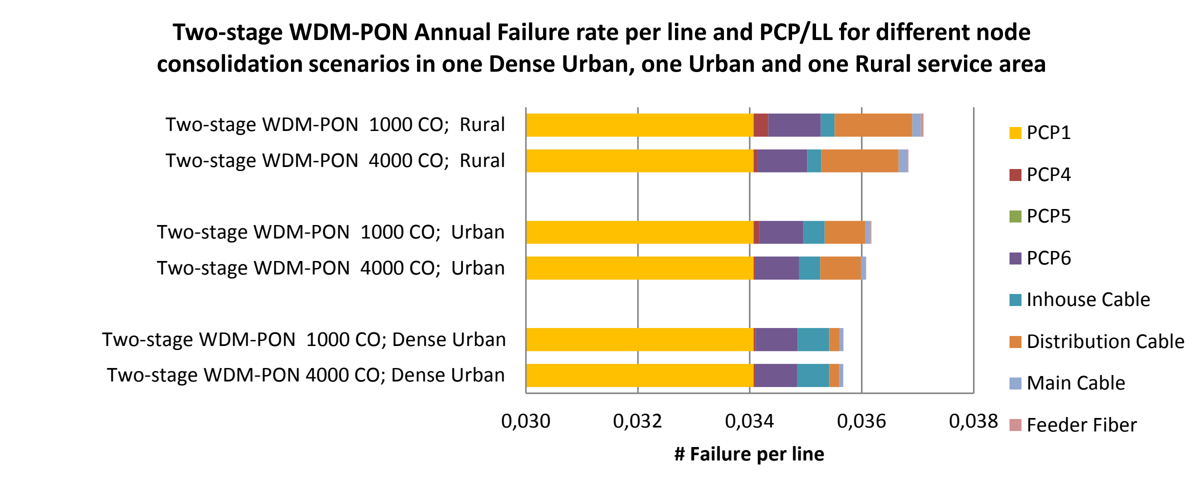


Figure 4-51: Annual failure rate per line and PCP/LL for Two-stage WDM-PON

IMPACT OF NODE CONSOLIDATION ON TRAVEL EFFORT

The travel effort analysis is based on the annual failure rate and the travel distance model described in Section 3.3.4. It is assumed that travel effort is not needed for ONT failures at PCP1. In the case of an ONT failure the user gets a new ONT device which is installed by the user (plug-and-play).

Figure 4-52 shows the annual travel time per line for two-stage WDM-PON. The annual travel times are shown for the node consolidation scenarios 1, 2 and 3 in dense urban, urban and rural service areas. The annual travel times are proportional to the annual failure rates. Most of the travel effort is caused by the distribution cable in urban and rural service areas and by the in-house cable in dense urban service areas.

The small increase of the travel time per line in node consolidation scenario 3 (1000 CAN locations) compared to scenario 2 (4000 CAN locations) is mainly caused by the active remote node equipment at PCP4. However, the results show that the impact of node consolidation on travel effort is small due to the relatively low number of failures per day and PCP/LL. As shown in Figure 4-50 there is not more than one failure per day and PCP/LL assuming a uniform distribution of failure events over time. This means that there is only a low probability to save travel time by fixing multiple failures with one travel activity.

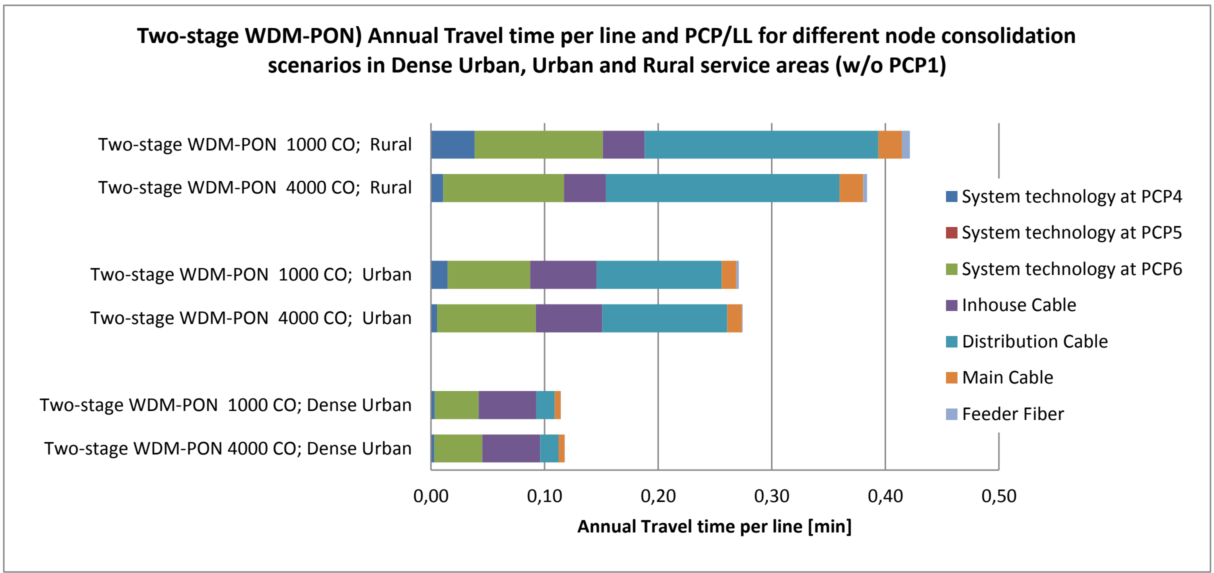


Figure 4-52: Annual travel time per line and PCP/LL for Two-stage WDM-PON

4.3.4 Control and management

Two-stage WDM-PON, like all NGOA, provides the means for end-to-end control, supervision, and management. Advantages over other NGOA solutions result from the full integration of access, first aggregation layer, and backhaul into one system covering PCPs 1-7. Also, in a wavelength-routed access WDM-PON, unambiguous OTDR measurements can be performed, as has already been discussed.

Control, supervision and management heavily depend on the available physical implementations of the Data Communications Network (DCN, i.e., the abstract network which carries management information and commands). The access WDM-PON will most likely make use of per-wavelength in-band DCN channels (because of cost restrictions). The backhaul WDM-PON can make use of any DCN implementation, ranging from in-band via out-band (i.e., OSC-like) to dedicated payload channels (e.g., management VLANs or even TDM slots of one of the wavelengths). Large active RNs may even be connected via dedicated external DCN. Hence, DCN connectivity in a two-stage WDM-PON can always be guaranteed.

The C&M of the second stage OLT (OLT-2) can in general use the same functions and methods as the WDM-PON OLT, with the potential addition of functionality for interacting with the first stage.

4.4 NG-AON

The next generation active optical network (NG-AON), presented in Section 2.2.4, contains active switch elements in the access network, with point-to-point links to the customers. The next-generation architecture includes more advanced C&M functions and multi-layer switching capabilities in the nodes, to increase the bandwidths, reduce operational costs and enable a more dynamic network. The two variations of AON, active-star and home-run (point-to-point), are similar in most aspects, with the main difference being the position of the first active switch element.

4.4.1 Power consumption

Table 4-7 shows energy consumption figures for two-stage WDM-PON and NG-AON architectures presented in sections 2.2.3 and 2.2.4. Cooling system and aggregation are not included.

Table 4-7: Energy Consumption in NG-AON

Architecture options	Different Variants	Sustainable datarate (first mile & feeder)	Client count (feeder)	*Total power consumption per client*	Power cons. at ONT	Power cons. per client at remote nodes	Power cons. per client at OLT
NG-AON	Point-to-Point (home run)	500 Mb/s	1	***5.4/5.7 W***	3.5 W	0 W	1.9/2.2 W
	Active star	500 Mb/s	80 (M=80)	***6.5 W***	3.5 W	2.2W	0.8W

In order to identify the impact of node consolidation on the overall power consumption in the access network Figure 4-53 shows the NG-AON power consumption per PCP layer of one dense urban and one urban service area for the three node consolidation scenarios described in Section 1.1.

In scenario 1 the Ethernet switches are located at the PCP5 node, whereas the scenarios 2 and 3 are explicitly designed for node consolidation applications which allow a shutdown of the legacy local exchange location (PCP5). In the scenarios 2 and 3 Ethernet remote nodes are used at the PCP4 location in addition to the Ethernet switches at the PCP6 location that serves the ONTs in the immediate vicinity.

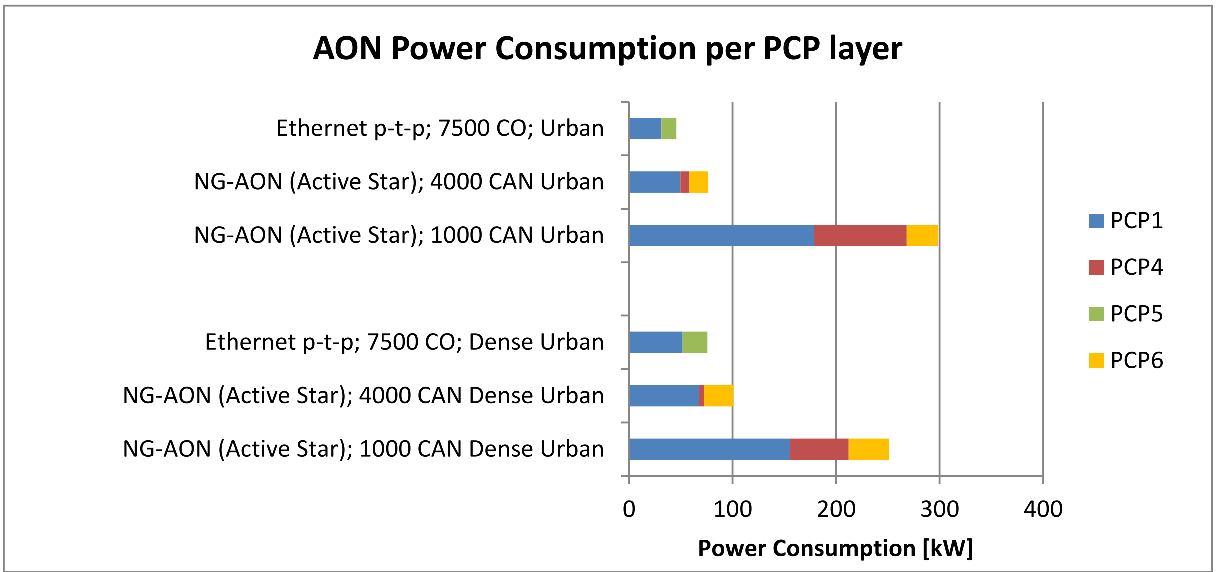


Figure 4-53: AON power consumption per PCP layer for urban and dense urban

The power consumption has been calculated for a guaranteed downstream data rate of 300 Mbit/s per ONT.

Figure 4-53 shows that the power consumption per service area increases with a higher level of node consolidation due to increasing number of users per consolidated service area and the higher power consumption of the remote nodes at PCP4.

The power consumption per service area is clearly dominated by the ONT part at the PCP1 (user flat) in both scenarios, e.g. between 31 kW (scenario 1) to 178 kW (scenario 3) for one urban service area. The remote node has a higher power consumption per port than a large

Ethernet switch at the PCP6 location, so that the high number of remote nodes in scenario 3 causes a power consumption of 56 kW (dense urban) and 90 kW (urban) at the PCP4 layer. It does not include the power consumption that would be caused by air-conditioning of a remote node in an outdoor cabinet. The PCP6 power consumption lies in the range of 29 kW (scenario 2) to 39 kW (scenario 3) for one dense urban service area and 18 kW (scenario 2) to 30 kW (scenario 3) for one urban service area.

Figure 4-54 shows the average power consumption per line and PCP for different node consolidation scenarios and service area types. The power consumption per line increases for scenarios with a higher level of node consolidation, which is mainly caused by the remote node equipment in the field.

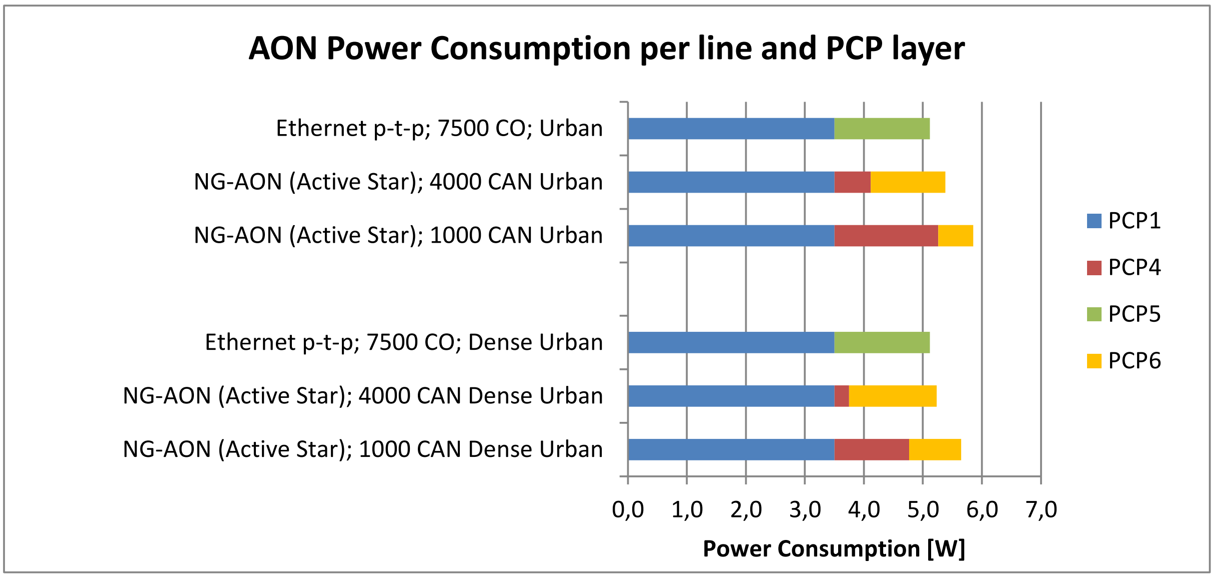


Figure 4-54: AON Power Consumption per line and PCP layer for Urban and Dense Urban

The overall power consumption of the AON architecture is already close to the lowest of the four OASE architectures, and a good explanation for this is that the AON approach already adopts some of the key techniques already advocated in the sections above to increase the energy efficiency of the hybrid WDM/TDM-PON and two-stage WDM-PON architectures. In particular, this is because the AON architecture employs an active intermediate node at the PCP5 (node consolidation scenario 1); in this case there is an intermediate Ethernet switch. This offers important traffic grooming and statistical-multiplexing functionalities, so that there are higher aggregated data-rates towards the CAN at PCP6 with the associated energy-efficiency savings associated with the higher bit-rates per wavelength. Although not discussed in detail at this stage of the project, the active intermediate node also allows the possibility of deploying a hierarchical CDN network, to further reduce the overall volume of traffic passing up and down the network, and hence reduce overall power consumption and improve the joule/bit energy efficiency metric.

4.4.2 Resilience

Resilience using protection paths could be created in several ways for AON. Two general schemes are presented here: either protection fibers from the first active node to a node in the central access node, or a protection fiber between two active nodes in the access network.

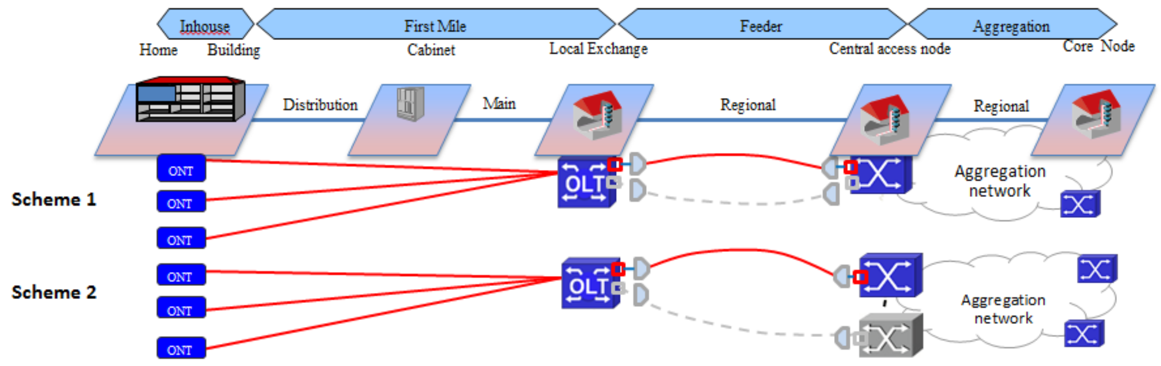


Figure 4-55: Protection schemes one and two, both based on extra fibers from the first active node to a node in a higher aggregation level.

The first two specific scenarios presented here are based on protecting fibers from the first active node to a node in the higher aggregation level. In scheme 1 we add an additional fiber from the OLT to the switch in the central access node and thereby provide protection against fiber breaks on the primary fiber. This scheme does not provide protection against faults in the central access node as both fibers terminate on the same node. Therefore another variation of the scheme can be created, seen as Scheme 2 in Figure 4-55, where the protection fiber connects to a different node in the central access node. This has the advantages to providing node protection as well as fiber protection. Therefore, Scheme 2 could further improve resiliency compared to Scheme 1.

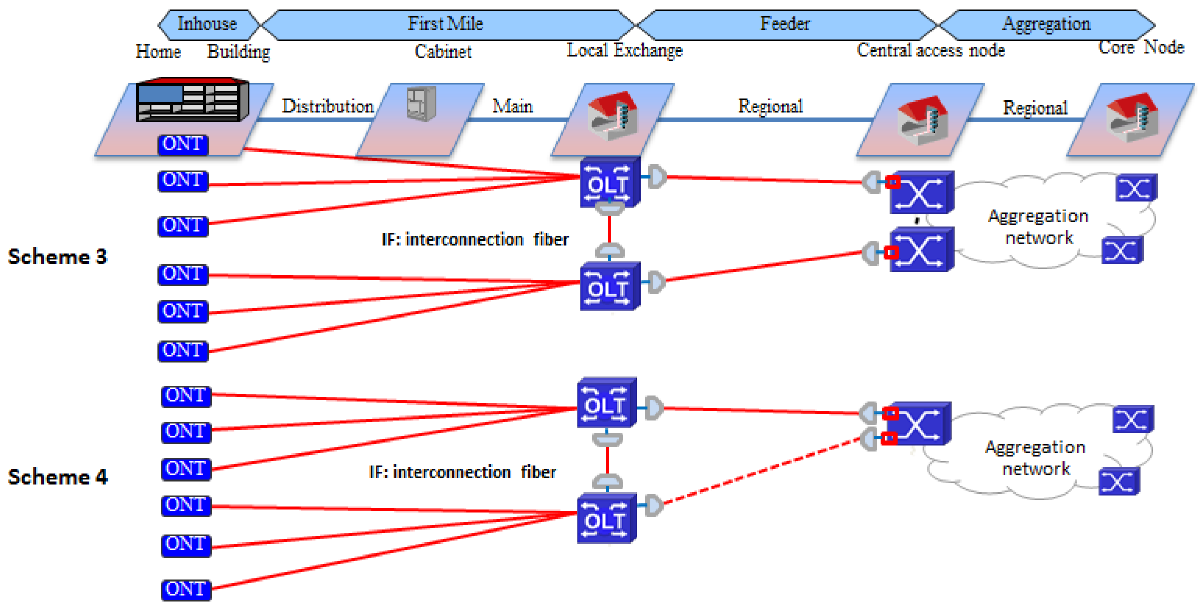


Figure 4-56: Schemes three and four of AON protection schemes, using interconnection between OLT nodes.

Schemes three and four, are presented in Figure 4-56, where two OLTs are connected via an extra fiber. In those two schemes the OLT is connected to different central access nodes (Scheme 3) or to the same node (Scheme 4). This means that if the fiber between the OLT and central access node breaks we simple reroute the traffic to the other OLT, whose feeder fiber is still operational. Besides, Schemes 3 and 4 also protects from faults in the central access node as the traffic can be routed via the other OLT and then to a different central access node. Compared with Scheme 1 and 2, these two schemes may have relatively low reliability, as their protection path needs to pass an extra OLT.

Figure 4-57 and Figure 4-58 show the connection availability and FOM values of NG-AON without and with the protection up to PCP5. Here, Scheme 2 is considered, which could show the highest reliability that protection up to PCP5 in NG-AON can reach. It can be clearly seen that with protection, the resiliency performance is increased. However, as the active remote node at PCP5 has high unavailability and not fully protected yet, the improvement on reliability by considering backup of FF and central access node is limited.

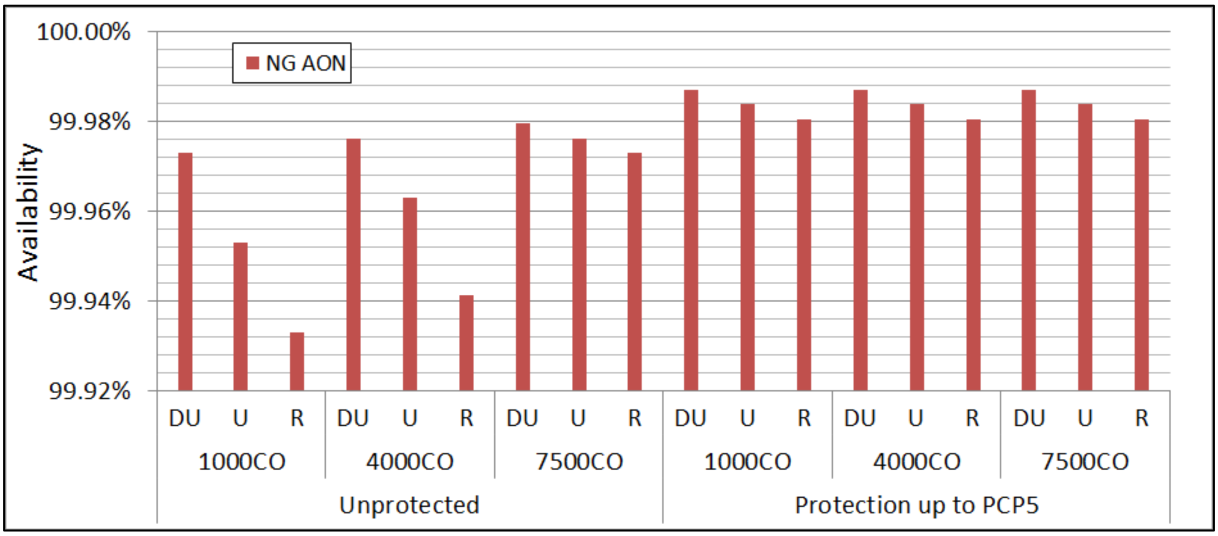


Figure 4-57: Connection availability of NG-AON

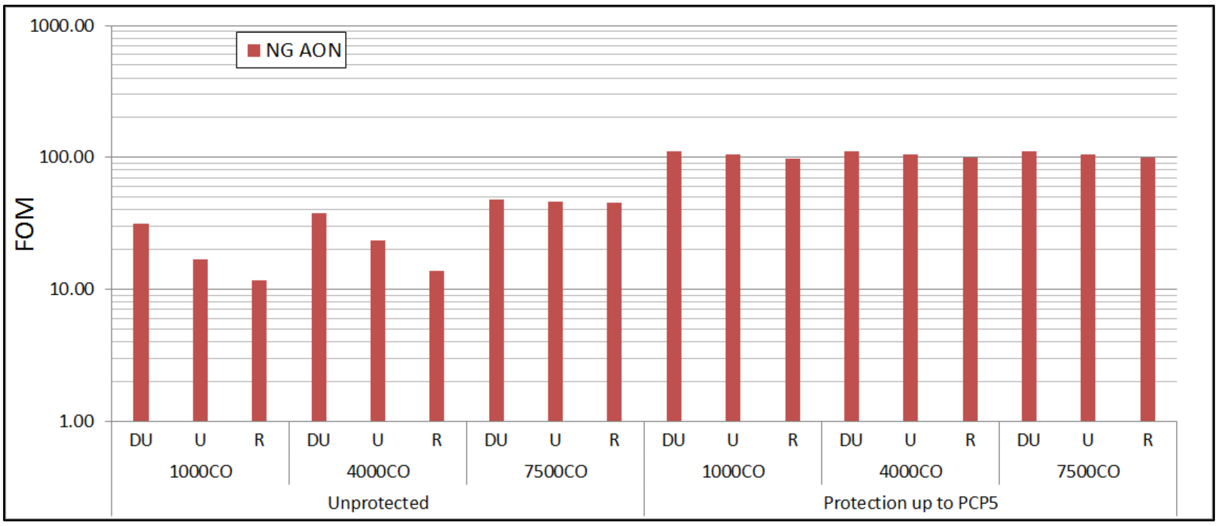


Figure 4-58: FOM of NG-AON

4.4.3 Operational complexity

We evaluated the operational impact in terms of energy consumption and footprint in combination with the three node consolidation scenarios defined in Section 1.1.

OPERATOR RELATED ENERGY CONSUMPTION ASSESSMENT IN NODE CONSOLIDATION

Figure 4-59 shows the network operator related power consumption without the ONT part for AON in one urban and one dense urban service area.

In the case of node consolidation the network operator related power consumption lies in the range of 26 kW (scenario 2) to 120 kW (scenario 3) for one urban service area and 33 kW (scenario 2) to 96 kW (scenario 3) for one dense urban service area.

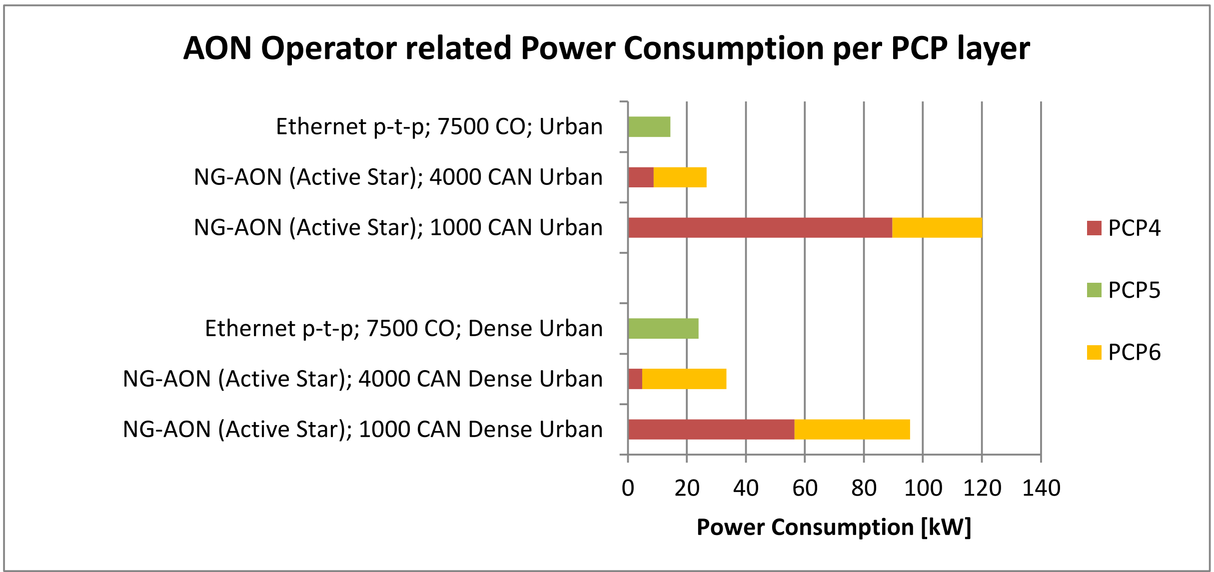


Figure 4-59: Network operator related power consumption for AON.

Figure 4-60 shows the average operator related power consumption per line and PCP for different node consolidation scenarios and service area types. The operator related power consumption per line increases for scenarios with higher level of node consolidation, which is mainly caused by the remote node equipment in the field. In scenario 3 the operator related power consumption per line is between 32% (dense urban) and 45% (urban) higher compared to scenario 1.

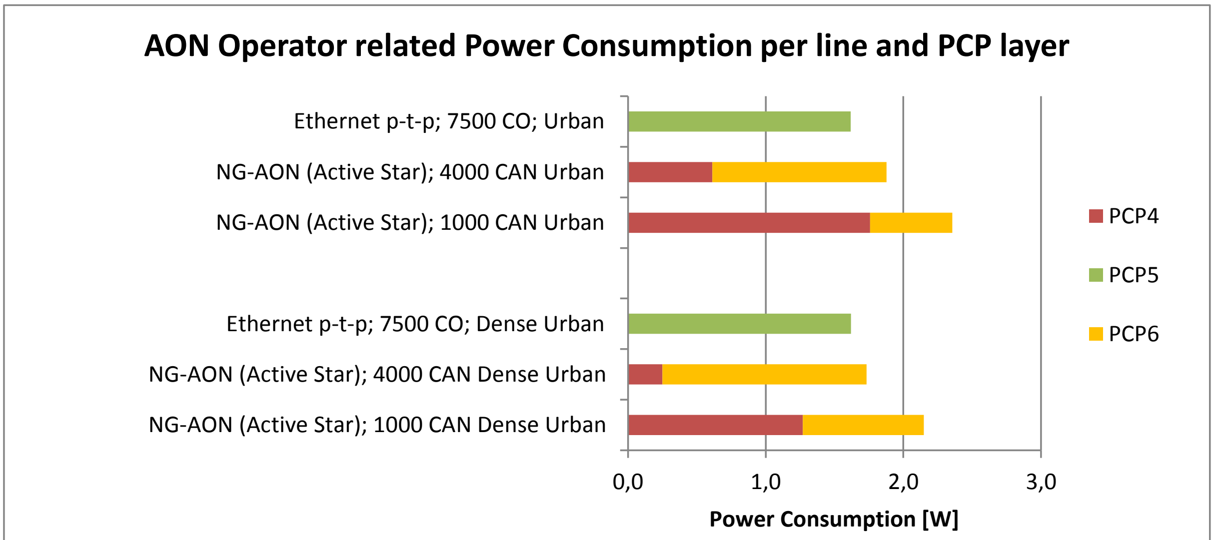


Figure 4-60: Network operator related power consumption for AON.

FOOTPRINT ASSESSMENT IN NODE CONSOLIDATION

The active remote Ethernet architecture is characterized by remote node Ethernet switches located at the PCP4 (outdoor cabinet). Figure 4-61 shows the model of an outdoor cabinet that is able to host the remote node Ethernet switches including the ODF equipment that is needed for fiber termination and fiber patching. This outdoor cabinet terminates up to 350 fibers using 7 splicing boxes. It can be populated with up to 12 remote node Ethernet switches with 33 Gigabit Ethernet ports each. . The remote node switch provides two 10 Gigabit Ethernet uplink ports. All uplink ports of one outdoor cabinet are aggregated via passive WDM technology that is located within the AWG box). The cabinet has the outside measurements of 2 m x 1.6 m x 0.5 m and a footprint of 1.0 m^2. The AON footprint calculation is based on the footprint model described in the OASE deliverable D4.3.1 extended by the outdoor cabinet model defined in this section.

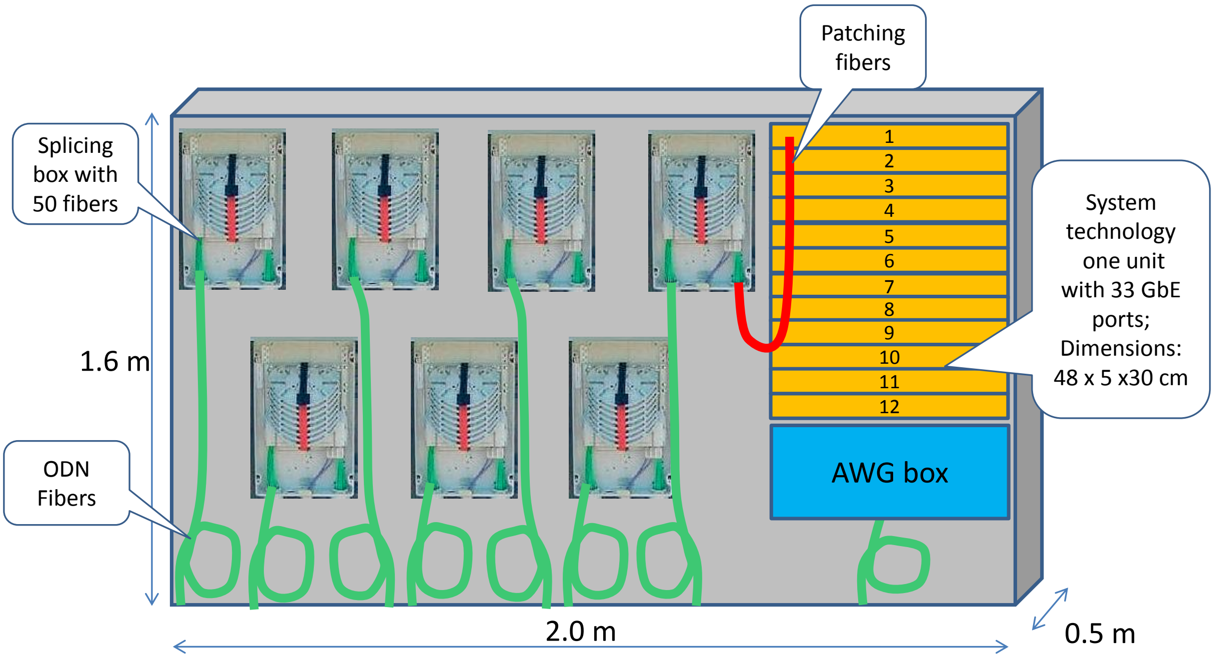


Figure 4-61: Outdoor cabinet model of the AON active star architecture.

Figure 4-62 shows the footprint per PCP layer of the AON architecture for the three node consolidation scenarios as described in Section 1.1. The footprint is shown for one dense urban (DU), one urban (U) and one rural (R) service area. In contrast to the scenarios 2 and 3, the scenario 1 is based on a simple PtP Ethernet approach without remote node Ethernet switches at PCP4. This means that all ONTs are served by Ethernet switches at PCP5. Figure 4-62 shows that the footprint per service area increases with a higher level of node consolidation due to increasing number of users per consolidated service area.

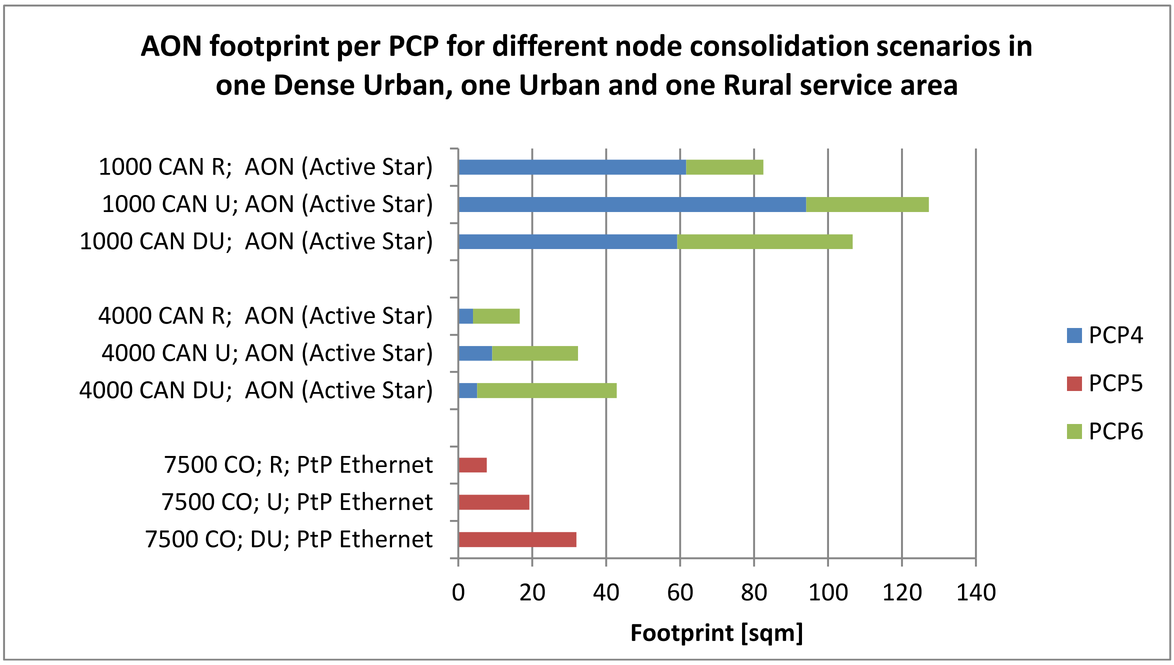


Figure 4-62: AON footprint per PCP layer for different node consolidation scenarios and service area types

The portion of the PCP4 footprint increases for scenario 3 due to the higher share of lines that are served by remote node Ethernet switches. Scenario 2 requires a footprint of 23.2 m^2 at PCP6 and 9.2 m^2 at PCP4 in one urban service area whereas scenario 3 occupies a footprint of 33.2 m^2 at PCP6 and 94.2 m^2 at PCP4 in the same service area type. Scenario 1 requires a footprint at PCP5 of 31.9 m^2 for one dense urban service area, 19.2 m^2 for one urban service area and 7.7 m^2 for one rural service area.

Figure 4-63 shows the AON footprint per line for different node consolidation scenarios and service area types. The footprint per line increases with the evolution from a simple PtP Ethernet architecture (7500 CO locations) to an active star approach.

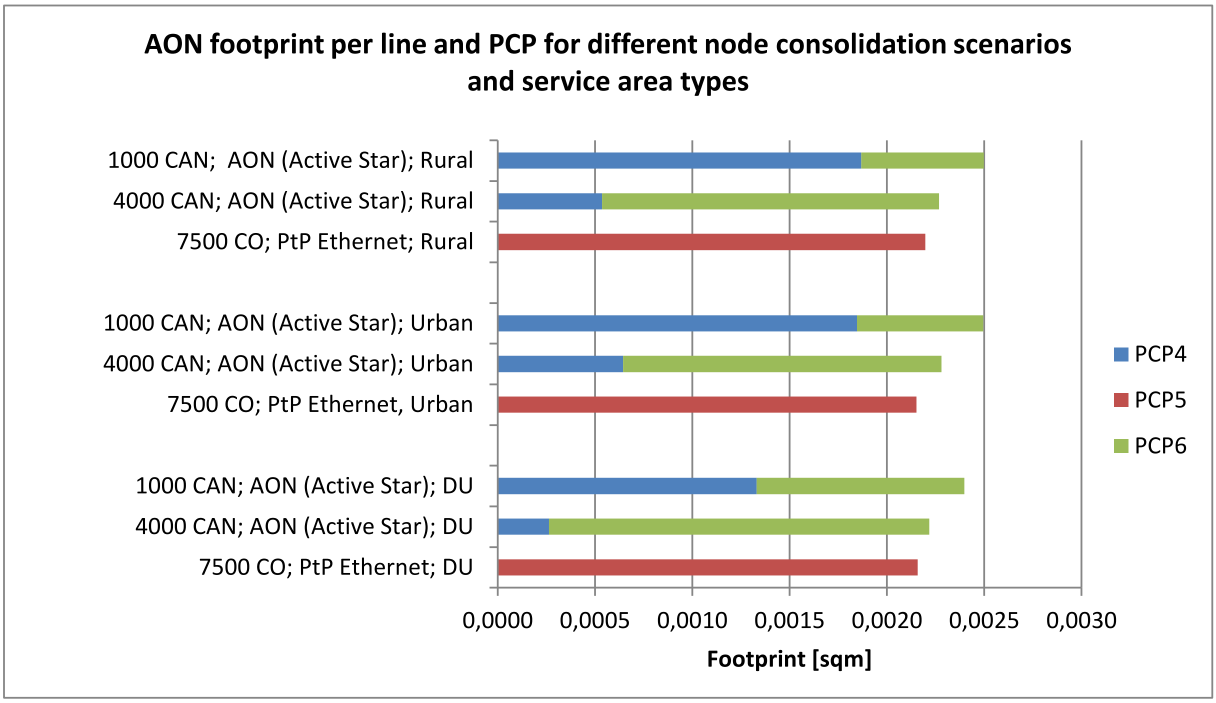


Figure 4-63: AON footprint per line

FAILURE RATE IN NODE CONSOLIDATION

The AON failure rate analysis is based on the MTBF values shown in Table 4-8.

Table 4-8: MTBF values for AON

Components	MTBF (hour)	MTBF (year)
AON system technology		
ONT	310.345	35,43
Shelf / Backplane	1.500.000	171,23
Baseline card (Switch/Router, CPU, Control and Management Plane) (~500G)	430.000	49,09
Power Supply (redundant)	500.000	57,08
OLT Passive shelf incl 2xAWG (40:1)	1.000.000	114,16
OLT 10G TRX (colored)	500.000	57,08
OLT 8x10G port card	57.971	6,62
OLT compact SFP	3.000.000	342,47
OLT Ethernet p-t-p port card	800.000	91,32
RN SFP	6.000.000	684,93
RN shelf	705.882	80,58
RN 10G TRX (colored)	500.000	57,08
RN2 2x40 channels (2x40:1 AWG)	4.000.000	456,62
Link Level		
Feeder Fiber 192 fibers	1.350.000	154,11
Feeder Fiber 1000 fibers	1.000.000	114,16
Main Cable	1.400.000	159,82
Distribution Cable	1.500.000	171,23
Inhouse Cable	525.000	59,93

Figure 4-64 shows the annual failure rate per PCP and LL for AON. The failure rates are shown for the node consolidation scenarios 1, 2 and 3 in one dense urban, one urban and one rural service area. The results show that the annual failure rate is clearly dominated by failures at PCP1 (ONT failures at the end-user site).

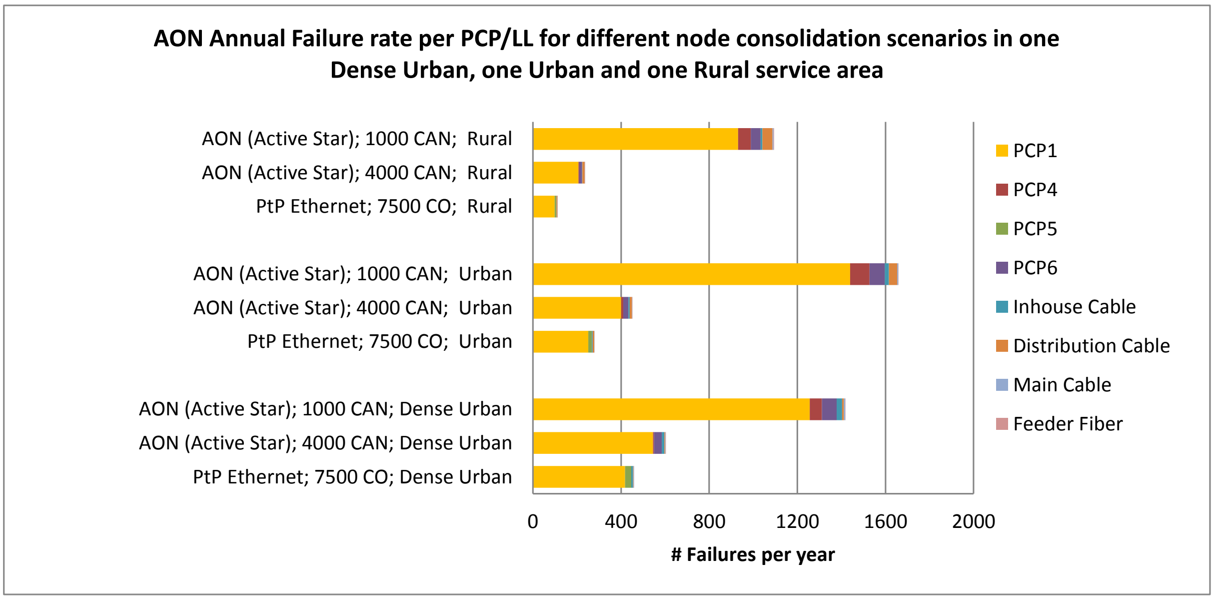


Figure 4-64: Annual failure rate per PCP and LL for AON

Figure 4-65 shows the annual failure rate per PCP/LL for AON without the PCP1 part. Apart from ONT failures at PCP1, most of the failures are caused by the active equipment at PCP4 (Outdoor Cabinet), PCP5 and PCP6 followed by the distribution cable in urban and rural service areas and the in-house cable in dense urban service areas, respectively.

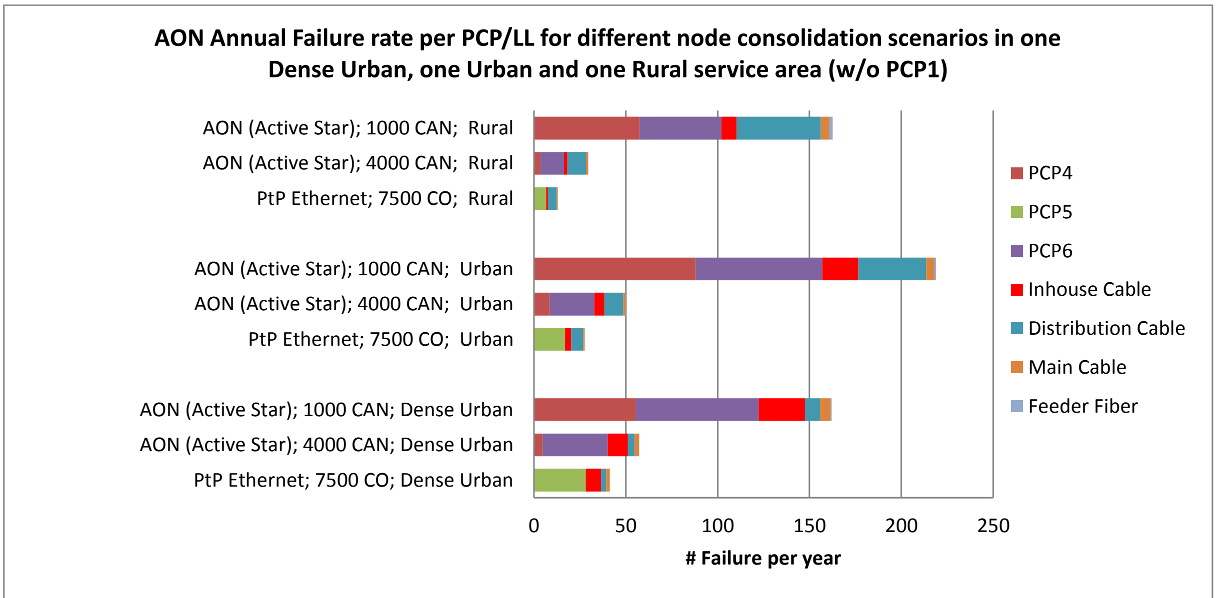


Figure 4-65: Annual failure rate per PCP/LL for AON (without PCP1)

Figure 4-64 and Figure 4-65 show that the annual failure rate per service area increases with a higher level of node consolidation due to the increasing number of users per consolidated service area. However, this does not mean that the failure rate <u>per line</u> increases in a similar way.

Figure 4-66 shows the annual failure rate per line that illustrates the impact of node consolidation on the failure rate. It shows a small increase of the failure rate with a higher level of node consolidation that is mainly caused by the active remote node equipment at PCP4. In general, the impact of node consolidation (scenarios 2 & 3) on the failure rate is negligible for AON.

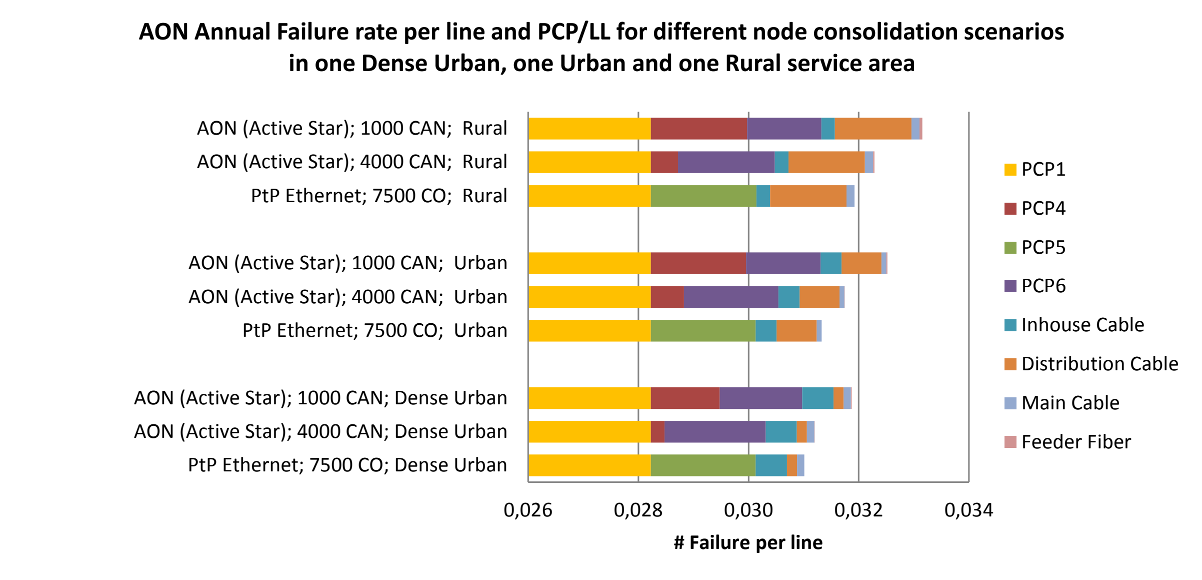


Figure 4-66: Annual failure rate per line and PCP /LL for AON

IMPACT OF NODE CONSOLIDATION ON TRAVEL EFFORT

The travel time analysis is based on the annual failure rate and the travel distance model described in Section 3.3.4. It is assumed that travel effort is not needed for ONT failures at PCP1. In the case of an ONT failure the user gets a new ONT device which is installed by the user (plug-and-play).

Figure 4-67 shows the annual travel time per line for AON. The annual travel times are shown for the node consolidation scenarios 1, 2 and 3 in dense urban, urban and rural service areas. The annual travel times are proportional to the annual failure rates. Most of the travel effort is caused by active AON equipment at PCP4, PCP5 and PCP6 followed by distribution cable in urban and rural service areas and the in-house cable in dense urban.

The travel effort increases in node consolidation scenario 3 for all service area types compared to scenario 1 whereas in node consolidation scenario 2 the travel time only increase for urban and rural service areas. The increasing travel times are mainly caused by the active remote node equipment at PCP4. A travel effort gain can be only realized in node consolidation scenario 2 for dense urban service areas because this scenario requires a relatively low number of active remote nodes. Node consolidation scenario 3 leads to an increase of the travel effort by 27% in dense urban, and by 38% in urban and rural service areas as compared to scenario 1.

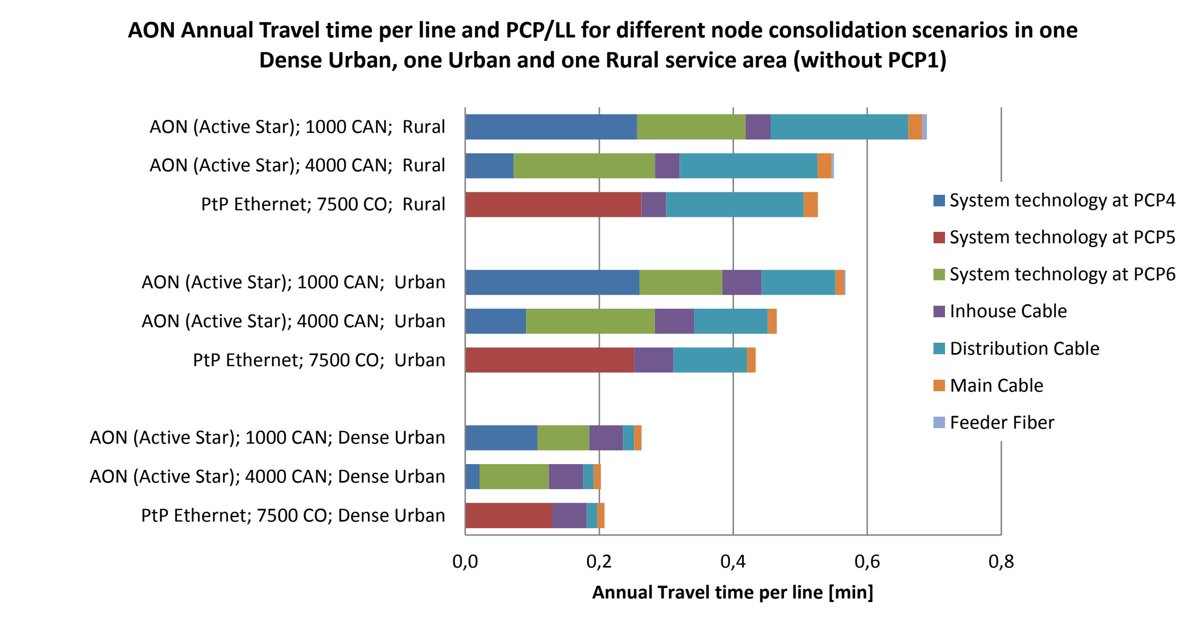


Figure 4-67: Annual travel time per line for AON

4.4.4 Control and management

This architecture is very easy to integrate into the C&M system of the higher aggregations levels as it uses the same well known standards as these systems. It also give a lot of possibilities when it comes to advanced end-to-end C&M functions, such as end-to-end resource allocations, for example via GMPLS. In AON the C&M could also include energy optimization on an end-to-end architecture, include the aggregation and core networks.

OpenFlow could also be used to control the functionality in the NG-AON network, and thereby give the benefit of centralized control functionality and the possibilities of advanced network handling that OpenFlow enables. These functions could be services triggering or advanced routing.

In Chapter 4, we have provided a comprehensive and quantitative study of the performance characteristics and properties of the four main NGOA architecture options and their subset variations. These were chosen to represent the key features to be expected from the diverse range of NGOA architectures that are expected to be deployed. In particular, depending on the topological, service area, and business case conditions presented in any particular roll-out scenario, a suitable combination of any of the architecture options described here should provide a credible performance model of the actual deployed architecture. In the next section, we now perform a side-by-side, quantitative performance comparison for the various architecture options, which provides a more synoptic presentation of the performance measures, and allows for a more visually direct comparison to be made.

5. Performance Comparison

This section provides a comparison of the performance of the selected variants of NGOA architecture options proposed in the OASE project. The comparison includes various architectural aspects in terms of energy consumption, footprint, failure rate, travel effort, connection availability, and failure impact. Regarding the architecture aspects as power consumption, footprint, failure rate, travel effort, we select the results of one type service area to present, as we have very similar findings in other types of service areas.

5.1 ENERGY CONSUMPTION ASSESSMENT IN NODE CONSOLIDATION

Figure 5-1 shows the power consumption per line and PCP layer for different NGOA architectures and node consolidation scenarios in a dense urban service area. In addition, it shows the power consumption per line for the reference architectures GPON and XG-PON. The power consumption has been calculated for a guaranteed downstream data rate of at least 300 Mbit/s per ONT. In this figure AON stands for NG-AON.

Figure 5-1 shows that the power consumption per line is clearly dominated by the ONT part at the PCP1 (user flat) for all architectures and node consolidation scenarios. The UDWDM-PON architecture causes the highest power consumption in all node consolidation scenarios followed by the WS-WDM-PON. The lowest power consumption has been calculated for the GPON reference architecture followed by NG-AON and XG-PON.

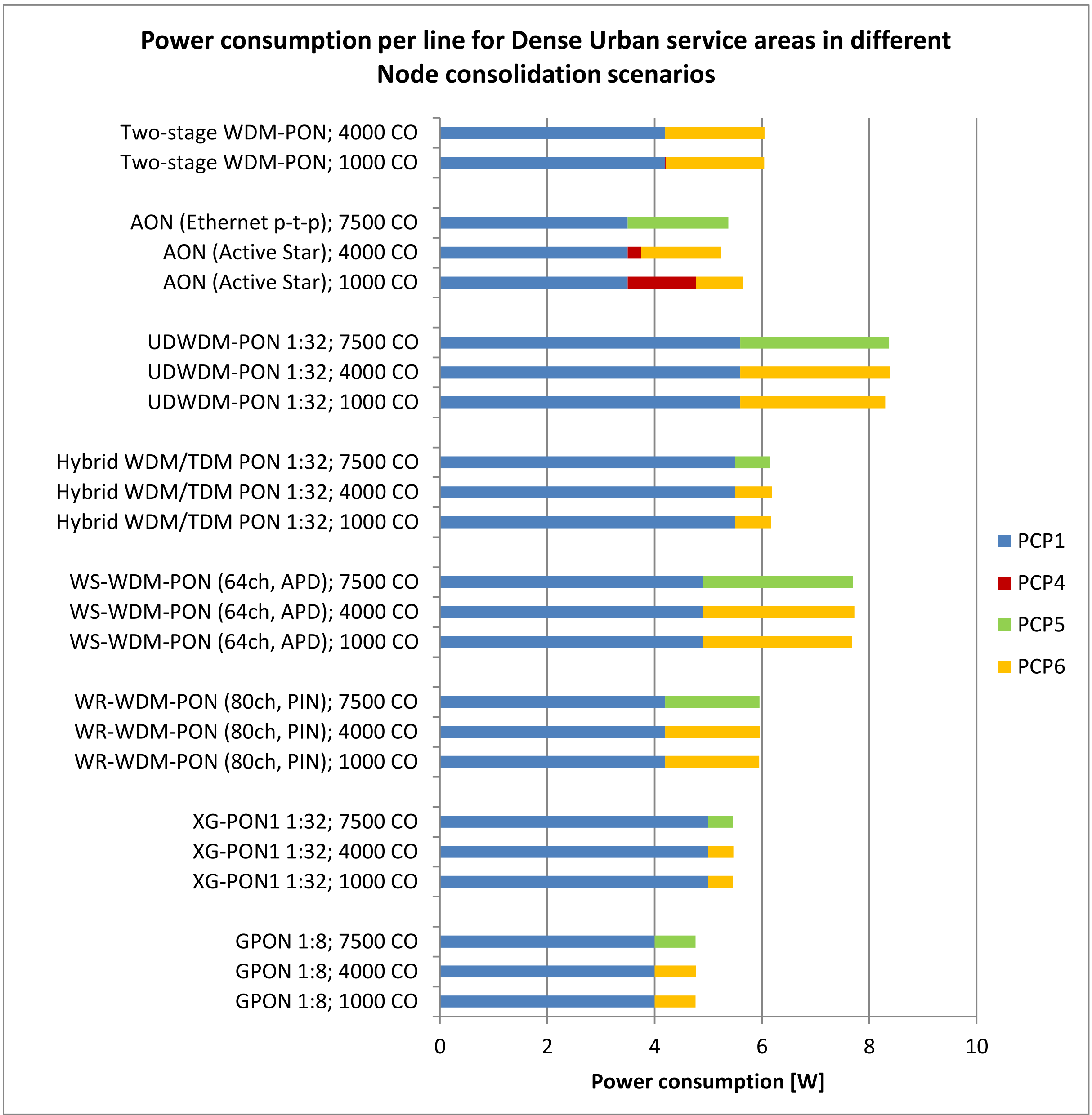


Figure 5-1: Power consumption per line for different NGOA/reference architectures and node consolidation scenarios (dense urban service area)

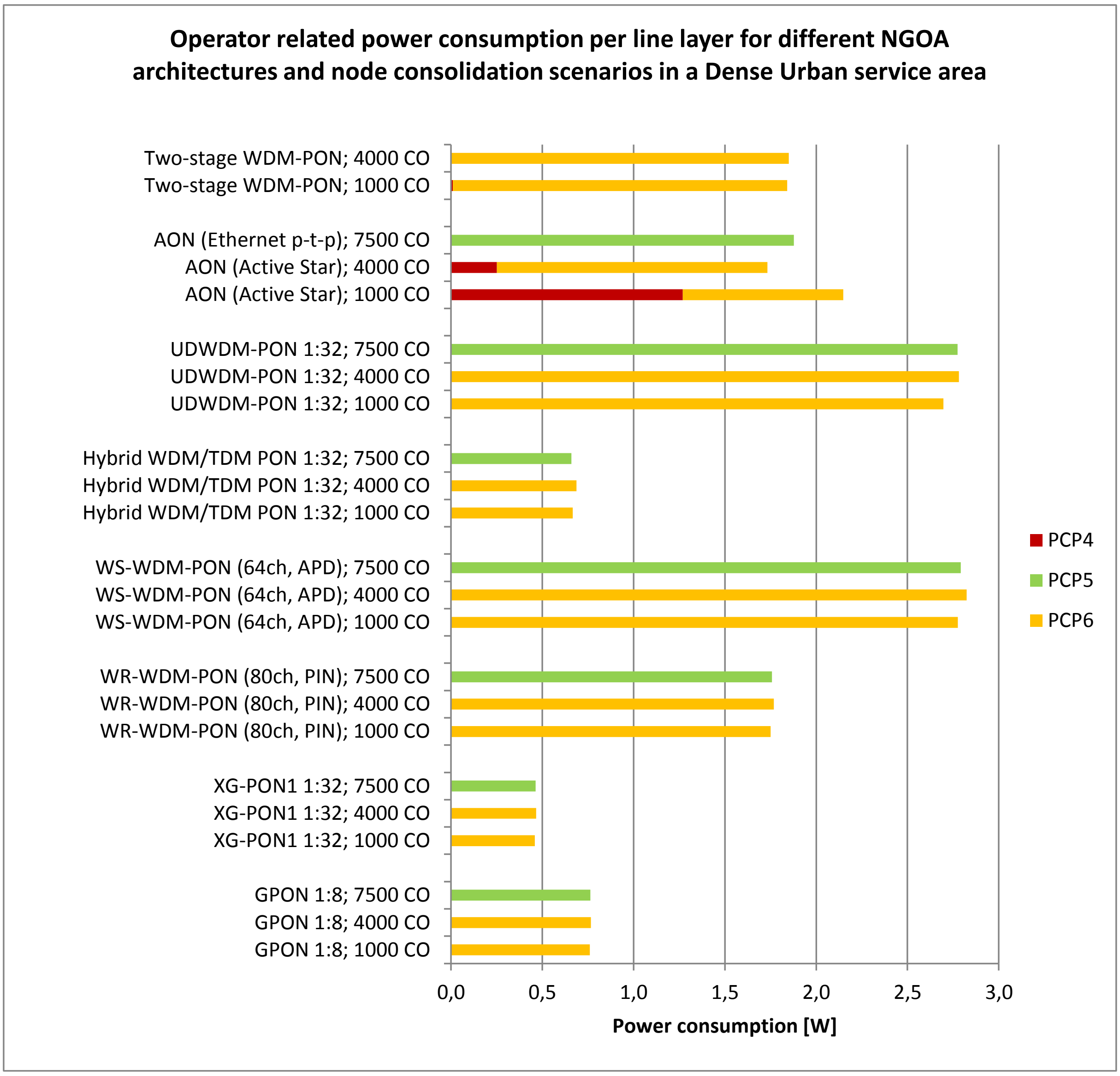


Figure 5-2: Network operator related power consumption per line for different NGOA architectures and node consolidation scenarios (dense urban service area)

Figure 5-2 shows the network operator related power consumption per line (without the ONT part) for all NGOA and reference architectures in a dense urban service area. In this figure AON stands for NG-AON. The UDWDM-PON and the WS-WDM-PON architecture cause the highest network operator related power consumption in all node consolidation scenarios followed by two-stage WDM-PON, NG-AON and WR-WDM-PON.

The lowest network operator related power consumption per line has been calculated for the XG-PON reference architecture followed by Hybrid WDM/TDM-PON.

Figure 5-1 and Figure 5-2 also show that the impact of node consolidation on the power consumption is more or less negligible for all architectures. We had the similar findings in urban and rural service areas. Just the NG-AON power consumption increases for active star scenarios with PCP5 node consolidation, which is mainly caused by the remote node equipment in the field.

5.2 Footprint assessment in node consolidation

Figure 5-3 shows the footprint per line for different NGOA architectures and node consolidation scenarios in one urban service area. In addition, it shows the footprint per line for the reference architectures GPON and XG-PON. In this figure AON stands for NG-AON.

The AON architecture requires the highest amount of footprint in all node consolidation scenarios followed by WS-WDM-PON, UDWDM-PON and GPON. The Hybrid WDM/TDM-PON requires the lowest amount of footprint followed by XG-PON.

Figure 5-3 also shows that the impact of node consolidation on the footprint aspect is more or less negligible for all architectures. Just the NG-AON footprint increases for active star scenarios with PCP5 node consolidation, which is mainly caused by the remote node equipment in the field.

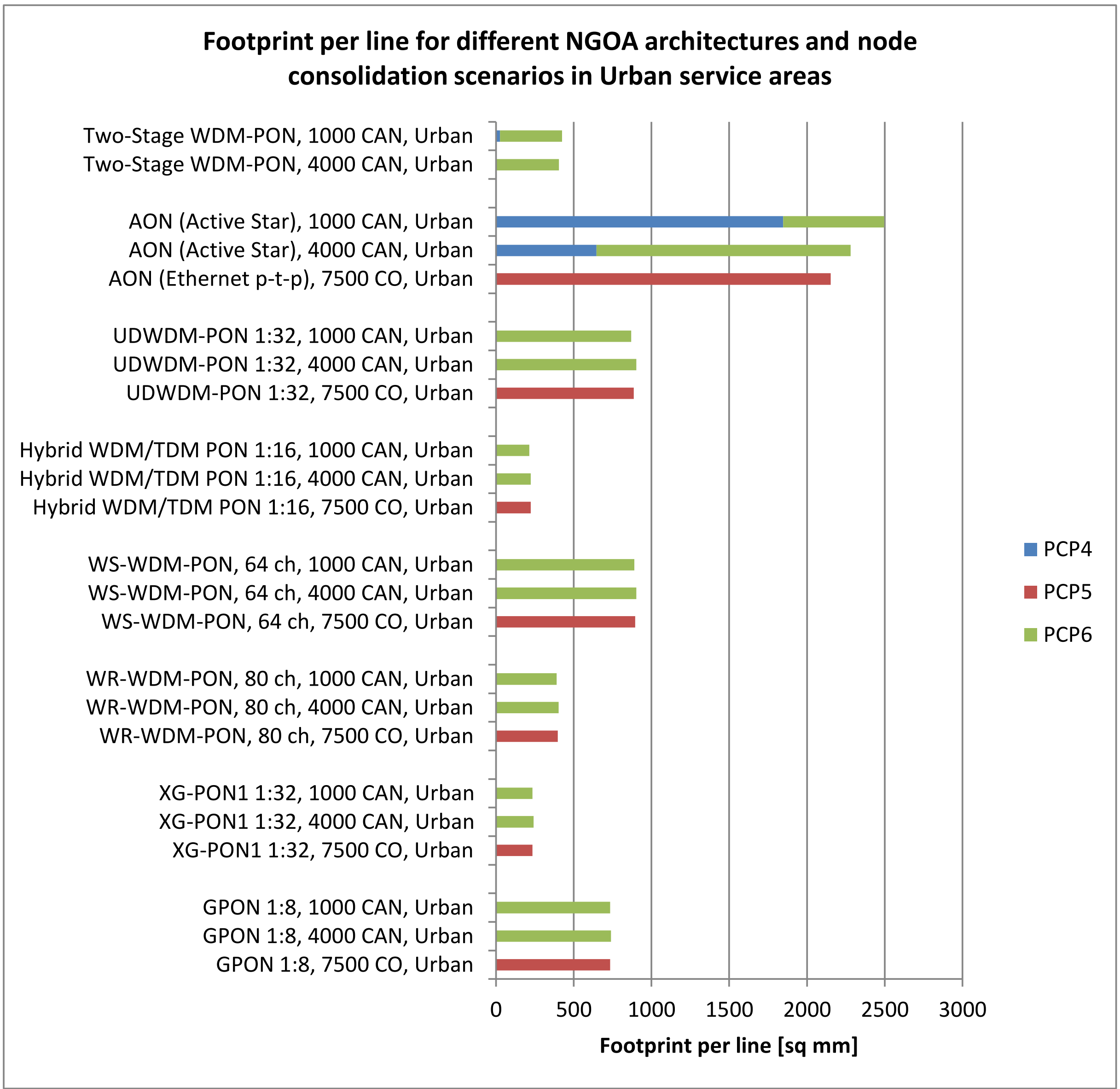


Figure 5-3: Footprint per line for different NGOA/reference architectures and node consolidation scenarios in urban.

5.3 Failure Rate Assessment

Figure 5-4 shows the annual failure rate per line for different NGOA architectures and the node consolidation scenarios in one urban service area. In addition, it shows the failure rate per line for the reference architectures GPON and XG-PON. In this figure AON stands for NG-AON. The results show that the annual failure rate is clearly dominated by failures at PCP1 (ONT failures at the end-user site). The NG-AON architectures (PtP Ethernet and active star) allow the lowest total failure rate followed by the GPON architecture due to the relatively high MTBF value of the ONT. The highest failure rate is caused by the UDWDM-PON architecture due the high number of ONT failures.

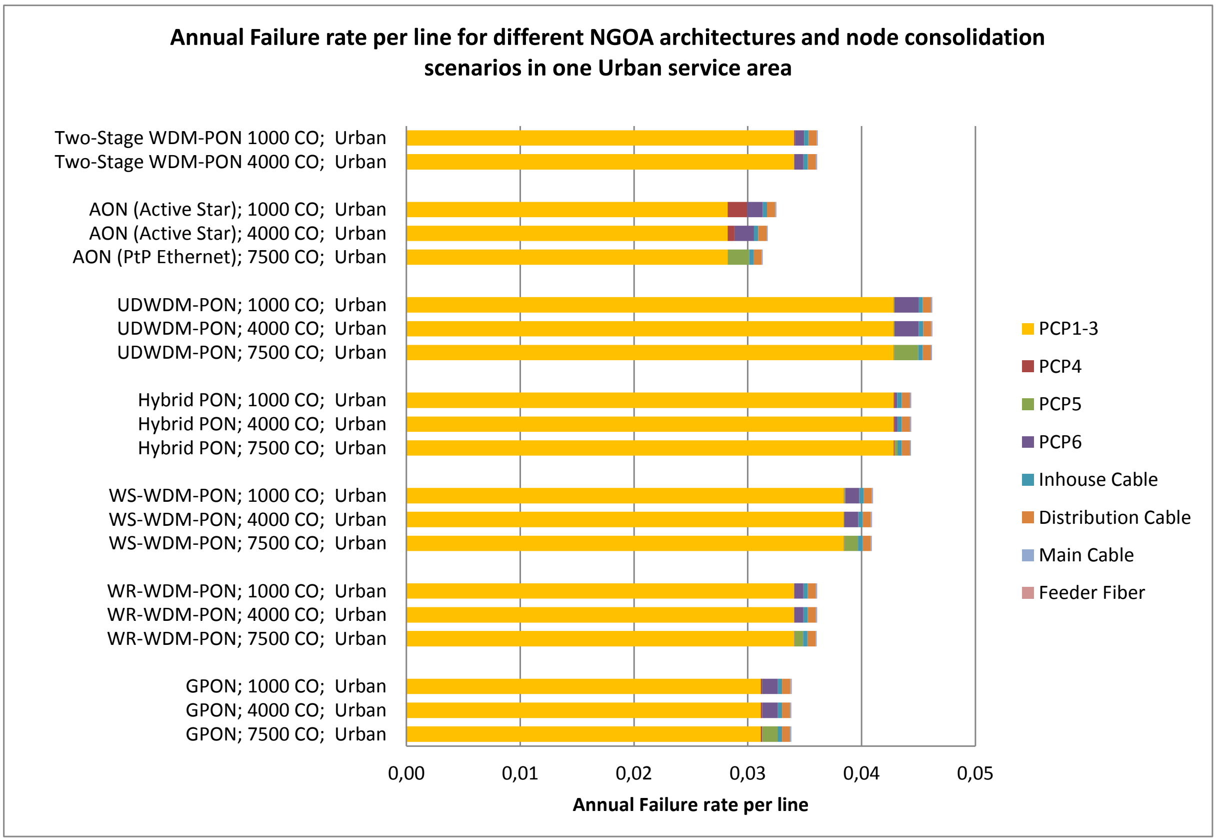


Figure 5-4: Annual failure rate per line for different NGOA and reference architectures in one urban service area

Figure 5-5 shows the annual failure rate per line for different NGOA and reference architectures in one urban service area without the PCP1 part. In this figure AON stands for NG-AON. The NG-AON and the UDWDM-PON architectures cause the highest failure rate at PCP4-6 followed by GPON, two-Stage WDM-PON and WR-WDM-PON. The lowest failure rate at PCP4-6 has been calculated for the hybrid WDM/TDM-PON architecture.

Figure 5-4 and Figure 5-5 show that the impact of node consolidation on the failure rate is more or less negligible for all architectures. Just the NG-AON failure rate increases for active star scenarios with PCP5 node consolidation, which is mainly caused by the remote node equipment in the field.

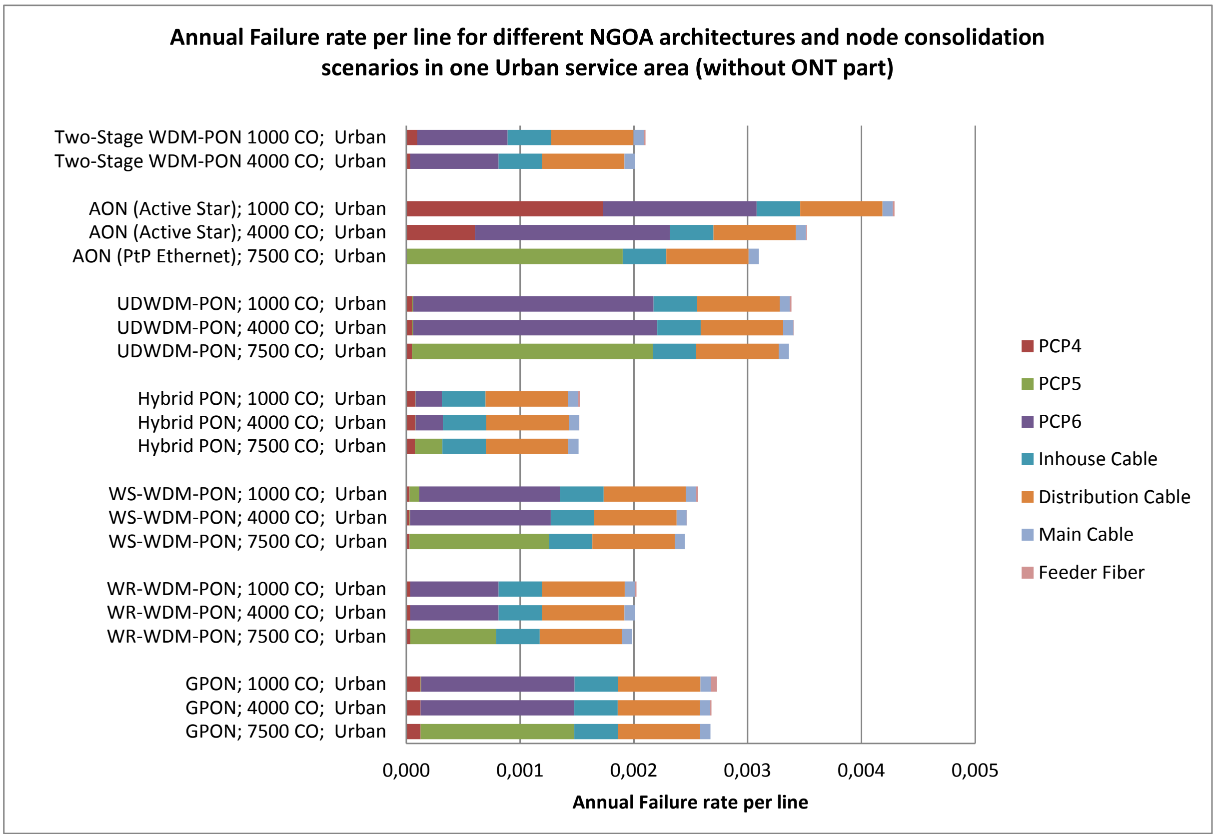


Figure 5-5: Annual failure rate per line for different NGOA and reference architectures in one urban service area (without PCP1)

5.4 Travel Effort Assessment

Figure 5-6 shows the annual travel time per line for different NGOA architectures and node consolidation scenarios in one urban service area. In addition, it shows the annual travel time per line for the reference architectures GPON and XG-PON. In this figure AON stands for NG-AON. The travel time analysis is based on the annual failure rate and the travel distance model described in Section 3.3.4. It is assumed that travel effort is not needed for ONT failures at PCP1. This means that in the case of an ONT failure the user gets a new ONT device which will be installed by the user (plug-and-play).

The NG-AON and the UDWDM-PON architectures cause the highest travel effort followed by GPON and WS-WDM-PON. The Hybrid WDM/TDM-PON architecture requires the lowest travel time followed by WR-WDM-PON and two-stage WDM-PON.

The average travel time per line decreases with higher level of node consolidation for all NGOA architectures due to the increasing share of maintenance offices which are co-located with local exchange (PCP5) and CANs (PCP6). Just the NG-AON travel effort increases for active star scenarios with PCP5 dissolution which is mainly caused by the active remote node equipment at PCP4/5 that provides lower MTBF values and requires longer travel distances.

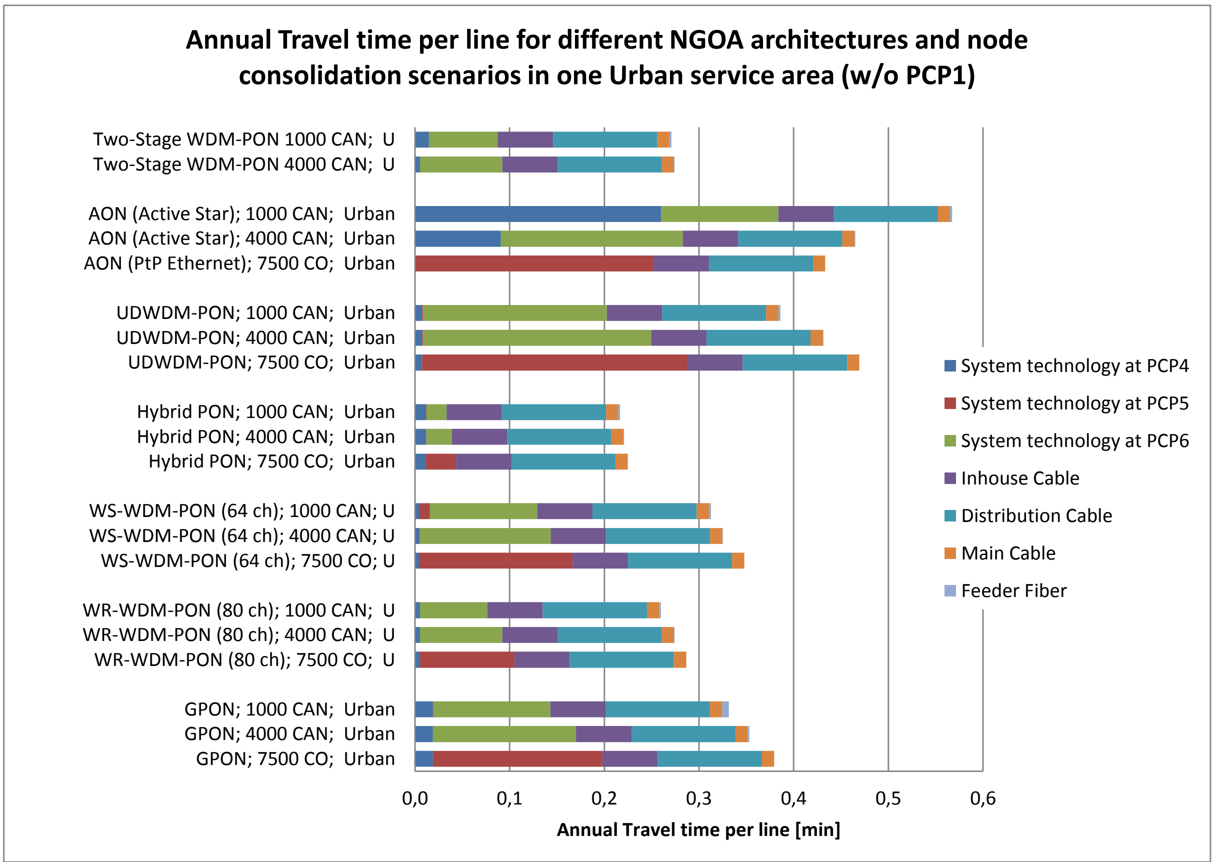


Figure 5-6: Annual travel time per line for different NGOA and reference architectures in one urban service area (without PCP1)

5.5 CONNECTION AVAILABILITY

Comparison of connection availability of the OASE architecture options without and with the protection down to PCP5 is shown in Figure 5-7. Here connection is referred to as the one between ONT and central access node. It can be observed the passive NGOA architecture options have apparently higher connection availability than the active ones. However, the difference among all the NGOA options considered in this deliverable is not significant, in particular when the protection scheme is considered. It is because the fiber failures limit the reliability performance.

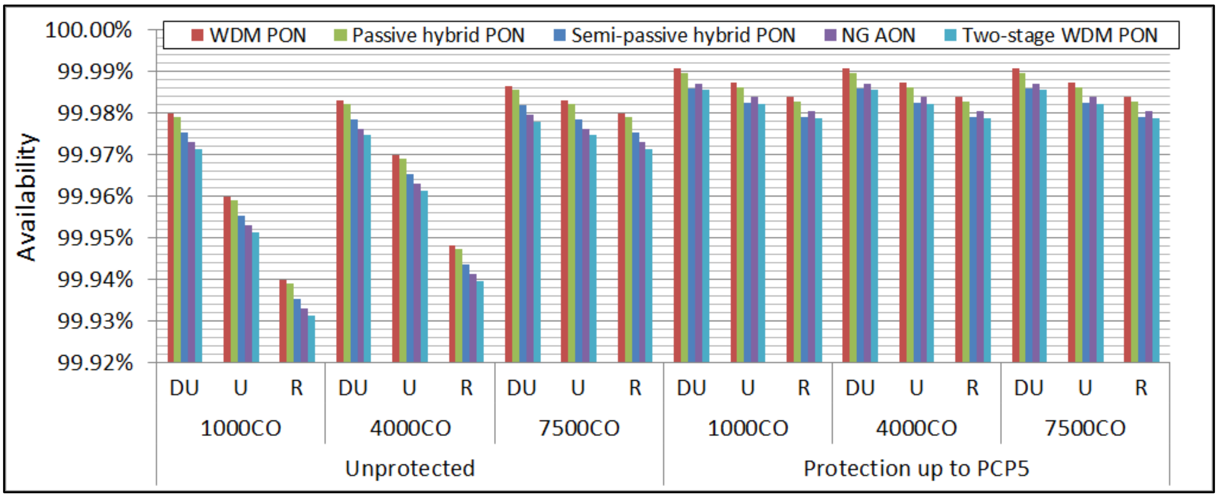


Figure 5-7: Connection availability without and with protection down to PCP5.

5.6 FAILURE IMPACT

Figure 5-8 shows FOM results of the OASE architecture options with and without the protection down to PCP5. Compared to connection availability, the difference on failure impact is more obvious among different architecture options. It is mainly because the active remote node has significantly higher unavailability than the passive one, while the remote node is shared among a large number of end-users in NGOA networks. In the considered protection schemes for active architecture options, the partial protection of the active equipment at the remote node at PCP5, i.e., uplink card, could efficiently reduce the impact of failures. However, due to the lack of the cost-effective resilience mechanism for the entire remote node, it can be seen that the proposed protection schemes for active architecture options result in apparently lower FOM than the one for their passive counterpart.

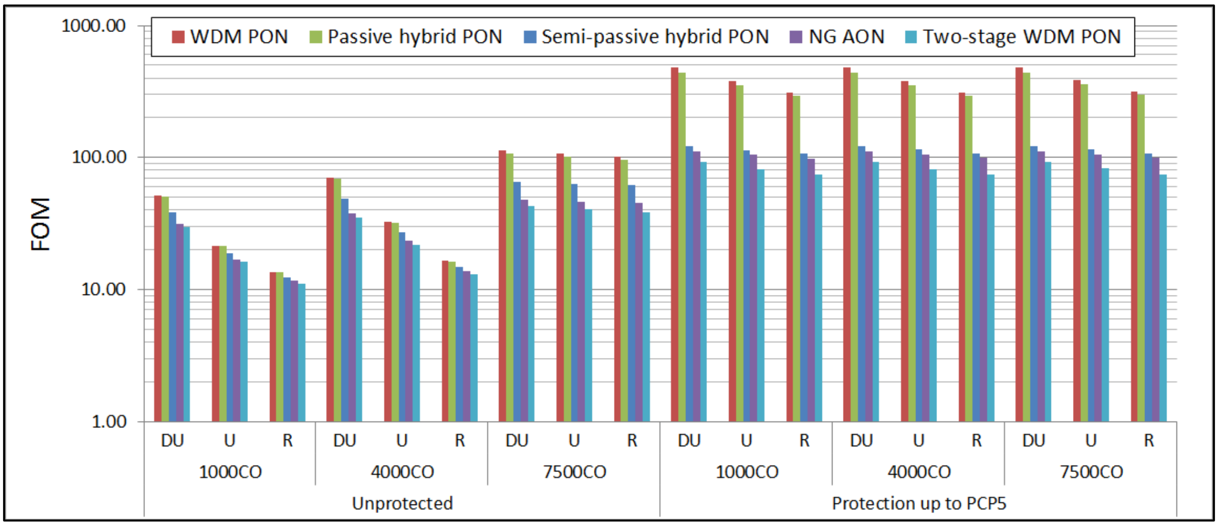


Figure 5-8: FOM without and with protection down to PCP5.

6. Conclusions

The document contains an overview of the four NGOA architecture options defined in the OASE deliverable D3.1 for the "2020" time horizon, namely, WDM-PON, Hybrid WDM/TDM-PON, two-stage WDM-PON, and NG-AON. The architectural aspects, with respect to impact on the aggregation network, energy consumption, resilience, operational aspects, control and management, resource allocation, migration and open access, have been described along with the underlying methodological approach (assumptions, explicit quantitative methods, and criteria) for evaluation.

An extensive assessment has been carried out to compare the four selected NGOA architecture options by mapping them to different node consolidation schemes and populated areas. According to the obtained evaluation results, passive NGOA architectures, i.e. WDM-PON and hybrid WDM/TDM-PON consume more power on a per-user basis than their active counterpart, namely two-stage WDM-PON and NG-AON; while the passive architectures have higher resiliency than the active approaches. From the operators' perspective, i.e. without considering the equipment located at the user side, thanks to its high splitting ratio hybrid WDM/TDM-PON always performs best on the operational aspects, such as footprint, failure rate, travel effort, and power consumption, among all four OASE architectures. On the other hand, resource allocation to schedule upstream bandwidth is an issue only for hybrid WDM/TDM-PON. An efficient algorithm for hybrid PON is needed to mitigate the performance degradation caused by reach extension due to node consolidation. For the impact on aggregation network, and control & management, it has been shown that there is no significant difference among the various architecture concepts. Regarding open access and migration, the assessment outcome has not been presented yet in this document and will be included in the other two relevant deliverables, namely D3.3 and D3.4, respectively.

It should be noted that apart from these technical-based aspects the ultimate choice of deployment of a particular NGOA architecture option also depends on the standard commercial criteria (techno-economic modeling, OpEx/CapEx, business models etc.) and regulatory environment that may be present. These business and regulatory aspects are the subject of the ongoing parallel OASE work packages WP5 and WP6. With the results from these other WPs, the final comparative analysis and conclusions will occur at the end of the project.

7. Appendix

Table 7-1 presents the MTTR values for OASE NGOA architecture options considered in WP3. This table serves as the input from the industry partners of the project to the resiliency performance evaluation performed in this document.

Table 7-1: MTTR values for OASE NGOA architecture options

Wavelength routed WDM-PON	MTTR (Hours)	Wavelength selective WDM-PON	MTTR (Hours)
OLT Shelf / Backplane (18 tributary slots)	4 h	OLT Shelf / Backplane (18 tributary slots)	4 h
OLT Power unit	4 h	OLT Power unit	4 h
OLT Switch/Route processor (~200G, 300Mb/s per client)	4 h	OLT Switch/Route processor (~100G, 32ch, 32ch 300Mb/s preamp)	4 h
OLT Switch/Route processor (~300G, 500Mb/s per client)	4 h	OLT Switch/Route processor (~200G, 64ch, 32ch 500Mb/s preamp, 64ch 300Mb/s preamp)	4 h
OLT Basic Downlink line card DWDM-PON port card 80 channels (for use in 80 config) (incl 80x1G Laser/Rx Array C-band, 1 diplexer) not incl EDFA preamp.	4 h	OLT Switch/Route processor (~300G, 128ch 300Mb/s per client, 64ch 500Mb/s preamp, 128ch 300Mb/s preamp)	4 h
OLT Basic Downlink line card DWDM-PON port card 80 channels (for use in 160 config) (incl 80x1G Laser/Rx Array C/S-band, 1 diplexer) not incl EDFA or TDFA preamp	4 h	OLT Switch/Route processor (~400G, 128ch 500Mb/s per client)	4 h
OLT Basic Downlink line card DWDM-PON port card 80 channels (for use in 360 config) (incl 80x1G Laser/Rx Array C/S-band, 1 diplexer, 2 interleavers) not incl EDFA or TDFA preamp	4 h	OLT Basic Downlink line card DWDM-PON port card 32 channels (for use in 32 config) (incl 32x1G Laser/Rx Array C-band, 1 diplexer) not incl EDFA preamp.	4 h
OLT EDFA Preamp	4 h	OLT Basic Downlink line card DWDM-PON port card 64 channels (for use in 64 config) (incl 64x1G Laser/Rx Array C-band, 1 diplexer) not incl EDFA preamp	4 h
OLT TDFA Preamp	4 h	OLT Basic Downlink line card DWDM-PON port card 128 channels (for use in 128 config) (incl 2x64x1G Laser/Rx Array C-band, 1 diplexer) not incl EDFA preamp	4 h
RN Passive RN chassis (not incl AWG, etc)	8 h	OLT EDFA Preamp	4 h
RN 80 channels (80:1 AWG)	8 h	RN2 Passive RN chassis (not incl band filter)	8 h
RN 80 channels protection (80:2 AWG)	8 h	RN2 Band filter (1:4)	8 h
RN 160 channels (2x 80:1 AWG, diplexer)	8 h	RN1 Passive RN chassis (not incl splitter)	8 h
RN 160 channels protection (2x 80:2 AWG, 2 diplexers)	8 h	RN1 Optical power splitter (1:32)	8 h
RN 320 channels (4x 80:1 AWG, 7 diplexers, interleavers 320 ch)	8 h	RN1 Optical power splitter (1:64)	8 h
RN 320 channels protection (4x 80:2 AWG, 7 diplexers, interleavers 320 ch)	8 h	DWDM-PON-ONT 1G tunable (APD, C-band) - for 80 ch	8 h
DWDM-PON-ONT 1G tunable (APD, C-band) - for 80 ch	8 h		
DWDM-PON-ONT 1G tunable (APD, C/S-band) - for 160, 320 ch	8 h		
UDWDM-PON	**MTTR (Hours)**	**Hybrid DWDM / TDMA PON**	**MTTR (Hours)**
OLT Shelf / Backplane (18 tributary slots)	4 h	OLT Shelf / Backplane (18 tributary slots)	4 h
OLT Power unit	4 h	OLT Power unit	4 h
OLT Switch/Route processor (~100G, 300Mb/s per client)	4 h	OLT Switch/Route processor (~600G)	4 h
OLT Switch/Route processor (~200G, 500Mb/s per client)	4 h	OLT Switch/Route processor (~700G)	4 h
OLT Basic Downlink line card DWDM-PON port card 32 channels (for use in 320, 640) - incl TRX, ASIC, but not TFF or circulators	4 h	OLT EDFA Booster	4 h
OLT TFF (10 ports)	4 h	OLT EDFA Preamp	4 h
OLT Circulator	4 h	OLT Downlink line card Hybrid-PON (10 x 10G)	4 h
OLT EDFA Booster	4 h	OLT Diplexer card (7)	4 h
RN3 Outdoor cabinet (for max 8 RE)	4 h	OLT Diplexer card (15)	4 h
RN3 EDFA based reach extender	4 h	RN3 Outdoor cabinet (for max 8 RE)	4 h
RN2 Passive RN chassis (not incl AWG, TFF)	8 h	RN3 EDFA based reach extender	4 h
RN2 TFF (1:20)	4 h	RN2 Passive RN chassis (not incl AWG,..)	8 h
RN2 AWG (1:40)	8 h	RN2 AWG (1:40)	8 h
RN2 AWG protection (2:40)	8 h	RN2 AWG protection (2:40)	8 h
RN2 AWG (1:80)	8 h	RN2 AWG (1:80)	8 h
RN2 AWG protection (2:80)	8 h	RN2 AWG protection (2:80)	8 h
RN1 Passive RN chassis (not incl splitter)	8 h	RN1 Passive RN chassis (not incl splitter)	8 h
RN1 Optical power splitter (1:8)	8 h	RN1 Optical power splitter (1:32)	8 h
RN1 Optical power splitter (1:32)	8 h	RN1 Optical power splitter (1:16)	8 h
UDWDM-PON-ONT 1G tunable (UDWDM)	8 h	Hybrid-PON ONT 10G tunable PIN (hardware + software failures)	8 h
		Hybrid-PON ONT 10G tunable APD (hardware + software failures)	8 h
Wavelength-Switched Hybrid DWDM / TDMA PON	**MTTR (Hours)**	**Two-stage WDM-PON**	**MTTR (Hours)**
OLT Shelf / Backplane (18 tributary slots)	4 h	OLT Active Shelf / Backplane (18 tributary slots)	4 h
OLT Power unit	4 h	OLT Power unit	4 h
OLT Switch/Route processor (~400G)	4 h	OLT Switch/Route processor (~800G)	4 h
OLT Switch/Route processor (~800G)	4 h	OLT 4:1 AWG	4 h
OLT EDFA Booster	4 h	OLT Downlink line card 4x40G channels (incl 4x40G TRx) (occupies 2 tributary slots)	4 h
OLT Downlink line card Hybrid-PON (10 x 10G)	4 h	RN1 Active Shelf / Backplane (18 tributary slots)	8 h
OLT Diplexer card (16)	4 h	RN1 Power unit	8 h

OLT Diplexer card (8)	4 h	**RN1 Switch/Route processor (~100G, 300Mb/s per client)**	8 h
OLT AWG (1:40)	4 h	**RN1 Switch/Route processor (~200G, 500Mb/s per client)**	8 h
OLT AWG (1:80)	4 h	**RN1 Control and management plane**	not considered
OLT Splitter card (8x1:4)	4 h	**RN1 Software**	not considered
OLT Splitter card (16x1:8)	4 h	**RN1 4:1 AWG**	8 h
OLT WSS (8x4:1) card	4 h	**RN1 Uplink line card optical 4x40G (incl 4x40G TRx) (occupies 2 tributary slots)**	8 h
OLT WSS (16x8:1) card	4 h	**RN1 Downlink line card DWDM-PON port card 80 channels (for use in 80 config) (incl 80x1G Laser/Rx Array C-band, 1 diplexer) not incl EDFA preamp.**	8 h
RN3 Outdoor cabinet (for max 8 RE)	4 h	**RN1 Downlink line card DWDM-PON port card 80 channels (for use in 160 config) (incl 80x1G Laser/Rx Array C/S-band, 1 diplexer) not incl EDFA or TDFA preamp**	8 h
RN3 EDFA based reach extender	4 h	**RN1 Downlink line card DWDM-PON port card 80 channels (for use in 360 config) (incl 80x1G Laser/Rx Array C/S-band, 1 diplexer, 2 interleavers) not incl EDFA or TDFA preamp**	8 h
RN2 Passive RN chassis (not incl AWG,..)	8 h	**RN Passive RN chassis (not incl AWG, etc)**	8 h
RN2 AWG (1:10)	8 h	**RN 80 channels (80:1 AWG)**	8 h
RN2 AWG protection (2:10)	8 h	**RN 80 channels protection (80:2 AWG)**	8 h
RN2 WSS option 1 (1:4 WSS, 1:10 AWG)	8 h	**RN 160 channels (2x 80:1 AWG, diplexer)**	8 h
RN2 WSS option 1 protection (2:4 WSS, 1:10 AWG)		**RN 160 channels protection (2x 80:2 AWG, 2 diplexers)**	8 h
RN2 WSS option 2 (1:4 WSS, 1:5 AWG)	8 h	**RN 320 channels (4x 80:1 AWG, 7 diplexers, interleavers 320 ch)**	8 h
RN2 WSS option 2 protection (2:4 WSS, 1:5 AWG)		**RN 320 channels protection (4x 80:2 AWG, 7 diplexers, interleavers 320 ch)**	8 h
RN1 Passive RN chassis (not incl splitter)	8 h	**ONT 1G tunable (APD, C-band) - for 80 ch**	8 h
RN1 Optical power splitter (1:32)	8 h	**ONT 1G tunable (APD, C/S-band) - for 160, 320 ch**	8 h
RN1 Optical power splitter (1:16)	8 h		
Hybrid-PON ONT 10G tunable APD (hardware + software failures)	8 h		
NG-AON	**MTTR (Hours)**		
OLT Active Shelf / Backplane (18 tributary slots)	4 h		
OLT Power unit	4 h		
OLT Switch/Route processor (~800G)	4 h		
OLT 4:1 AWG	4 h		
OLT Downlink line card 4x40G channels (incl 4x40G TRx) (occupies 2 tributary slots)	4 h		
RN1 Active Shelf / Backplane (18 tributary slots)	8 h		
RN1 Power unit	8 h		
RN1 Switch/Route processor (~100G, 300Mb/s per client)	8 h		
RN1 Switch/Route processor (~200G, 500Mb/s per client)	8 h		
RN1 Control and management plane	not considered		
RN1 Software	not considered		
RN1 4:1 AWG	8 h		
RN1 Uplink line card optical 4x40G (incl 4x40G TRx) (occupies 2 tributary slots)	8 h		
RN1 Downlink line card optical 24 CompactSFP (equal to 48 x1G,not incl pluggables) (occupies 3 tributary slots)	8 h		
RN1 Pluggable 2x1G (compact SFP)	8 h		
PtP-ONT 1G (hardware + software failures)	8 h		

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