Technical Assessment and Comparison of Next-Generation Optical Access System Concepts

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Abstract:
This deliverable presents an updated technical assessment and comparison of system concepts for next-generation optical access based on OASE requirements. For the considered systems, detailed cost, power and performance models are developed, while the issues associated with resilience, security, upgradeability and mobile backhaul are presented. A broad range of design alternatives are considered for each system concept presenting different trade-offs between cost, power, reach, client-count per feeder fibre, footprint and capacity.

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Executive Summary

This document provides the final technical assessment and quantitative comparison of NGOA systems concepts identified in the OASE project. Starting from four classes of architectures: WDM-PON; hybrid WDM/TDM-PON; next-generation active optical network (NG-AON); and two-stage WDM-PON backhaul concepts; key system variants have been additionally identified so as to provide a comprehensive survey. This being the final deliverable D4.2.2, it completes the preliminary quantitative assessment carried out in the earlier deliverable D4.2.1 based on a subset of the technical requirements identified in the deliverable D2.1. Deliverable D4.2.2 presents an updated performance assessment compared to deliverable D4.2.1 regarding cost, energy consumption, footprint, data-rates, reach and client-count per OLT. It furthermore extends deliverable D4.2.1 with a qualitative assessment of the remaining technical requirements relating to: resilience, security, upgradeability, and mobile backhaul capability. In performing the technical assessment of each system variant, their topological layout as related to the physical connection points (PCPs) is delineated, and their techno-economic performance characteristics for 300 Mbit/s and 500 Mbit/s sustainable data-rates have been calculated.

A detailed discussion of the underlying methodology and assumptions employed in the quantitative assessment is given, with particular regard to: the attenuation model adopted (specifically, as this relates to the reach requirement); the cost and power consumption for each system and subsystem components; and the rack and shelf assumptions made for footprint calculations. In addition, a qualitative discussion of an underlying framework to analyse system resilience, security, upgradeability and mobile backhaul capability is provided.

Having provided the raw data related to each system variant, these are presented in an extensive and updated set of tables, which are also briefly summarized in side-by-side comparative format. These tabulations form the main, substantive output results presented in this deliverable, and form the quantitative inputs to be fed into workpackage WP5 for a comprehensive techno-economic analysis.

Several of the relevant technical requirements identified in the deliverable D2.1 (e.g. reach, customers per feeder fibre) are specified as permissible ranges allowing for flexibility in the system design in order to ensure that the overarching OASE objective of minimum total-cost of ownership (TCO) is met. In this deliverable D4.2.2, a large number of system variants are found to satisfy at least the lower bound of these ranges. It is not possible to further select or reduce the number of candidate systems based on technical requirements solely. It is found that systems satisfying the higher level of end requirements in general also are more expensive in terms of system cost. Hence to further select promising candidates requires an understanding of the detailed trade-off between the system cost and the impact of system performance on operational expenditure (OpEx). Even though design parameters that drive capital expenditure (CapEx) are well understood from the analysis in this deliverable, to further select suitable NGOA design variants, design parameters that drive OpEx must also be quantified in order to identify the suitable NGOA system variants. This will be part of the comprehensive techno-economic analysis in WP5.

In combination with the accompanying deliverable D4.3.2 (which examines more operational aspects to system requirements) the results presented here provide important insights into the system technology solutions that will satisfy the technical and techno-economic demands of future NGOA networks. Together with the emerging results from WP3 (open access and

migration studies) and WP6 (regulatory and competition issues) the results presented here will offer critical data to help estimate the most-likely evolution paths of sustainable next-generation optical access networking.

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Abbreviations

AES	Advanced Encryption Standard
ALS	Automatic Laser Shutdown
AON	Active Optical Network
APD	Avalanche PhotoDiode
ARN	Active Remote Node
ATM	Asynchronous Transfer Mode
AV	AVailability
AWG	Arrayed-Waveguide Grating
BBU	Base-Band Unit
BER	Bit Error Rate
BS	Base Station
CAN	Consolidated [or Central] Access Node
CapEx	Capital Expenditure
CDN	Content Distribution Network
CML	Chirp-Managed Laser
CO	Central Office
CoMP	Coordinated Multi-Point
CP	Central Processor
CPE	Customer Premises Equipment
CPRI	Common Public Radio Interface
DoW	Description of Work
DBPSK	DuoBinary Phase Shift Keying
DSP	Digital Signal Processor
DWDM	Dense WDM
EAM	Electro-Absorption Modulator
EDFA	Erbium-Doped Fibre Amplifier
EOL	End Of Life
EPON	Ethernet PON
Eth/ETH	Ethernet
FD	Frame Delay
FDV	Frame Delay Variation
FEC	Forward Error Correction
FIT	Failure In Time
FLR	Frame Loss Ratio
FP	Flexibility Point
FSAN	Full Service Access Network
FSR	Free Spectral Range
FTTH	Fibre to the Home
GPON	Gigabit PON
IL	Insertion Loss
IP	Internet Protocol
IRZ	Inverse RZ
LAN	Local Area Network
LD	Laser Diode
LED	Light Emitting Diode
LER	Label Edge Router

LL	Link Layer
LT	Line Termination
LTE	Long-Term Evolution
LTE-A	LTE Advanced
MAC	Media Access Control
MBH	Mobile BackHaul
MDU	Multi-Dwelling Unit
MEF	Metro Ethernet Forum
MEMS	Micro-Electro-Mechanical System
MFH	Mobile FrontHaul
MFL	Multi-Frequency Laser
MSAN	Multi-Service Access Node
MTBF	Mean Time Between Failure
MTTR	Mean Time To Repair
MUX	MUltipleXer
NGOA	Next Generation Optical Access
NIST	National Institute of Standards and Technology
NSN	Nokia-Siemens Networks
NT	Network Termination
OA	Open Access
OAM	Operation, Administration, Maintenance
OAN	Optical Access Network
OASE	Optical Access Seamless Evolution
ODB	Optical DuoBinary
ODN	Optical Distribution Network
OEO	Optical-Electrical-Optical
OFDMA	Orthogonal Frequency Division Multiplexing Access
OLT	Optical Line Terminal
ONT	Optical Network Termination
OOK	On-Off Keying
OpEx	Operational Expenditure
OTDR	Optical Time Domain Reflectometry
OTN	Optical Transport Network
PCP	Physical Connection Point
PD	Photo Diode
PHY	PHYsical
PIC	Photonic Integrated Circuit
PLR	Packet Loss Ratio
PON	Passive Optical Network
PoP	Point of Presence
PS	Power Splitter
PtMP	Point-to-Multi-Point
PtP	Point-to-Point
QoE	Quality of Experience
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RE	Reach Extender
REAM	Reflective EAM
RF	Radio Frequency

RN	Remote Node
ROADM	Reconfigurable Optical Add-Drop Multiplexer
RRU	Remote RF Unit
RSOA	Reflective SOA
Rx	Receiver
RZ	Return-to-Zero
SBS	Stimulated Brillouin Scattering
SFF	Small Form Factor (none-pluggable)
SFP	Small Formfactor Pluggable
SLA	Service Level Agreement
SOA	Semiconductor Optical Amplifier
SP	Service Provider
TCO	Total Cost of Ownership
TCP/IP	Transmission Control Protocol/Internet Protocol
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TEC	Thermo-Electric Cooler
TF	Tuneable Filter
TL	Tuneable Laser
T-LD	Tuneable Light Diode
Tx	Transmitter
TXFP	Tuneable XFP
UDWDM	Ultra-Dense WDM
VLAN	Virtual LAN
WBF	Wavelength Blocking Filter
WDM	Wavelength Division Multiplexing
WR	Wavelength-Routed
WS	Wavelength-Selected
WSS	Wavelength Selective Switch
XFP	eXtended Formfactor Pluggable

1. Introduction

This deliverable D4.2.2 (M27) provides the final in-depth study of next-generation optical access (NGOA) system technologies, with a particular focus on a comparative assessment of their technical performance in the context of the technical requirements for such system technologies as previously outlined within this OASE project. It completes the earlier interim deliverable D4.2.1 (M22) that provided an initial quantitative assessment of the costs, power consumption, reach, data-rates, and client count numbers for a set of possible NGOA systems and their variants. The earlier deliverable D4.1 [1] in this particular workpackage WP4 (System concepts for next-generation optical access networks) provided a comprehensive background overview of the current system and sub-system technologies, each with a very different set of characteristics, functionalities and operational performance; not necessarily compatible with each other, or offering a coherent expectation of the technological evolution of NGOA, but generally pulling in the same technology direction (e.g. greater bandwidths) as one considers the broad trends in NGOA evolution.

Subsequent to the deliverable D4.1 (Month 10 of the project), in the first year of the OASE project there has been a deeper investigation of the candidate architectures satisfying the criteria identified in deliverable D2.1 [2] (M9). This study of candidate architectures was presented in deliverable D3.1 [3] (M12) which proposed a set of four generic architecture concepts, each of which offers a realistic solution satisfying the deliverable D2.1 NGOA technical requirements.

During the second year and first couple of months of the third year of the OASE project, we have again been concentrating on the requirements identified in deliverable D2.1 to better understand them in the context of the architecture choices of deliverable D3.1; but also to iterate around and understand their effect on the underlying system technologies, which will provide each of the architectural functionalities. In particular, the implications with respect to cost, energy consumption, reach, physical footprint, and failure rates have been separately considered for each of the system technologies under consideration. These are a subset of the overall list of requirements, which can be straightforwardly quantitatively evaluated. The remaining requirements, i.e. resilience, security, upgradeability, and mobile backhaul capability, are of a more qualitative nature, and are now presented in greater depth in this deliverable. It should also be noted that this deliverable only addresses the technical requirements of the systems and sub-systems as listed in deliverable D2.1. A companion deliverable to this present deliverable, D4.3.2, is examining those requirements, which have a specific operational impact on the deployment of the architectures under consideration. Naturally, there is always going to be some overlap between these two distinct areas: technical, and operation requirements, as they cannot be sharply delineated. However, a separate study covering these two aspects is required so as to adequately address their features as appropriate. The results from this deliverable and its companion, D4.2.2 and D4.3.2, respectively, will be fed into WP5 to provide the raw data for a comprehensive techno-economic comparative analysis.

2. NGOA candidate architectures

By way of placing the subsequent analysis and technical assessment of the related system technologies and concepts into context, in this chapter we briefly summarise the four main NGOA candidate architectures, as previously discussed in depth in the deliverable D3.1 [3]. These four architecture candidates were selected based on the list of technical performance requirements as initially drawn up in the deliverable D2.1 [2]. In particular these requirements are summarised as follows:

- FTTH residential peak data rates ≥1 Gbit/s
- Business, backhaul (fixed, mobile) peak date rate: ≥10 Gbit/s
- Radio access network (RAN) transport: Low delay, synchronization
- Average sustainable downstream based on peak-hour service usage of 500 Mbit/s per optical network unit (ONT)/customer
- Support of more traffic symmetry, with ratio of at least 1:2 between upstream and downstream
- Support from 256 to 1024 ONTs/customers per feeder fibre
- Support of 128 Gbit/s to 500 Gbit/s aggregate capacity per feeder fibre
- Support of 20 to 40 km passive reach option for the working path, depending on the degree of node consolidation
- Support of 60 to 90 km extended reach option for the protection path, depending on the degree of node consolidation
- Extended reach should be realized passively (preferred solution)
- Legacy optical distribution network (ODN) compatibility desirable
- Flexible and agnostic interfaces (optical and service layers)
- Security better than XG-PON1

These requirements are open to revision and refinement as part of an ongoing iterative process centered on WP2 of the OASE project. However, the next requirements iteration is only due to be reported in year 3 of the project. In the meantime, we have been forming an understanding of the implications of these current set of requirements on NGOA architecture design and their associated system technologies and concepts.

In addition to these quantitative and qualitative requirements, in the context of WP3 which provides an in-depth study into the design and topology issues of NGOA architectures, there is also a set of nine architectural Challenges, where each architecture should also be able to comment on or address in some way. These nine challenges are as follows:

1. Dynamic capacity allocation (optimal use of available capacity/end-to-end resource reservation)
2. Quality of Service (QoS) (distinguishing different services/users in a fair way)
3. Open access (allowing multiple operators/service providers in a fair way)
4. Extensibility (extending the network according to network demand and number of users)

5. Energy efficiency
6. Migration (migrating or upgrading the network towards new technologies/standards)
7. Resilience (protection/recovery)
8. Security
9. Future traffic patterns

The manner in which architecture qualitatively addresses each of these challenges should ultimately help to determine which architecture is most likely to be successfully deployed, given an additionally favourable techno-economic argument and a positive business case (with appropriate regulatory approval etc.). The following sections briefly describe the candidate NGOA architectures, each summarising the vision or design-rationale that inspires each architecture, as well as the respective functional topology, and a summary of how each of the architecture meets the nine challenges that also need to be satisfied by each NGOA architecture.

2.1 WDM-PON

In WDM-PON each end-user is served by a dedicated wavelength. The spacing of adjacent wavelengths can vary from dense WDM (DWDM) through to ultra-dense WDM (UDWM)-PONs, and dynamic bandwidth allocation strategies can also be adopted to optimally exploit the available system bandwidth.

2.1.1 Vision and functional architecture

Future WDM-PONs are expected to operate with hundreds of wavelengths and deliver at least 1 Gbit/s data rates per channel over tens of kilometres in order to meet the requirements of next generation FTTH access networks. Today we can see two main trends in WDM-PON design which will play a role in the future. Both of these trends are based on a tree-based network architecture (Figure 2-1). The first design uses a wavelength-selective remote-node based on, for example AWGs, and allows for broadband ONTs without additional wavelength selection. The other uses a legacy ODN based on passive power-splitters, and is a broadcast-and-select network, meaning that the overall signal is broadcast from the optical line terminal (OLT) to all connected ONTs, such that each ONT ultimately selects its dedicated information. As this ODN is transparent, a wavelength-selective ONT is therefore mandatory. If a cost-efficient wavelength-selective ONT can be delivered, one can imagine a future WDM-PON which uses an AWG in the upper part of the tree architecture and a power-splitter in the lower part. This would only slightly decrease the flexibility, but would enhance the performance and support legacy infrastructure. In both approaches, at best, a colourless ONT is required. The functional diagram (Figure 2-2) for a wavelength-split (filtered) WDM-PON is shown below.

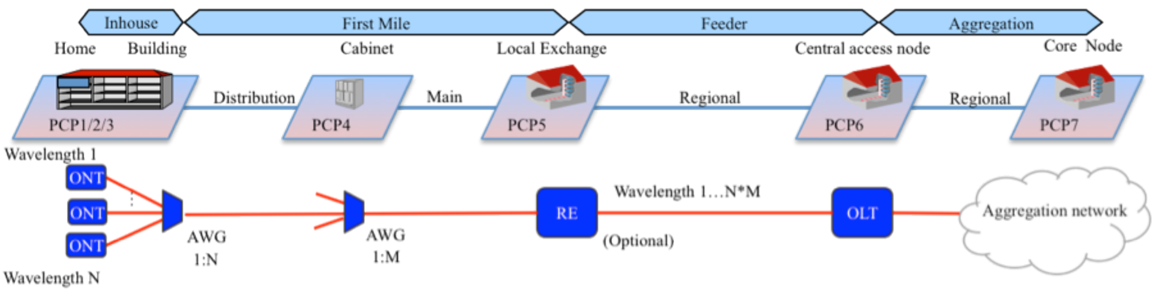


Figure 2-1: Wavelength routed WDM-PON reference architecture.

Application Layers	5 - 7		FP1 RGW*	FP2 ONT (with integr. RGW)					FP5 Edge Router, BRAS
Transport Layer	4								
Network Layer	3								
Packet/Framing Layer	MPLS							FP3/4 OLT	
	ETH MAC		(Opt.)						
Optical/Copper Layer	PHY	ETH							
		TDM		Opt.				Opt.	
	WDM						RE		
Physical Infrastructure Layer	Fibre/Copper		Ethernet	Fiber Socket	AWG	Band Splitter, Interleaver	Fiber	OMDF	OMDF
	Cable						Splices (opt.)		
*) For integrated RGW/ONU, this box is put at PCP2			PCP1 In-home	PCP2 Flat	PCP3 Building	PCP4 Distribution Cable	PCP5 Main Cable	PCP6 Regional Cable	PCP7 Core

Figure 2-2: Functional architecture diagram for wavelength-splitting WDM-PON.

For a wavelength-split WDM-PON, a major parameter is the maximum client count, i.e., the maximum number of accessible wavelengths (where for *N* clients, *2N* wavelengths must be accessible in single-fibre working, unless wavelength re-use is performed between upstream and downstream, which in turn limits the maximum reach). The number of *2N* may also heavily depend on the WDM-PON details, in particular the general colourless approach, or seeded-reflective vs. low-cost tuneable approach that may be adopted. Depending on the AWG characteristics this approach will be limited to about 96 channels per direction per used transmission band (e.g. C- and/or L-band).

The functional architecture diagram (Figure 2-3) for a WDM-PON based on a power-splitter infrastructure (broadcast & select) is shown below.

Layer			PCP1	PCP2	PCP3	PCP4	PCP5	PCP6	PCP7
Application Layers	5 - 7		FP1 RGW*	FP2 ONT (with integr. RGW)					FP5 Edge Router, BRAS
Transport Layer	4								
Network Layer	3								
Packet/Framing Layer	MPLS							FP3/4 OLT	
	ETH MAC		(Opt.)						
Optical/Copper Layer	PHY	ETH							
		TDM		Opt.				Opt.	
	WDM						RE		
Physical Infrastructure Layer	Fibre/Copper		Ethernet	Fiber Socket	Splitter (opt.)	Splitter	Splitter (opt.)	OMDF	OMDF
	Cable								
*) For integrated RGW/ONU, this box is put at PCP2			PCP1 In-home	PCP2 Flat	PCP3 Building	PCP4 Distribution Cable	PCP5 Main Cable	PCP6 Regional Cable	PCP7 Core

Figure 2-3: Functional architecture diagram for power-splitter based WDM-PON

Additionally mixed functional architectures with wavelength splitting at PCP5 or even PCP4 are feasible which still support once deployed legacy ODN infrastructure.

2.1.2 System Challenges

As with all access networks, major open issues with WDM-PONs relate to the importance of the system components and technologies needing to be very cost-competitive, very low in form factor, and very low in energy consumption. These requirements mainly translate into the appropriate availability of three key components: a lowest-cost tuneable laser for ONT applications; a highest-density, lowest-energy-consuming multi-channel transceiver array (photonic integrated circuit or PIC) for OLT applications; and a lowest-insertion-loss, highest-port-count, athermalized, cyclic, multi-band, low-cost AWG. Obviously, all three components constitute major challenges, and are not available today. Without them, WDM-PONs won't be successful in the access arena; however, with them, an access WDM-PON has the potential to outperform any other solution with regard to cost, energy consumption and reach when it comes to high sustainable per-client bit rates.

Table 2-1 analyses the list of system challenges in the context of WDM-PON architectures. It thus covers broadcast & select, as well as wavelength-splitting concepts.

Table 2-1: Comments on the exclusive list of system challenges for WDM-PON

Next Generation Wavelength Division Multiplexed Optical Access Networks (NG-WDM-OAN)	
Comments on the exclusive list of system challenges:	
Challenge	Comments
1	Dynamic capacity allocation. The potential for statistical multiplexing gains also needs to be considered and analysed in the WDM-PON context.
2	QoS. The level of isolation/virtualization needs to be understood, and how this can be achieved in a realistic manner also needs further study.

3	Open access. Understanding the technical and economic constraints for an open access network on virtual PtP connection in WDM-PON (e.g. wavelength unbundling) vs. bit stream access methods needs consideration.
4	Extensibility. How to ensure scaling in the number of users and bandwidth per user without disturbing existing connections at lowest cost is an important issue; whilst how individual users can be upgraded (w.r.t. data rates) without disturbing other users also needs to be analysed for power-splitter as well as wavelength-splitter architectures.
5	Energy efficiency. The right level of necessary electrical signal processing and optical transport needs to be investigated.
6	Migration. The use of infrastructure migration paths based on either power splitting or wavelength splitting, e.g. from a tree or GPON-based architecture, needs to be understood, so as to allow for cost-optimized migration.
7	Resilience. The influence of network elements and link contributions needs to be investigated, particularly for longer reach scenarios.
8	Security. The influence of virtual point-to-point connections on a shared physical medium access architecture (e.g. power splitter-based) needs to be analysed and compared to a wavelength splitter-based architecture.
9	Future traffic patterns. How to handle a future content delivery network (CDN) with more local traffic needs ongoing study. From the point of view of a pure WDM-PON architecture, this can either be handled at the OLT or potentially at an active remote node.

2.2 HYBRID WDM/TDM-PON

Another viable candidate for NGOA fulfilling the initial basic technical OASE requirements set out by deliverable D2.1 is a PON solution with hybrid WDM/TDM employing wavelength routing. Note that the wavelength-routed hybrid WDM/TDM-PON is also referred to as wavelength-switched or semi-passive hybrid WDM/TDM-PON (to avoid confusing with the wavelength-routed WDM-PON). In Chapter 5, we use the term semi-passive hybrid WDM/TDM PON, and for completeness, also passive hybrid WDM/TDM PON is assessed.

2.2.1 Vision and functional architecture

This solution builds on the typical tree structure, and goes into the direction of node consolidation. The proposed wavelength-routed hybrid WDM/TDM-PON consists of a flexible remote node with active optical switches at the first splitting node after the OLT, as shown in Figure 2-4. In deliverable D3.1, it was stated that the exact implementation of this wavelength-routing device (or configurable optical switch) will be further investigated in the course of the OASE project, but that it can consist of e.g. SOA (semiconductor optical amplifier) switches, MEMS (micro-electro-mechanical system) switches, WSSs (wavelength selective switches), ROADMs (reconfigurable optical add-drop multiplexers). In this deliverable D4.2.2, we propose the use of a WSS-based routing device, as it fits well with the main goals we expect from such a device, i.e. to increase the flexibility of the network in a cost-effective way.

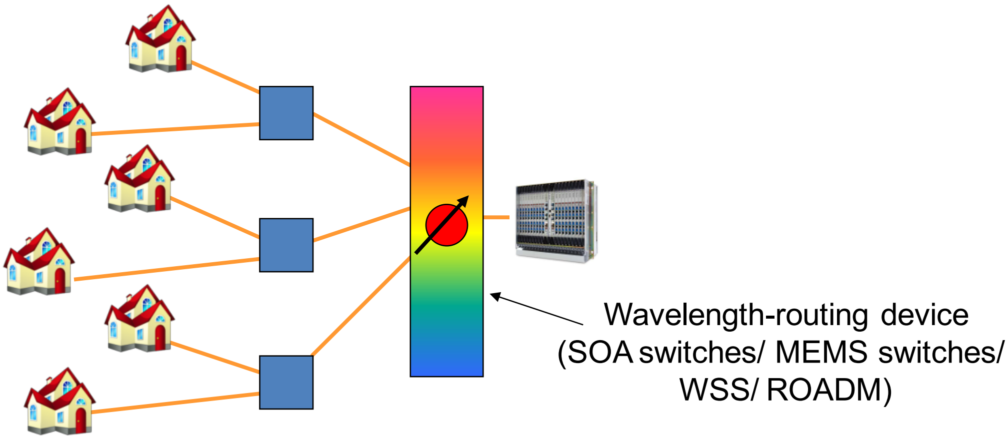


Figure 2-4: Wavelength-routed hybrid WDM/TDM-PON with flexible remote node at first splitting stage

The functional architecture diagram for the wavelength-routed hybrid WDM/TDM-PON is shown in Figure 2-5. The configurable optical switch or wavelength router is placed in PCP5, and as wavelength-routing is done, PCP5 is terminated at the WDM layer at PCP6.

Layer		PCP1 In-home	PCP2 Flat	PCP3 Building	PCP4 Distribution Cable	PCP5 Main Cable	PCP6 Regional Cable	PCP7 Core
Application Layers	5 - 7	FP1 (IP/L2) RGW*	FP2 (optic) ONT (with integr. RGW)					FP5 Edge Router, BRAS
Transport Layer	4							
Network Layer	3							
Packet/Framing Layer	MPLS						OLT (FP3/4)	
	ETH MAC							
Optical/Copper Layer	PHY ETH							
	PHY TDM							
	WDM					Config-urable optical switch		
Physical Infrastructure Layer	Fibre/Copper	Ethernet	Fiber Socket	Fiber Power splitter**	Power splitter Fiber**		OMDF	OMDF
	Cable							
*) For integrated RGW/ONU, this box is put at PCP2 **) Alternatives		PCP1 In-home	PCP2 Flat	PCP3 Building	PCP4 Distribution Cable	PCP5 Main Cable	PCP6 Regional Cable	PCP7 Core

Figure 2-5: Functional architecture diagram for wavelength-routed hybrid WDM/TDM-PON

2.2.2 System Challenges

Table 2-2 analyses the list of system challenges in the context of wavelength-routed hybrid WDM/TDM-PON architectures.

Table 2-2: Comments on the exclusive list of system challenges for wavelength-routed hybrid WDM/TDM-PON

Wavelength-routed hybrid WDM/TDM-PON	
Comments on the exclusive list of system challenges:	
Challenge	Comments
1	Dynamic capacity allocation. The wavelength-routed hybrid WDM/TDM-PON has inherent flexibility in terms of wavelength and time slot allocation. A suitable and fair media access control (MAC) protocol is under study that can exploit the flexibility available within the architecture.
2	QoS. Like challenge 1, the design of the MAC protocol is under study to address the need of different service classes keeping the service level agreement (SLA) in mind.
3	Open access. The wavelength routing facility at the remote node can ensure the open access between service providers at the wavelength granularity. However, a suitable dynamic wavelength allocation scheme has to be designed. For bit stream open access with TDM share, the MAC protocol has to be further enhanced to take care of both users as well as service providers' SLA.
4	Extensibility. Extensibility is one of the natural and inherent facilities of the proposed wavelength-routed hybrid WDM/TDM-PON. We refer to deliverable D3.1 [3] (section 8.2) for further details.
5	Energy efficiency. Energy efficiency is also one of the natural and inherent facilities of the proposed wavelength-routed hybrid WDM/TDM-PON. We refer to deliverable D3.1 [3] (section 8.2) for how the OLT can be operated in an energy-efficient way according to traffic demand. Moreover, we propose to include the option of turning off the ONTs as required through a coordinated MAC protocol.
6	Migration. Migration is one of the major challenges that have to be addressed in the near future for smooth transition of technologies. In the first instance, we propose to use WDM to segregate legacy users and NG users coexisting on the same technology, by grouping them through wavelength-routing. We refer to deliverable D3.1 [3] (section 8.2) for further details. If required and technically feasible, we need to further enhance the MAC protocol for TDM multiplexing of legacy users with NG users.
7	Resilience. Resilience is one of the major challenges with the tree architecture. Further research is required for better resilient systems that can be realized in a reasonably cost-effective manner.
8	Security. Security is again one of the major challenges due to the broadcast nature of the tree structure. However, the wavelength-routed architecture does provide some basic security.

9	Future traffic patterns. Enhancement of architectures as well as MAC protocols will be studied under OASE for supporting emerging traffic scenarios like local multicast and local peer to peer traffic. The remote node with routing capabilities can be designed for keeping the local traffic local, but will still be controlled by the OLT.

2.3 NEXT-GENERATION AON

Next-generation active optical network (NG-AON) is the third candidate for NGOA fulfilling the initial basic technical OASE requirements. This section presents the basic philosophy behind this solution, describes its preliminary functional architecture, and lists the challenges to be met in order to make the solution implementable.

2.3.1 Vision and functional architecture

Current access and aggregation networks, both with AON- and PON-based access, are mainly built according to a tree topology (see Figure 2-6), which makes them similar from a topological point of view. Whereas the main trend for NG-PON is towards consolidation of central offices, the focus for NG-AON is towards utilizing the inherent possibility of resilience in mesh topologies, whilst new locality paradigms in content distribution networks (CDNs) are also in focus (see Figure 2-7).

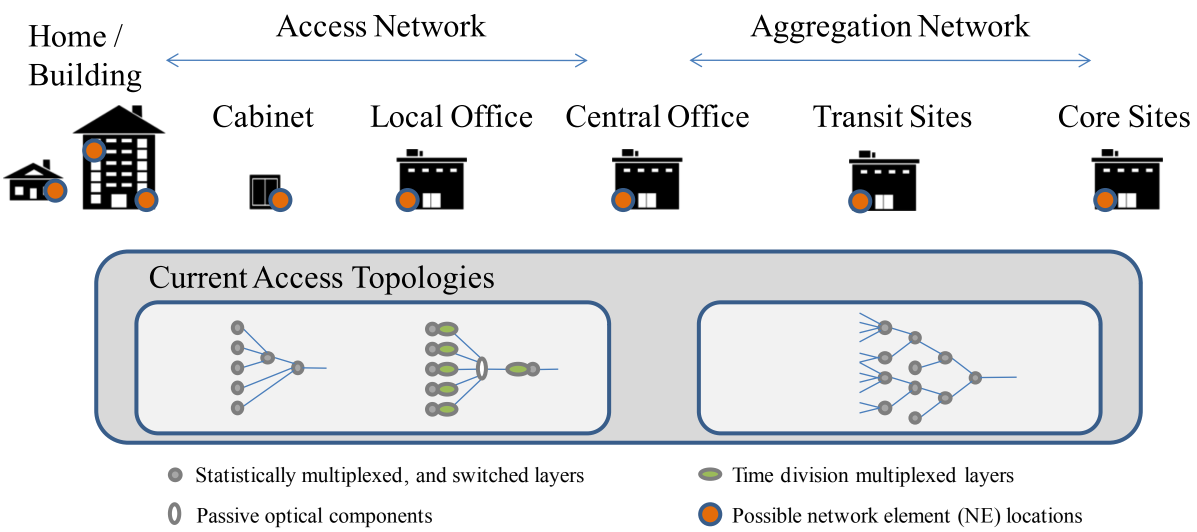


Figure 2-6: The picture schematically describes AON Ethernet active star and Home Run, as well as a TDM-PON based access. Also described is the distribution or aggregation part of the network, which is mainly tree-based in current deployments.

The resilience requirement is mainly driven by the increased dependence on a high bandwidth and high quality broadband infrastructure, e.g., by private and business customers, public services and healthcare ("broadband is the fourth utility"). When it comes to locality aware CDNs, their relevance is made important by, e.g., future peer-to-peer protocols or local caching of information in a "publish and subscribe" type model. The goal here is to offload links towards the core and adhere to the locality in the traffic patterns by allowing local bridging points in well-placed locations. The end result would be a higher degree of mesh or ring topologies, and load balancing in the end-to-end network instead of overloading the central parts.

While not its driving force, consolidation of central offices continues to be a valid option in NG-AON. This can be achieved by the use of already-existing long haul interfaces (up to 120 km is standardized), point-to-point WDM-PON hybrids, and/or dynamically switched optical networks hybrids (rings or mesh) for access distribution means. The latter meets future bandwidth and resilience requirements, and there are also some solutions that could meet the locality requirement through optical sub-wavelength switching.

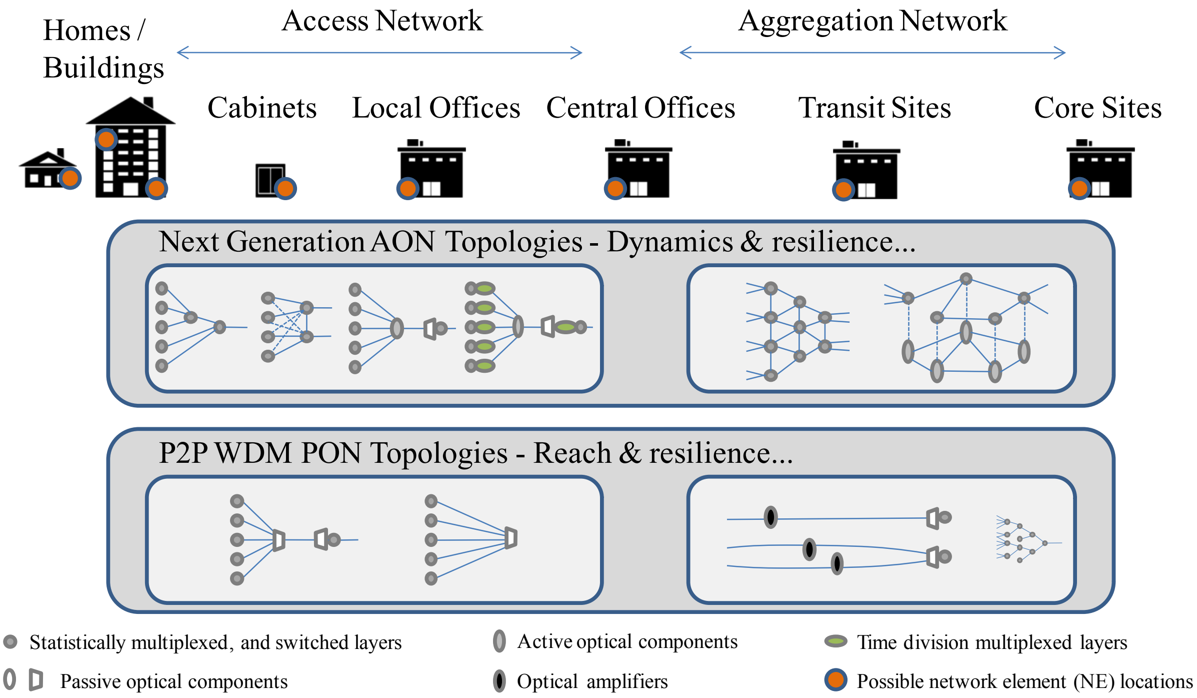


Figure 2-7: New locality paradigms in content distribution networks.

With reference to Figure 2-7, the upper figure schematically shows a number of data plane architectures, where the distinctive mark is the use of active elements, both electrical and all-optical. It also shows a trend in moving towards a higher degree of mesh or rings in order to meet future resilience requirements. The bottom picture indicates active and passive WDM hybrid solutions in order to utilize the fibre medium to a higher degree.

While the main challenges for NG-PON are on the data plane level, i.e. on link level optical transmission and system solutions, in NG-AON the research scope is mainly on an end-to-end network level. The main reason for this is that the physical medium aspects in point-to-point systems are less complex than shared-medium systems (e.g. optical splitter-based), and transport link technology for point-to-point at 1 Gbit/s and higher is rather mature.

In Figure 2-8 the functional architecture for NG-AON is shown, which highlights its great flexibility in offering many possible variants, e.g. the gateway is split (or not, as the case may be); or it allows for gateway forwarding on IP and Ethernet. A dynamic optical transport network (OTN) is shown, which is meant to indicate a ROADM based optical network that can handle the large bandwidth needs of an aggregation network handling an average sustainable bandwidth per customer of 500 Mbit/s. This number also indicates that there might be a need for dynamics at the optical level with a granularity of at least 1 Gbit/s.

Layer		PCP1	PCP2	PCP3	PCP4	PCP5	PCP6.1	PCP6.2	PCP7
Application Layers	5-7								
Transport Layer	4		IP based control*	IP based control*	IP based control*	IP based control*	IP based control*	IP based control*	IP based control
Network Layer	3		FP2 (IP) *	FP3* (IP) *	FP3* (IP) *	FP3* (IP) *	FP3* (IP) *	FP3* (IP) *	FP3 (IP*/Eth*) FP5 / FP6 LER*
Packet/Framing Layer	MPLS		*	*	*	*	*	*	
	ETH MAC		FP2 Eth. ONU	FP3/4* Eth* OLT **	FP3/4* Eth* OLT **	FP3/4* Eth* OLT **	FP3*/4 Eth* OLT **	FP3*/4 Eth	
Optical/Copper Layer	PHY ETH								
	PHY TDM								
	WDM						Dynamic OTN *		
						P2P WDM * **			
			P2P WDM PON * **						
Physical Infrastructure Layer	Fibre/Copper*/ Wireless*		ODF Fibre socket	ODF λ-splitter*	ODF λ-splitter*	ODF λ-splitter*	ODF	ODF	ODF Fibre Socket
	Cable		*						
*) Not necessarily present **) Mutually exclusive		PCP1 In-home	PCP2 Flat	PCP3 Building	PCP4 Distribution cable	PCP5 Main cable	PCP6.1 Regional cable	PCP6.2 Regional cable	PCP7 Core

Figure 2-8: Functional architecture diagram for NG-AON

2.3.2 System challenges

Table 2-3 indicates how the NG-AON architecture addresses the nine challenges, with a focus on the associated systems issues.

Table 2-3: Comments on the exclusive list of system challenges for NG-AON

Next-generation active optical network (NG-AON)	
Comments on the exclusive list of system challenges:	
Challenge	Comments
1	Dynamic capacity allocation. A unified control plane might need to be extended to meet the special requirements in the context of a combined access and aggregation network.
2	QoS. The level of isolation/virtualization needs to be understood, and how this can be achieved in a realistic manner.
3	Open access. The level of control and transparency of the open access (dependent on the type of service provider and QoS aspects, see above) needs consideration.
4	Extensibility. Point-to-point active architectures are very flexible due to the relative simplicity of the data plane. This means that there is a high number of possible network designs making it relatively easy to extend. From a bandwidth point of view, the inclusion of optical technologies also enhances the extensibility.

5	Energy efficiency. The high number of nodes and electronically processed data planes needs attention, with new energy-efficient functions in components and sub-systems, the efficient management of these functions, and their end-to-end network control. The integration of all-optical forwarding elements, w.r.t. to the ease of electronic processing needed, is also an issue. Intelligent traffic management (e.g. CDNs, see Challenge 9 below) at active nodes also can enable more energy-efficient routing strategies.
6	Migration. Unified control planes, virtualization of control and data planes, and network programmability are part of AON's flexibility, and allow easier technology migration.
7	Resilience. Meshed technologies inherently allow for redundant nodes and links, increasing resilience. However, the coordination between the layers in failure/fault scenarios is a challenge in a multi-layer scenario.
8	Security. Point-to-point architectures have an inherently higher degree of security compared to shared medium architectures.
9	Future traffic patterns. There are indications of future CDNs being more local in nature and a highly distributed and meshed topology should have a major advantage in this.

2.4 WDM-PON BACKHAUL

The final architecture considered is the two-stage WDM-PON backhaul concept, which addresses both access and aggregation/backhaul functionalities.

2.4.1 Vision and functional architecture

The combined access/backhaul two-stage WDM-PON backhaul architecture is split into two parts: The part towards the core network is the aggregation WDM-PON; whilst the other part towards the end-user is the access WDM-PON. The latter is almost identical with the (wavelength-split) WDM-PONs discussed earlier, except that it additionally contains integrated backhaul (or uplink) interfaces based on tuneable XFPs (T-XFPs). These T-XFPs allow the two network sections to be interconnected at an active (intermediate) node. In this node, an optical-electrical-optical (OEO) conversion is done, with statistical multiplexing as an option. Of course, the access network part could also be an AON, or hybrid WDM/TDM-PON as previously discussed. However, for simplicity we discuss here an integrated two-stage WDM-PON concept. The aggregation WDM-PON part serves delivers the bandwidth for the access WDM-PON, but also supports other backhaul traffic (wireline (MSAN, GPON), wireless etc.), and can directly connect business customers with dedicated high bandwidths. The use of a simple WDM-PON with tuneable lasers is one of the most promising candidates to provide the highest bandwidth at the lowest overall system cost. Due to the OEO conversion in the intermediate active site, other access technologies could also be used, enabling migration to other technology solutions, e.g. (X)G-PON, and AON etc.

The functional architecture diagram for the most relevant implementation of the WDM-PON backhaul is shown in Figure 2-9. Note, that many other configurations exist due to the high flexibility of the combined access+backhaul approach. However, due to the very long reach capability, it makes the most sense to accommodate the aggregation OLT in PCP7, as is shown in the functional diagram, and also in Figure 2-10.

Layer			PCP1	PCP2	PCP3	PCP4	PCP5	PCP6	PCP7a	PCP7b
Application Layers	5 - 7		FP1 RGW*	FP2 ONU (with RGW)						FP5 Edge Router, BRAS
Transport Layer	4									
Network Layer	3									
Packet/Framing Layer	MPLS						FP3 Access OLT		FP4 Aggr. OLT	
	ETH MAC		(Opt.)							
Optical/Copper Layer	PHY	ETH								
		TDM		Opt.			Opt.		Opt.	
	WDM			ONU			OLT		OLT	
Physical Infrastructure Layer	Fibre/Copper		Ethernet	Fibre Socket	Fibre AWG**	AWG BS / IL**	BS / IL Fibre**	AWG	OMDF	OMDF
	Cable									
*) For integrated RGW/ONU, this box is put at PCP2 **) Alternatives			PCP1 In-home	PCP2 Flat	PCP3 Building	PCP4 Distribution Cable	PCP5 Main Cable	PCP6 Regional Cable	PCP7a Core	PCP7b Core

Figure 2-9: Functional architecture diagram for two-stage WDM-PON Backhaul

The corresponding architecture block diagram is shown in Figure 2-10.

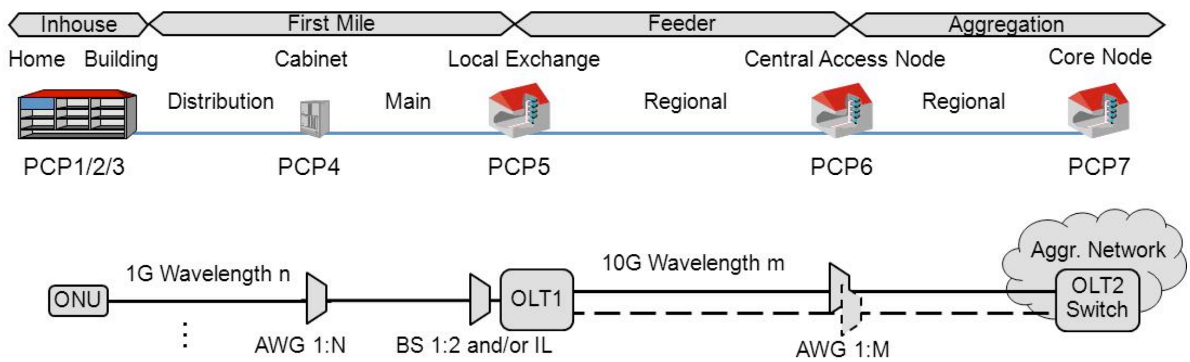


Figure 2-10: Two-stage WDM-PON Backhaul reference architecture

2.4.2 Backhaul System challenges

The challenges to be tackled are addressed to the backhaul part of the network, since the front, access section of the network (e.g. WDM-PON, Hybrid PON, and AON) is already considered earlier, and the two sections are separated with regeneration/termination in between. Most of the open issues relate to the definition of the wavelength grid (including number of wavelengths), the associated availability of suitable components, and the auto-tuning of these components. If the backhaul WDM-PON must use single (main or regional) fibres, it must potentially make use of cyclic AWGs. In this case, the upstream/downstream wavelength grids may also deviate from one another. This must be considered for the transceivers intended for this application, i.e., tuneable XFPs. In this context, it is expected that T-XFPs for the L-band will only become available over the next few years, and it is likely that they will be based on a standard 50-GHz grid. There could be a certain mismatch with single-fibre working, which could be potentially overcome by de-tuning the T-XFPs onto the respective L-band grid (e.g., ~48.5 GHz). Furthermore, in order to achieve a fully flexible concept, an additional issue is that the T-XFPs in the active intermediate site (cabinet or local exchange) should be able to autonomously tune onto the correct wavelength. This is necessary to support arbitrary active equipment which has to be backhauled. Hence, concepts for autonomous tuning of decentralized pluggables (T-XFPs here) must be developed. Such concepts can, for example, be based on establishing embedded communications channels (ECCs) to/from these T-XFPs. Subject to the availability of C-band and L-band T-XFPs, concepts with regard to both channel grid compatibility and autonomous tuning need to be developed.

The evolved-list challenges are addressed by the two-stage WDM-PON architecture concept as listed in Table 2-4.

Table 2-4: Comments on the evolved list of system challenges for two-stage WDM-PON Backhaul

WDM-PON Backhaul	
Comments on the evolved list of system challenges, specifically addressing Backhaul Network:	
Challenge	Comments
1	Dynamic capacity allocation. WDM-PONs (if not combined with means for optical switching, e.g. see Hybrid WDM/TDM-PON) provide static transport pipes with a maximum guaranteed bandwidth. In the context of the two-stage WDM-PON, flexibility and dynamic bandwidth allocation can be provided in the two OLTs (aggregation OLT, access OLT), within the limits of the maximum per-channel bandwidth. This can include over-subscription (statistical multiplexing) to be provided in the access OLT.
2	QoS. QoS, service classes and associated customer classes can be provided on the upper layers (Layer-2). On the wavelength layer it can be possible to assign different clients with different per-wavelength bandwidths, e.g., 1G vs. 10G. However, this may contradict the OLT multi-channel integration approach.
3	Open access. Access can be provided on a per-wavelength layer, whilst an additional (Layer-1) TDM layer is also possible. Further, access can be provided on higher layers, e.g., VLAN.
4	Extensibility. The general advantages of WDM transport apply. WDM is inherently transparent with regard to bandwidth, protocols, and even requirements like latency. It is also possible to extend total capacity through the use of cyclic, multi-band AWGs.
5	Energy efficiency. Depending on available components (low-power tuneables, PICs, etc.), WDM-PONs are the most energy-efficient for high sustainable bit rates, since no component has to run on aggregated capacities but rather on per-client capacity. Further, the integration of access and backhaul helps eliminate additional (transponder) interfaces. Finally, ODN insertion loss is lowest in a wavelength-split PON which allows transceivers to run on lower power.

6	Migration. Migration is possible because the backhaul part can also be used for (X)G-PON backhaul, and is generally technology agnostic to the actual access architecture solution.
7	Resilience. Several variants of protection and dual-homing can be provided for both the backhaul and the access parts.
8	Security. Security in a wavelength-split WDM-PON is already inherently higher than in broadcast PONs. Neighbouring-channel separation is typically >20dB, and separation with regard to non-adjacent wavelengths is even higher. Hence, there is less chance for rogue ONTs or malicious users to disturb the rest of the PON.
9	Future traffic patterns. Future traffic patterns (peer-to-peer, local traffic) can be considered through both OLTs (aggregation, access OLT) involved in the two-stage WDM-PON concept. Depending on the functionality implemented in these OLTs, local traffic switching can be implemented on two network levels, thus providing high flexibility with regard to unknown future requirements.

2.5 BRIEF OVERVIEW OF CANDIDATE ARCHITECTURES

Having briefly discussed the four candidate architectures and presented some of the key systems issues associated with each, we provide a synoptic figure representing the four NGOA architectures, side-by-side, to facilitate easier comparison of their respective topologies. We note in particular the use of either (X)G-PON or Ethernet-based AON access networks in the two-stage access+backhaul (aggregation) representation of Figure 2-11(D).

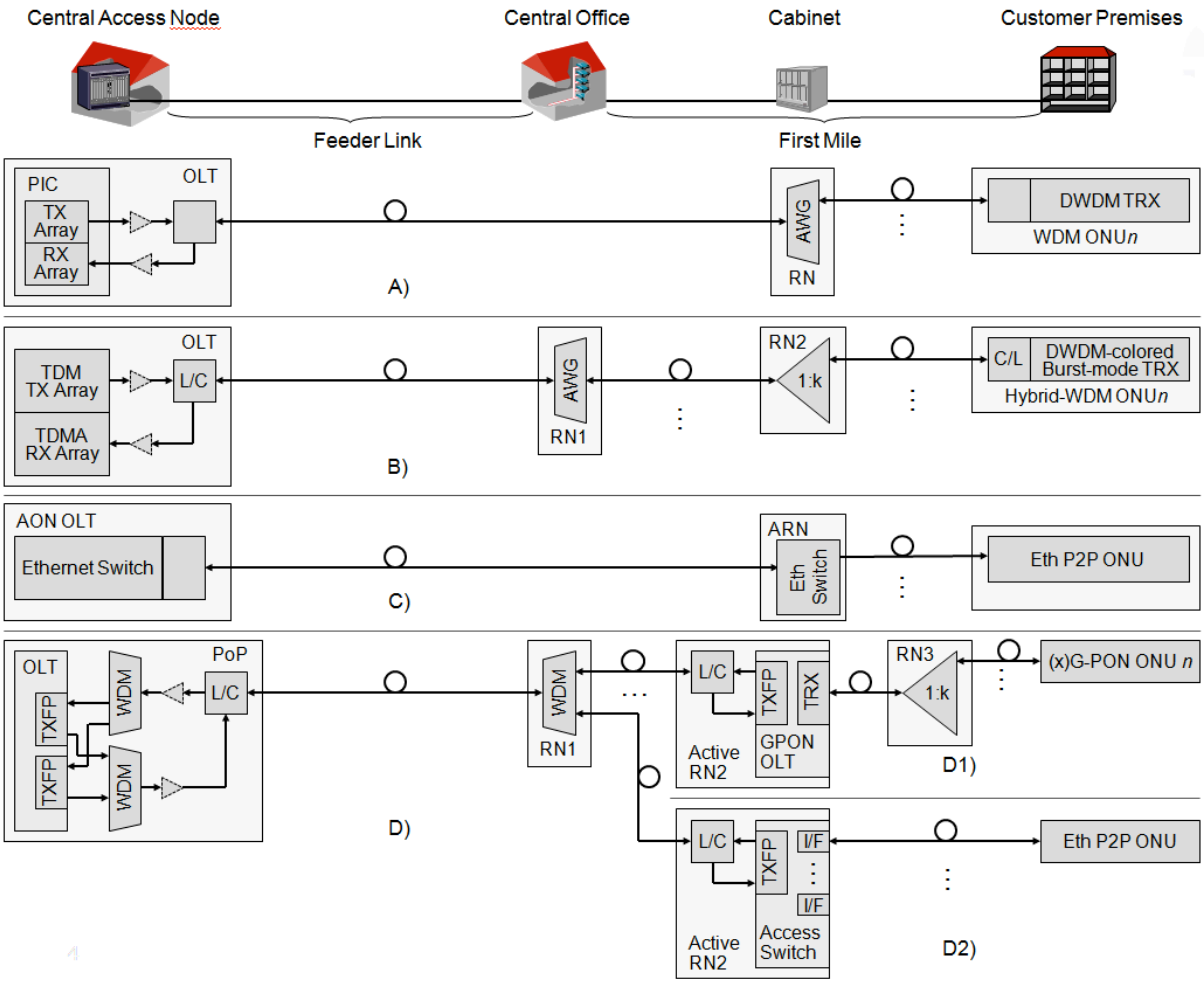


Figure 2-11: Topological representation of the four candidate NGOA architectures, side-by-side: A) WDM-PON, B) Hybrid WDM/TDM-PON, C) NG-AON, D) WDM-PON Backhaul network.

3. Technical requirements for next generation optical access systems

A comprehensive discussion and analysis of the choices of technical requirements anticipated for future NGOA architectures and (sub-)systems has been presented in the previous deliverable D2.1 [2]. In that deliverable, a complete identification of the various service-based, network, and operational requirements were described, and which formed the boundary conditions to assist in the choice and selection of the architecture options described in the subsequent deliverable D3.1 [3]. In this deliverable D4.2.2 we are focusing on the candidate system technologies which will underpin the anticipated NGOA architectures as summarized in the previous chapter.

By way of reminder of what the specific technical requirements are, this chapter presents a brief summary of those key requirements, which have been designed to be generic and agnostic to any particular technology choices and/or architecture options. At this stage of the OASE project these are the requirements as provisionally identified during the 1st year of the project. Following from the initial choices of technologies, systems and architectures, and also in the light of the subsequent and ongoing experience and accumulated knowledge into the issues facing NGOA network deployment, these requirements may be further refined, modified and adapted in an iterative fashion – indeed this is how the OASE project has been constructed. This iterative informing and feedback process between the various workpackages of the project is highlighted in the following Figure 3-1.

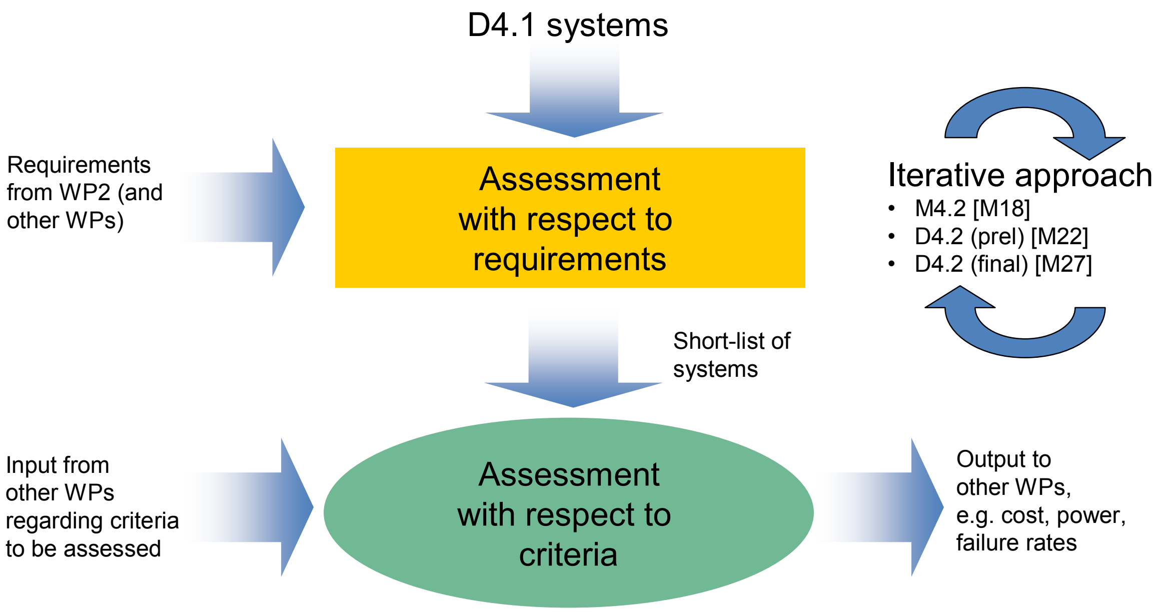


Figure 3-1: Functional relationship diagram for WP4 as it iteratively relates to other WPs

For example, without prejudicing the upcoming WP2 re-review of the requirements and their consolidation into the associated deliverable D2.2, one particular implicit requirement related to the number of feeder fibres per architecture is assumed to be one; however, in the interests of flexibility for enabling physical Open Access potentialities, multiple feeder fibre options should also be allowable. That said, this particular requirement is probably more related to operational aspects and requirements for system technologies, which is covered by the accompanying deliverable D4.3.2.

The NGOA requirements have been grouped into three distinct areas: service, network and operational requirements. The first two are covered in this deliverable D4.2.2, whilst the latter one is covered in deliverable D4.3.2.

As part of the iterative aspect to the ongoing consideration and evaluation of the requirements as initially presented in deliverable D2.1, we have also assigned a simple priority or importance classification to the requirements as identified: High, Medium, and Low. This has assisted in understanding which requirements should be emphasised and allowed to exert a greater influence on the choices associated with system technology selection.

In the earlier interim deliverable D4.2.1 we provided an initial assessment of those requirements which are most closely related to the issues of cost (CapEx), energy consumption, physical footprint, failure rates, reach, and client-count; i.e. the criteria items 1-4, 9, headlined Bandwidths, QoS, Architecture Design Rules, Extensibility, and Costs. In this final version of the deliverable D4.2.2 we have provided a more qualitative assessment of the remaining criteria, and how they relate to the various system designs. In addition, failure rates are now examined in greater detail in the accompanying deliverable D4.3.2. We have also updated the quantitative studies of the initial requirements 1-4, & 9, to provide a more accurate assessment of their relative values.

The service and network criteria (as relevant to this deliverable D4.2.2), complete with their associated quantitative requirements and assigned priority ratings are now tabulated as follows:

Table 3-1: Criteria/Requirements/Priorities

CRITERIA	REQUIREMENT	PRIORITY
1. Bandwidths:		
• FTTH residential peak rate	≥1 Gbit/s	High
• Business, backhaul peak rate	≥10 Gbit/s	High
• Average sustainable D/S based on peak-hour service usage	500 Mbit/s per ONT/Customer	High
• U/S – D/S traffic symmetry	<1:2 ratio	Medium
• Aggregate capacity per feeder fibre	128 Gbit/s - 500 Gbit/s	Medium
2. QoS:		
• Residential/business: delay	< 1ms (for highest service class)	High
• Residential/business: jitter	<< 1ms (for highest service class)	High
• Residential/business: BER	< 1,00E-07 (for highest service class)	High
• Residential/business: Packet loss rate:	< 1,00E-05 (for highest service class)	High
• RAN transport: delay	5 ms for S1, 20 ms for X2	High
	5 ms for S1, 1 ms for X2 (CoMP)	Low
• RAN transport: synchronization	freq. ±50 ppb, timing 1-50 µs	High
	freq. ±5 ppb, timing 1 µs (CoMP)	Low
3. Architecture Design Ratios:		
• No. of ONTs/customers per feeder fibre	256-1024	Medium
4. Extensibility:		
• Base Reach	Support 20-40 km passive reach option for working path	High
• Extended Reach	Support 60-90 km extended reach	High

	option for protection path, depending on degree of node consolidation	
• Extended Reach Realisation	Passive	Low
5. Upgradeability:		
• ODN compatibility	Legacy ODN (GPON)	High
• Migration	Allow co-existing generations	High
• Interfaces (optical & service layers)	Flexible & agnostic interfaces	High
• Future Proof	Future traffic patterns	High
• CDN's	Incorporate CDN	High
6. Mobile Backhaul		
• Mobile fronthaul	≥10 Gbit/s	Low
• Mobile convergence	Allow wireless final-drop access	High
7. Resilience:		
• Resilience	(Where does protection start?)	High
• Dual Homing	(Where does dual homing start?)	High
8. Security		
• Rogue ONTs	Immune to rogue ONTs etc.	High
• Malicious user	No Hacking	High
9. Costs:		
• Energy Efficiency	Power per line ≤ than today	High
• CapEx	Low cost	High
10. Regulatory:		
• Open Access	L1-L2	High

Of particular relevance is that we have now chosen to make mobile backhaul an explicit criterion in its own right, rather than as a part of the upgradeability criterion. Although still not particularly quantifiable (in terms of creating a useful analysis to differentiate between different NGOA system variant solutions) the emergence of the importance of mobile convergence (including mobile fronthaul discussed in 6.4) requirements has become significantly more apparent over the course of the OASE project. Although OASE is primarily concerned with optical technology solutions for next-generation access networks, the importance of wireless technologies (e.g. final-drops etc.) is increasingly clear.

The quantitative results described in the subsequent chapters of this deliverable will be used in conjunction with other data from deliverable D4.3.2, as well as other results from the other work-packages, to conduct a comprehensive comparative techno-economic study of the various systems and their variants. Those requirements that do not allow for such a direct quantitative comparative analysis (e.g. upgradeability, security, mobile backhaul capability) are also important criteria, and will also be of significant importance when planning migration and roll-out strategies, and which system solutions to deploy. However, since their evaluation is more subjective in nature (and will often also be critically dependent on the context of any deployment, in terms of legacy, co-existence, green/brown-field, etc.) an equivalent quantitative approach is not appropriate at this stage. However, in this deliverable, we provide the outlines of an analytical framework that can be employed and elaborated upon, in undertaking a future comparative analysis.

4. Methodology and assumptions

In order to create a suitable level playing-field for the assessment of the various systems and subsystems, we discuss in this chapter the methodology and underlying assumptions made in order to perform a useful comparative analysis. In the contexts of the architectural levels, we have already discussed the nine challenges that will be used for the comparison of the candidate architectures. This is in addition to the set of basic requirements (WP2) which all architectures are also assumed to satisfy. However, in order to perform an insightful analysis of the system and subsystem technologies we need a set of additional criteria which we will consider and which will form the basis for this initial comparative analysis. In the earlier deliverable D4.2.1, the basic criteria for differentiating between the NGOA concepts considered were cost, energy consumption, reach, client count per OLT port, and floor space. The assessment with respect to these criteria is based on the developed models, which are elaborated upon in more detail in this chapter. Assessment of reach and client count per OLT port is based on power budget modelling, whilst cost, floor space and energy consumption is based on modelling of the different system configurations. In this current deliverable D4.2.2 we are also providing additional detail on the resilience, security, upgradeability, and mobile backhaul requirements which NGOA systems will have to satisfy. These criteria are discussed in Chapter 6. Quantifying adherence to these requirements is not so obvious; in which case we do not provide any additional quantitative analysis of the systems as to how they satisfy these additional requirements. Indeed, our expectation is that each system will satisfy these base requirements, so that on their own they won't act as a differentiating factor between the various system variants; as long as each requirement is satisfied. Instead, we present generic solutions and technology approaches to satisfy these requirements, which will be in general applicable to all the systems studied in this deliverable.

4.1 Attenuation model

For fair comparison of the NGOA concepts, the same attenuation model was applied in all investigations (Figure 4-1). It comprises a total penalty of 5.5 dB for in-house patching, cabling, and additional measurement couplers etc. in the central access node (CAN) and the central processor (CP). We accounted for 2 dB loss at the CP and 3.5 dB at the CAN. An End-of-Life (EOL) fibre attenuation of 0.34 dB/km for the C/L-band and 0.44 dB/km at 1310 nm is assumed. These values cover older (feeder) fibre with non-perfect characteristics and also include an EOL margin for fibre repair. In terms of power budget, laser safety is the primary limiting factor for systems with high channel count per fibre. Therefore, all system configurations have been designed to comply with laser safety class 1M (i.e., a total power of +21.34 dBm for wavelengths >1400 nm) without fast power shutdown. For some systems, where necessary, per-wavelength power has been further decreased to an optimum level with regard to fibre non-linearity.

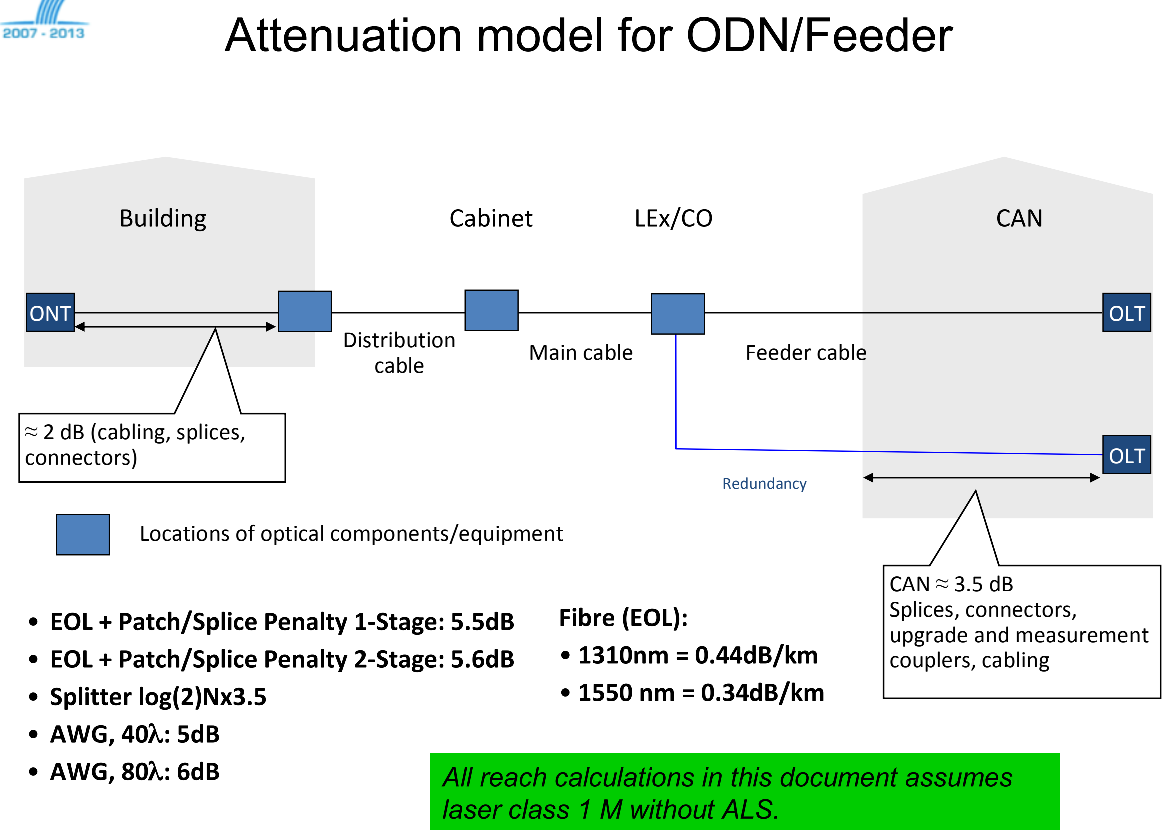


Figure 4-1: OASE attenuation model

4.2 Components and Subsystems

Cost and power consumption parameters have been adjusted to the 2020 time horizon. Reasonable assumptions on the evolution of technology as well as cost and power consumption have been made. The calculations regarding cost, power consumption, form factor and reach are based on the respective performance of the key components or sub-systems of the respective system configurations. The relevant parameters are summarized in Table 4-1. Most of these parameters have been published in [1], and they have been extensively discussed in industry fora like FSAN, conferences and workshops ([4], [5]), research projects ([6], [7]), and bilaterally with various components vendors. All cost figures assume forward pricing at fully ramped-up high production volumes, while the relative cost values are provided with respect to a simple style G-PON ONT. Cost values for reference technologies, GPON and XG-PON, are less aggressive in the sense that they do not assume a leap in technology. Relative cost values are based on a complexity analysis and the potential for monolithic integration of the respective components. They are also based on long-term observations of the cost differences of transceivers running at 1, 2.5, and 10 Gbit/s, respectively.

All power consumption figures assume power and energy efficient design (e.g., transmitters without a thermo-electric cooler (TEC), 40 nm complementary metal-oxide semiconductor (CMOS) technology). Power-saving modes have not yet been considered. Optical power budget and insertion loss (IL) figures are standard values which are achievable under cost-effective mass production. The components figures for power budgets/IL, power consumption, and cost are subject to uncertainty increasing in this order (i.e. power budget/IL are very stable, while relative cost exhibits the highest uncertainty). However, in a network-wide analysis which also takes fibre and duct cost, fibre downtime, systems failure rate and other operational expenditures (OpEx) aspects into consideration, the influence of any single cost figure is low. Changing single figures within reasonable limits of ±20 % has no significant impact on the results presented hereinafter. For clarity, we therefore do not present error bars.

Table 4-1: Components and sub-system parameters

Component or Sub-system	Power Budget / Insertion Loss	Power Con.	Rel. Cost
Tuneable Laser / PIN-PD TRX (SFF, 1.25 Gbit/s)	28 dB	W	1.1
Tuneable Laser / APD TRX (SFF, 1.25 Gbit/s)	38 dB	1.2 W	1.6
TRX Array 40 x 1G, PIN-PD	28 dB	20.0 W	40
Opt. Frontend heterodyne QPSK (1.25 Gbit/s)	45 dB	1.2 W	2.2
Intradyne ADC / DSP (1.25 Gbit/s QPSK)	-	1.0 W	0.2
Opt. Frontend heterodyne QPSK (8 x 1.25 Gbit/s)	45 dB	3.0 W	12
Intradyne ADC / DAC / DSP (8 x 1.25 Gbit/s QPSK)	-	2.0 W	1.6
Tuneable 10 Gbit/s burst-mode TRX, incl. FEC	35 dB	2.3 W	3.0
TRX Array 10 x 10G burst-mode, incl. FEC	35 dB	20.0 W	26.3
SFP, 1310 nm, 10 dB	10 dB	0.5 W	0.3
Tuneable XFP (TXFP), 26 dB	26 dB	3.5 W	8
Multi-terminal card for 8 x TXFP/SFP+	-	8.0 W	8
FEC (1.25 Gbit/s, NECG = 3 dB)	+3 dB	0.2 W	0.1
Pre-Amplifier card (EDFA)	+10 dB	12.0 W	15
Fibre attenuation, C/L-band	0.34 dB/km	-	-
EOL penalty for fibre repair and in-house cabling	5.5 dB	-	-
Athermal cyclic AWG 1:20 / 1:40 / 1:80 (200 / 100 / 50 GHz)	5.0 / 5.0 / 6.0 dB	-	6 / 12 / 24
Diplexer / circulator / interleaver 25 GHz	1.5 / 1.0 / 2.5 dB	-	0.3 / 2 / 12
$1:2^N$ power splitter/combiner (PS)	$N \cdot 3.5$ dB	-	0.2
ONT (housing, System-on-Chip, PSU, client interfaces)	-	3.0 W	0.6
OLT Shelf (20 slots, PSU, management), per slot	-	6.0 W	5.0
Aggregation switch, per 1 Gbit/s	-	1.0 W	0.1

Transceiver power budgets, FEC gain, components and fibre IL, and penalty together account for the achievable fibre power budget or reach capability. Laser safety class 1M poses a limitation on allowable per-channel transmit power for WDM configurations with high channel count. For low channel count (e.g., 20 channel Hybrid WDM/TDMA-PON), we limit the maximum per-channel fibre-coupled transmitted power to +7 dBm in order to avoid excessive stimulated Brillouin scattering (SBS). In addition, we also limit the per-channel transmitted power for the coherent UDWDM-PON (with $\Delta f = 3$ GHz) for channel count <240 to -2 dBm in order to avoid excessive penalties caused by four-wave mixing. Above 240 channels, per-channel power is then limited by laser safety only. For both the low-cost tuneable laser and the seeded reflective electro-absorption modulator semiconductor optical amplifier (REAM-SOA), the guaranteed EOL fibre-coupled modulated transmitted power is assumed to be up to +6 dBm. For direct-detection PIN-PD/APD (at 1.25 Gbit/s, incl. forward error correction net effective coding gain (FEC NECG) = 3 dB) receiver sensitivity is assumed to be -25 dB / -35 dB, and for heterodyne QPSK (at 1.25 Gbit/s, incl. FEC NECG = 3 dB, polarization diversity) sensitivity is assumed to be -50 dBm.

The OLT and ONT can each be partitioned into a baseline part carrying common components and a system specific part carrying the system specific components. Models are presented in Figure 4-2 and Figure 4-3.

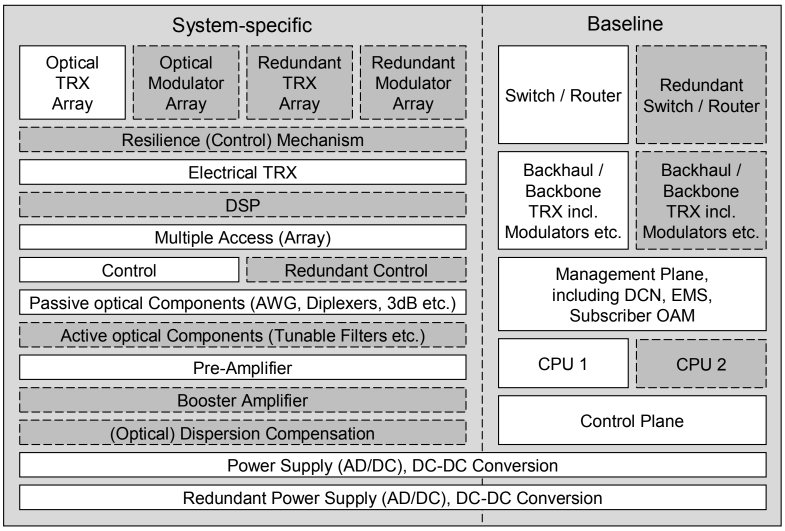


Figure 4-2: OLT model

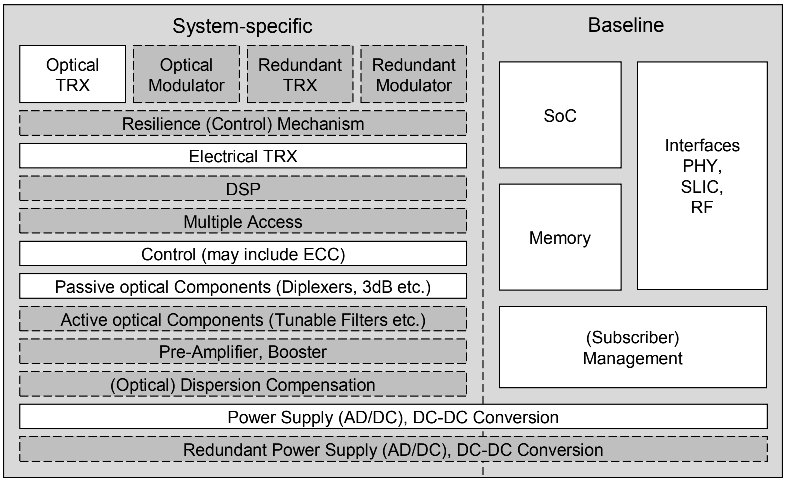


Figure 4-3: ONT model

In order to appropriately compare floor space and power consumption characteristics, we have assumed the following rack and shelf model in all configurations (Figure 4-4): a rack with 44 height-units and total height of 77'' which carries (maximally) four shelves. Each shelf includes mechanics, backplane, redundant power supply, management, and Layer-2 (L2) switching which can be incremented in steps of 100 Gbit/s. The guaranteed data rate of 300 Mbit/s or 500 Mbit/s per client is also assumed for dimensioning the required L2 switch capacity. Each shelf provides 20 slots, where two slots per shelf are reserved for the uplink.

The following cost and power assumptions are therefore used:

- Basic shelf cost: 100 (cost share / tributary slot: 100/18=5.56)
- Basic shelf power: 90W (power consumption share / tributary slot = 90W/18 = 5W)
- L2 switch cost: 0.1/Gbps
- L2 switch power consumption: 1W/Gbps

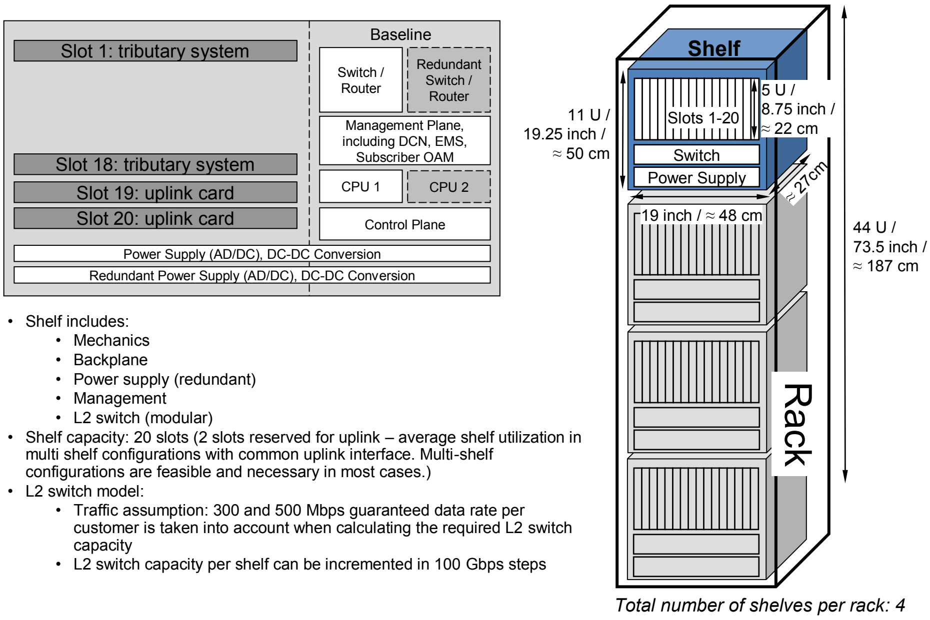


Figure 4-4: Rack/shelf model

A modified rack/shelf model (Figure 4-5) has been used for concepts based on WDM-PON backhauling of active remote nodes. An extra passive type shelf is introduced which carries the 2x40ch AWGs used in the WDM-PON backhauling concept.

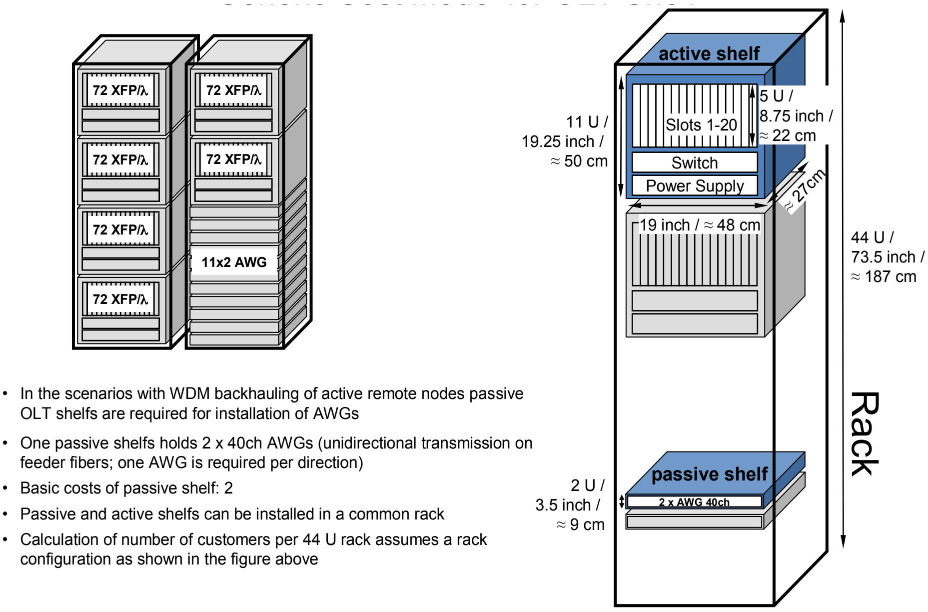


Figure 4-5: Modified rack/shelf model for hybrid active systems based on WDM-PON backhaul

A generic equipment model were also developed for the active remote nodes. Figure 4-6, Figure 4-7, Figure 4-8, Figure 4-9 show the model adjusted to the three drop technologies addressed by WDM-PON backhaul.

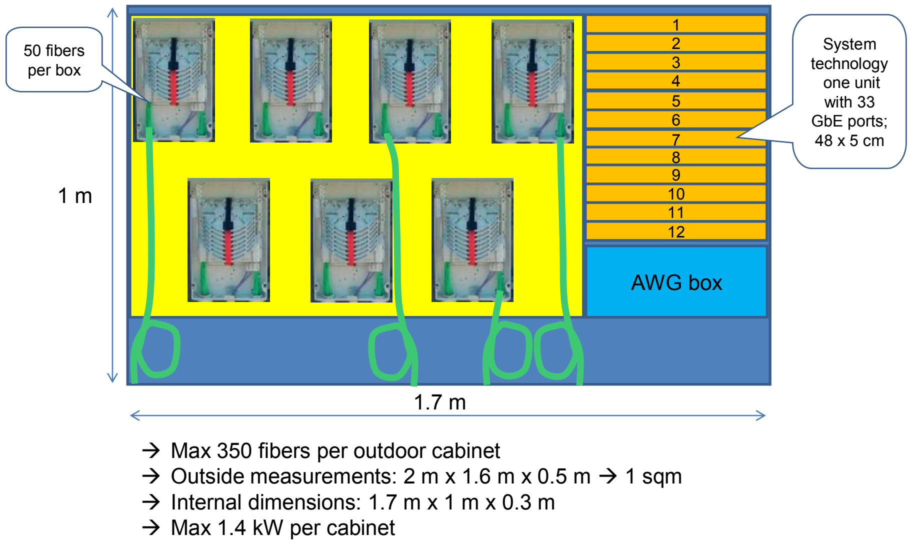


Figure 4-6: Remote node model: Ethernet PtP backhauled by WDM-PON

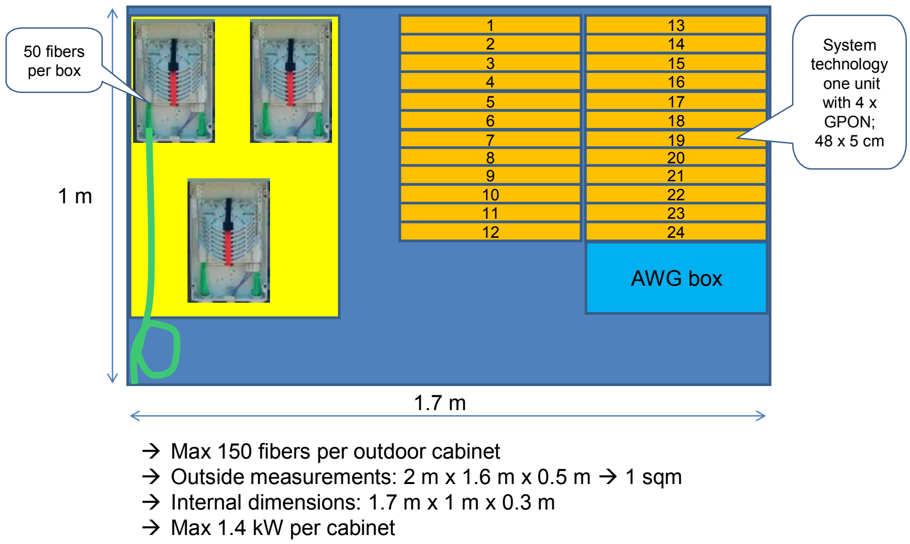


Figure 4-7: Remote node model: GPON backhauled by WDM-PON

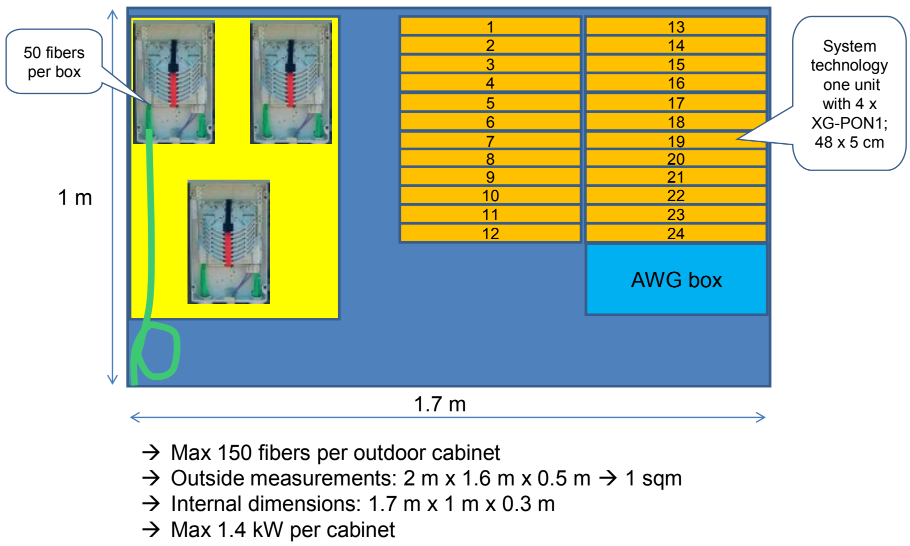
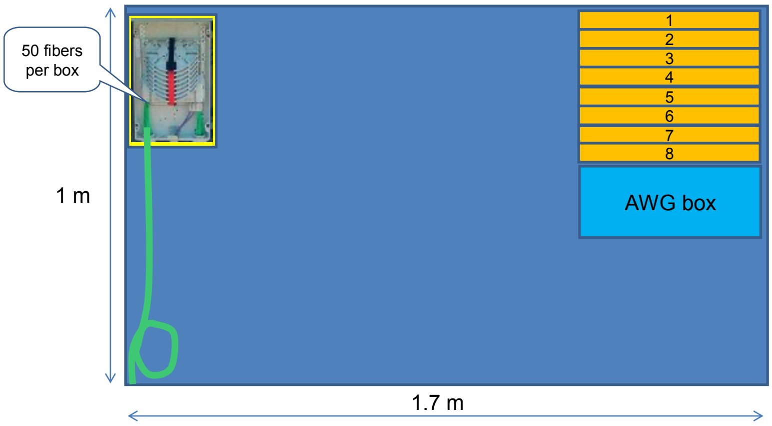


Figure 4-8: Remote node model: XG-PON backhauled by WDM-PON



→ Max 150 fibers per outdoor cabinet
→ Outside measurements: 2 m x 1.6 m x 0.5 m → 1 sqm
→ Internal dimensions: 1.7 m x 1 m x 0.3 m
→ Max 1.4 kW per cabinet

Figure 4-9: Remote node model: DWDM-PON backhauled by WDM-PON

5. Quantitative assessment of NGOA candidate systems

Having discussed the basic methodology, requirements and underlying assumptions to be employed in our assessment of the systems and sub-systems for NGOA, in this chapter we now present the various architecture flavours which deploy the systems technologies in various topological arrangements. As discussed earlier in Chapter 2, there are four main architecture classes that we are studying in depth: WDM-PON; hybrid WDM/TDM-PON; next-generation AON; and WDM-PON backhaul. However, within each of these architecture classes there are various architectural variants or flavours which need to be considered so as to form a comprehensive assessment. Each section of this chapter considers an architecture class, but discusses the various most-attractive variants which we consider as realistic candidate solutions for NGOA. Each architecture variant is described at its system level in some detail, outlining the design choices that have been made, and the topological and system layouts adopted. As already described in Chapters 3 & 4, the specific NGOA requirements that we are quantitatively concentrating on in this deliverable D4.2.2 are: cost; energy consumption; reach; and client count per OLT port.

The following diagram (Figure 5-1) depicts the relationships of the various architectural variants within a cut-down family-tree arrangement of possible NGOA architectures. The original more comprehensive OASE tree diagram was first shown in the deliverable D2.1 [2]. Here, the architecture flavours which are being studied in greater depth in this deliverable are also shown in the various architecture classes, to provide additional context for these variants and how they represent a cross-section of the available possible variations, and also to provide a good overall overview. The hybrid-PON class is connected to both the passive and active RNs of the tree, to signify the passive and semi-passive hybrid WDM/TDM-PONs studied here. In the following discussion, cost all data are reported in terms of the GPON ONT cost which was set to 1.

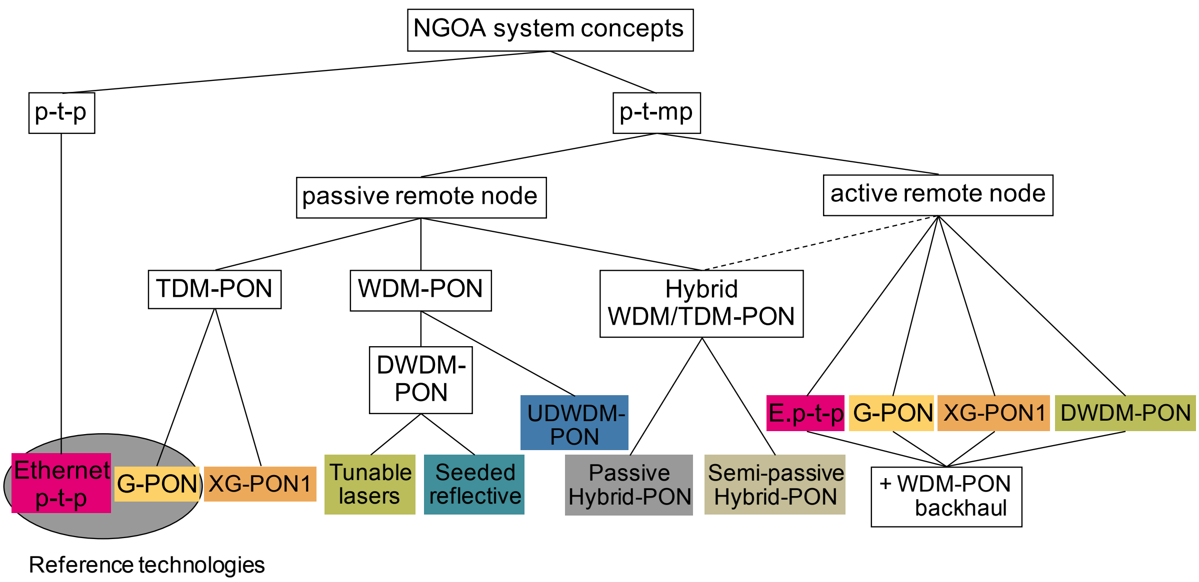


Figure 5-1: OASE system concepts

5.1 G-PON and XG-PON1 Reference Technologies

TDM-PON systems provide limited reach and capacity in relation to the NGOA requirements as listed in deliverable D2.1. As a benchmark of current state-of-art systems, the cost and performance models for G-PON and XG-PON1 are here reported for reference, and also as elements in the hybrid active concepts which are based on WDM-PON backhaul. In particular, cost and power consumption values are calculated for current (2012) and future (2020) designs, to provide a suitable reference platform for the comparative studies of the NGOA system variants.

5.1.1 G-PON

Figure 5-2 shows the PCP assignments for an architecture based on G-PON. The G-PON OLT would typically be placed at PCP5 or potentially at PCP6 with use of active reach extension. The cost and power models for G-PON are presented in Figure 5-3 and Figure 5-4. Two power budget classes are considered for the OLT and the reach-extender optics.

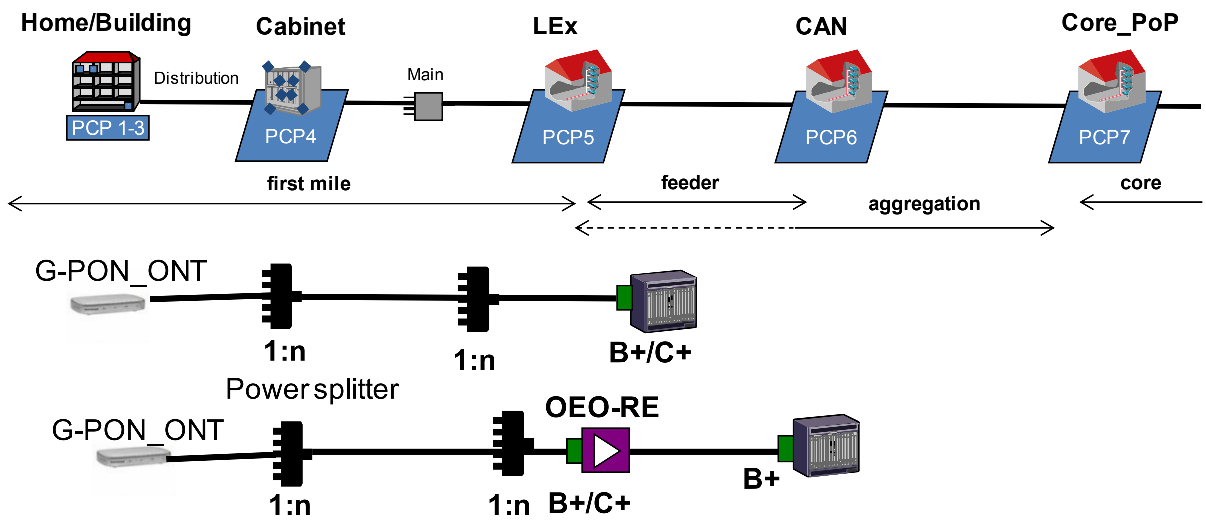


Figure 5-2: G-PON system and assignment to PCP sites

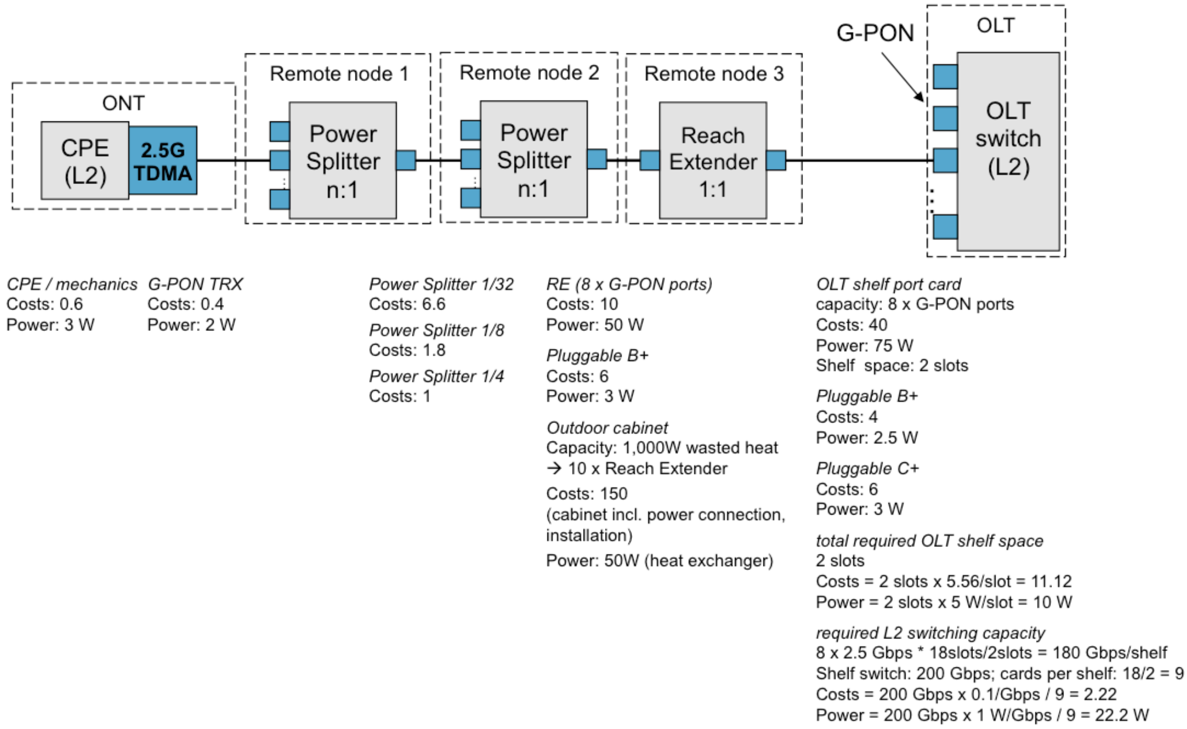


Figure 5-3: G-PON cost and power model (values in 2012)

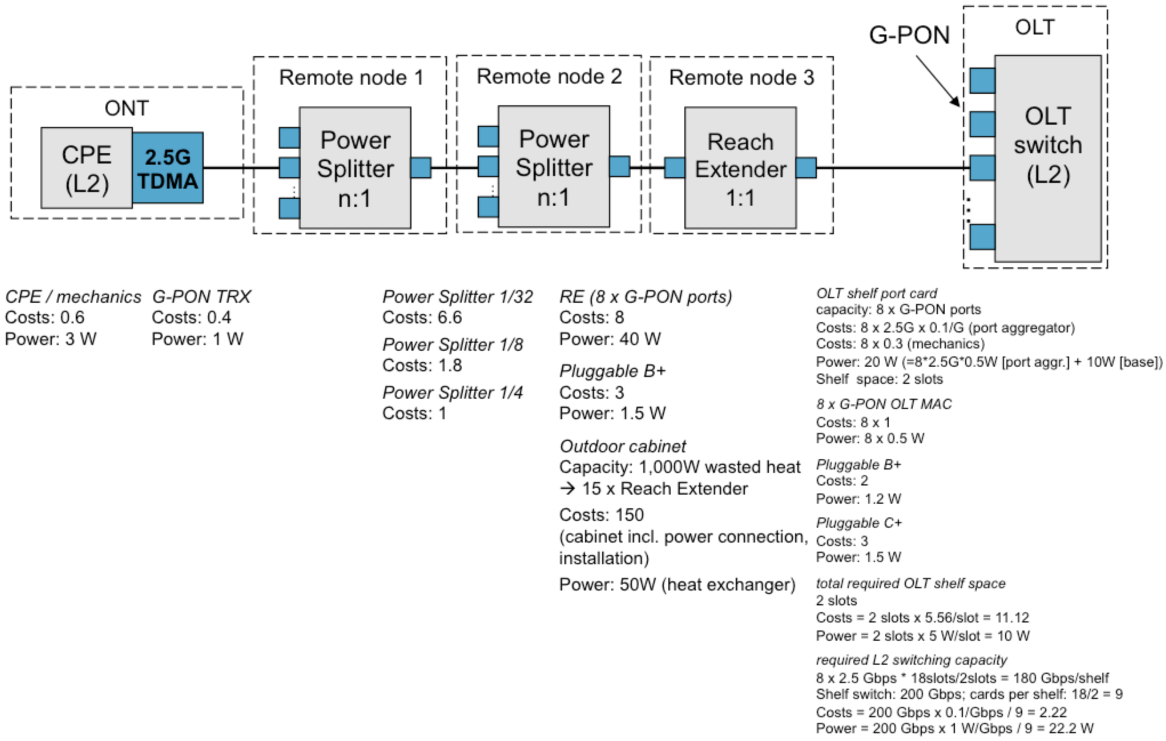


Figure 5-4: G-PON cost and power model (values in 2020)

Various G-PON design configurations are compared in terms of cost, power consumption and performance for the current (2012) and 2020 timeframes in Table 5-1, Table 5-2, Table 5-3 and Table 5-4. Configurations considered are B+/C+ OLT optics and B+ OLT optics combined with a reach extender (RE). All cost data were normalized with respect to the cost of a GPON ONT which was set to 1. We see that G-PON in general has difficulties complying with the sustainable bandwidth requirements for splitting ratios beyond 1:4.

Table 5-1: Cost analysis of G-PON (values in 2012)

Implementation Option	Power-split	Reach	Sustainable datarate (first mile & feeder) *down-/up-link*	Client count (feeder)	*Costs per client (w/o feeder fibers)*	Costs ONT	Costs per client remote nodes	Cost per client OLT	Number of clients/20-slot OLT shelf
B+ (28 dB) / C+ (32 dB)	1:32	11 / 20 km	78/39 Mbps	32	*1.53 / 1.6*	1	0.2	0.33 / 0.4	2,304
RE & B+	1:32	60 km	78/39 Mbps	32	*1.83*		0.5	0.33	2,304

Table 5-2: Cost analysis of G-PON (values in 2020)

Implementation Option	Power-split	Reach	Sustainable datarate (first mile & feeder) *down-/up-link*	Client count (feeder)	*Costs per client (w/o feeder fibers)*	Costs ONT	Costs per client remote nodes	Cost per client OLT	Number of clients/20-slot OLT shelf
B+ (28 dB) / C+ (32 dB)	1:4	35 / 44 km	625/312 Mbps	4	*2.54/2.78*	1	0.24	1.3/1.54	288
B+ (28 dB) / C+ (32 dB)	1:8	27 / 36 km	312/156 Mbps	8	*1.86/2*		0.22	0.64/0.78	576
B+ (28 dB) / C+ (32 dB)	1:32	11 / 20 km	78/39 Mbps	32	*1.36/1.4*		0.2	0.16/0.2	2,304
RE & B+	1:4	60 km	625/312 Mbps	4	*3.88*		1.58	1.3	288
RE & B+	1:8	60 km	312/156 Mbps	8	*2.52*		0.88	0.64	576
RE & B+	1:32	60 km	78/39 Mbps	32	*1.58*		0.42	0.16	2,304

Table 5-3: Power consumption analysis of G-PON (values in 2012)

Implementation Option	Power-split	Reach	Sustainable datarate (first mile & feeder) *down-/up-link*	Client count (feeder)	*Total power cons. per client*	Power cons ONT	Power cons. per client remote nodes	Power cons. per client OLT	Number of clients/20-slot OLT shelf
B+ (28 dB) / C+ (32 dB)	1:32	11 / 20 km	78/39 Mbps	32	*5.5 / 5.5 W*	5 W	0 W	0.5 / 0.5 W	2,304
RE & B+	1:32	60 km	78/39 Mbps	32	*5.8 W*		0.3 W	0.5 W	2,304

Table 5-4: Power consumption analysis of G-PON (values in 2020)

Implementation Option	Power-split	Reach	Sustainable datarate (first mile & feeder) *down-/up-link*	Client count (feeder)	*Total power cons. per client*	Power cons ONT	Power cons. per client remote nodes	Power cons. per client OLT	Number of clients/20-slot OLT shelf
B+ (28 dB) / C+ (32 dB)	1:4	35 / 44 km	625/312 Mbps	4	*6 / 6.1 W*	4 W	0 W	2 / 2.1 W	288
B+ (28 dB) / C+ (32 dB)	1:8	27 / 36 km	312/156 Mbps	8	*5 / 5.1 W*		0 W	1 / 1.1 W	576
B+ (28 dB) / C+ (32 dB)	1:32	11 / 20 km	78/39 Mbps	32	*4.25 W*		0 W	0.25 W	2,304
RE & B+	1:4	60 km	625/312 Mbps	4	*7.6 W*		1.6 W	2 W	288
RE & B+	1:8	60 km	312/156 Mbps	8	*5.8 W*		0.8 W	1 W	576
RE & B+	1:32	60 km	78/39 Mbps	32	*4.45 W*		0.2 W	0.25 W	2,304

5.1.2 XG-PON1

For XG-PON1, the PCP assignments are similar to those for architectures based on G-PON, with the cost and power models for XG-PON1 in 2012 presented in Figure 5-5, and in the 2020 frame as shown in Figure 5-6. Three different budget classes are considered for the OLT and reach-extender optics (i.e. Nom1, Nom2a and Nom2b).

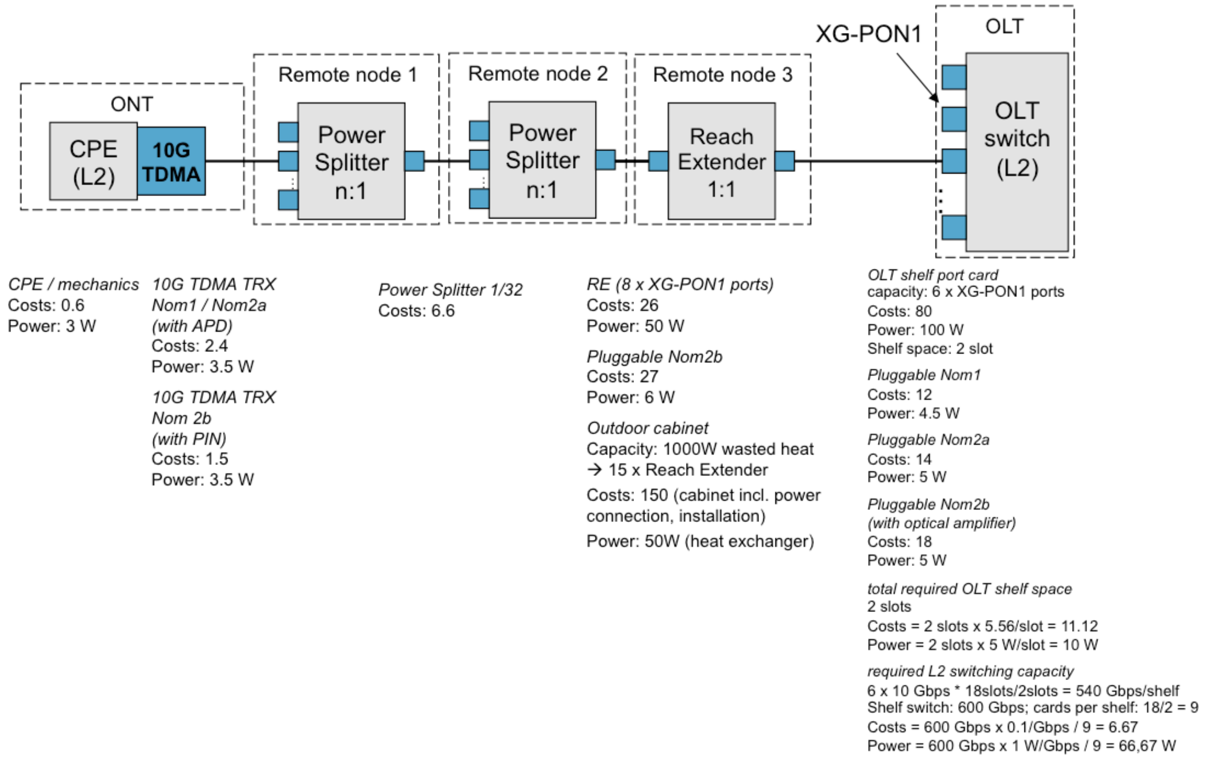


Figure 5-5: XG-PON1 cost and power model (values in 2012)

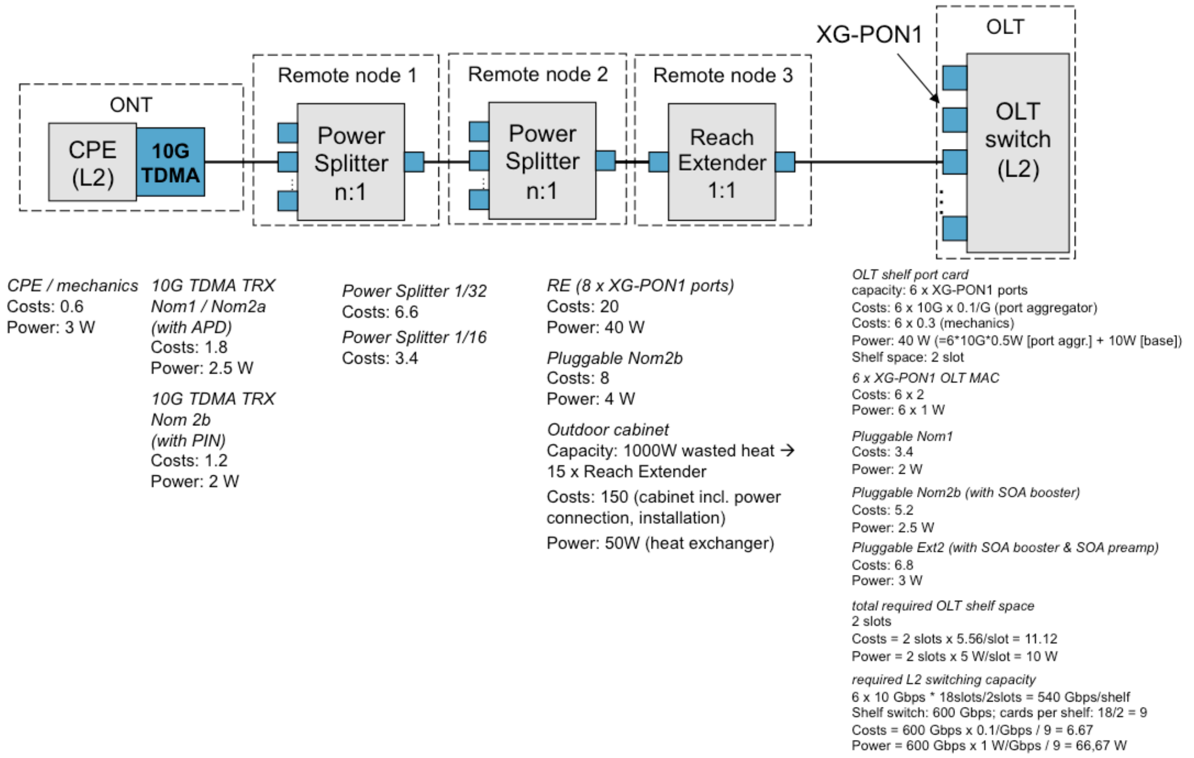


Figure 5-6: XG-PON1 cost and power model (values in 2020)

Cost and power consumption analysis of various design alternatives (Table 5-5 to Table 5-8) show that XG-PON1 may cater for the sustainable bandwidth requirements of NGOA but have difficulties in simultaneously supporting the reach targets.

Table 5-5: Cost analysis of XG-PON1 (values in 2012)

Implementation-Option	Power-split	Reach	Sustainable datarate (first mile & feeder) *down-/up-link*	Client count (feeder)	*Costs per client (w/o feeder fibers)*	Costs ONT	Costs per client remote nodes	Cost per client OLT	Number of clients/20-slot OLT shelf
Nom2b (31 dB)	1:32	18 km	312/78 Mbps	32	*3.38*	2.1	0.2	1.08	1,728
RE (Nom2b)*	1:32	60 km	312/78 Mbps	32	*4.2*		1.22	0.88	1,728

*Nom1@OLT

Table 5-6: Cost analysis of XG-PON1 (values in 2020)

Implementation-Option	Power-split	Reach	Sustainable datarate (first mile & feeder) *down-/up-link*	Client count (feeder)	*Costs per client* (w/o feeder fibers)*	Costs ONT	Costs per client remote nodes	Cost per client OLT	Number of clients/20-slot OLT shelf
Nom2b (31 dB)	1:16	26 km	625/156 Mbps	16	*2.74*	1.8	0.22	0.72	864
Ext2 (35dB)	1:16	35 km	625/156 Mbps	16	*2.84*		0.22	0.82	864
Nom2b (31 dB)	1:32	18 km	312/78 Mbps	32	*2.36*		0.2	0.36	1,728
Ext2 (35dB)	1:32	27 km	312/78 Mbps	32	*2.42*		0.2	0.42	1,728
RE (Nom2b)*	1:16	60 km	625/156 Mbps	16	*3.34*		0.94	0.6	864
RE (Nom2b)*	1:32	60 km	312/78 Mbps	32	*2.68*		0.58	0.3	1,728

*Nom1@OLT

Table 5-7: Power consumption analysis of XG-PON1 (values in 2012)

Implementation-Option	Power-split	Reach	Sustainable datarate (first mile & feeder) *down-/up-link*	Client count (feeder)	*Total power consumption per client*	Power cons. ONT	Power cons. per client remote nodes	Power cons. per client OLT	Number of clients/20-slot OLT shelf
Nom2b (31 dB)	1:32	18 km	312/78 Mbps	32	*7.6 W*	6.5 W	0 W	1.1 W	1,728
RE (Nom2b)*	1:32	60 km	312/78 Mbps	32	*8 W*		0.4 W	1.1 W	1,728

*Nom1@OLT

Table 5-8: Power consumption analysis of XG-PON1 (values in 2020)

Implementation-Option	Power-split	Reach	Sustainable datarate (first mile & feeder) *down-/up-link*	Client count (feeder)	*Total power consumption per client*	Power cons. ONT	Power cons. per client remote nodes	Power cons. per client OLT	Number of clients/20-slot OLT shelf
Nom2b (31 dB)	1:16	26 km	625/156 Mbps	16	*6.4 W*	5 W	0 W	1.4 W	864
Ext2 (35dB)	1:16	35 km	625/156 Mbps	16	*6.4 W*		0 W	1.4 W	864
Nom2b (31 dB)	1:32	18 km	312/78 Mbps	32	*5.7 W*		0 W	0.7 W	1,728
Ext2 (35dB)	1:32	27 km	312/78 Mbps	32	*5.7 W*		0 W	0.7 W	1,728
RE (Nom2b)*	1:16	60 km	625/156 Mbps	16	*7 W*		0.6 W	1.4 W	864
RE (Nom2b)*	1:32	60 km	312/78 Mbps	32	*6 W*		0.3 W	0.7 W	1,728

*Nom1@OLT

5.2 WDM-PON

5.2.1 WDM-PON with (Tuneable) Lasers and Laser-Arrays

A directly-detected, WDM-PON with tuneable lasers at the ONTs and multi-channel transceiver arrays at the OLT is one of the candidate architecture solutions for NGOA. This WDM PON can be based on filters, wavelength routed (WR) or splitters, wavelength selected (WS). In case of WS-WDM-PON an additional tuneable filter at the ONT receiver is needed. The reason for focusing on the WR-WDM-PON solution is the inherent long-reach capability (due to the use of filters, rather than power splitters). Both concepts support 1.25 Gbit/s or more per client in a dedicated, symmetrical way. One requirement which is particularly salient for the WR-WDM-PON architecture is the client count, which is a function of the number of wavelengths.

WR-WDM PON:
Given the near-future availability of 80-port, nominal-50GHz cyclic athermalized AWGs (the related requirements have been fed into ITU SG15, Q6, in H1/2011), and a tuneable-laser-based WR-WDM-PON can support 80 bi-directional (symmetrical) clients using the C-Band for the upstream and L-Band for the downstream, respectively. (The assignment of the directions of propagation to the wavelengths bands can be reversed, but C-Band up / L-Band down is the convention which is currently being discussed within the ITU.) Two approaches allow an increase in the client count: 1) The use of cyclic AWGs allows low-loss access to several further band orders, i.e., the O-Band, E-Band, and U-Band. Given the grid (currently being discussed within the ITU) two cyclic filter orders fall into the S-Band. Both bands (in particular the lower one with regard to wavelength) do not interfere with increased water-peak absorption. Hence, an extension into the S-Band can double the client count. In both the OLT and the ODN, additional S-Band/C-Band (S/C) diplexers will be additionally required. In the ODN this allows for the use of cascaded RNs. 2) The second approach requires AWGs with a (semi-) flat-top transmission characteristic. This seems to be the common requirement or view in the ITU since it supports multiple WDM channels within one passband port. This holds, for example, for the pre-filtered UDWDM approach. With a flat-top characteristic, the AWGs and hence the ODN can also support two sets of 50-GHz channels which are interleaved with a 25 GHz offset relative to each other. The respective individual wavelengths can easily be achieved since all transmitters are at least partly tuneable. (This even holds for the OLT array which is either partly thermally tuneable, or full-band tuneable, in the same way that the ONT transmitters are tuneable.) Interleaving thus allows for a further duplication of the channel count and enables a total of 320 clients in a WR-WDM-PON. Beyond this, an even denser spacing with a fan-out using filters and power splitters is also feasible. This is subject to further investigation. However, the basic (80-channel) configuration is shown in Figure 5-7.

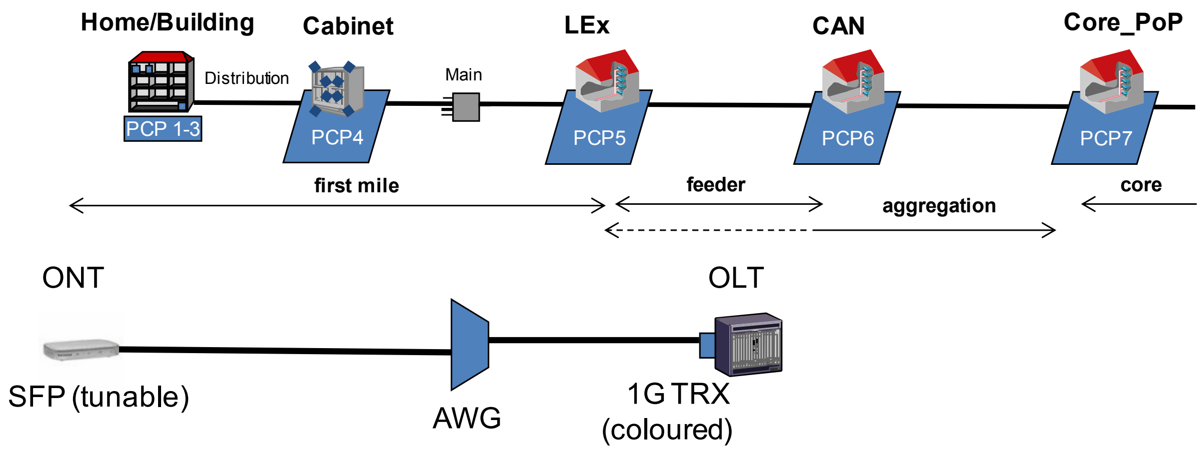


Figure 5-7: Tuneable-based WR-WDM-PON: assignment to PCP sites

The detailed analyses of WR-WDM-PON with tuneable transmitters, with respect to cost, power consumption, reach and client count follows the same approach, which is used for all other NGOA contenders. The analysis is shown in Figure 5-8 for an 80-channel configuration, which uses APD receivers.

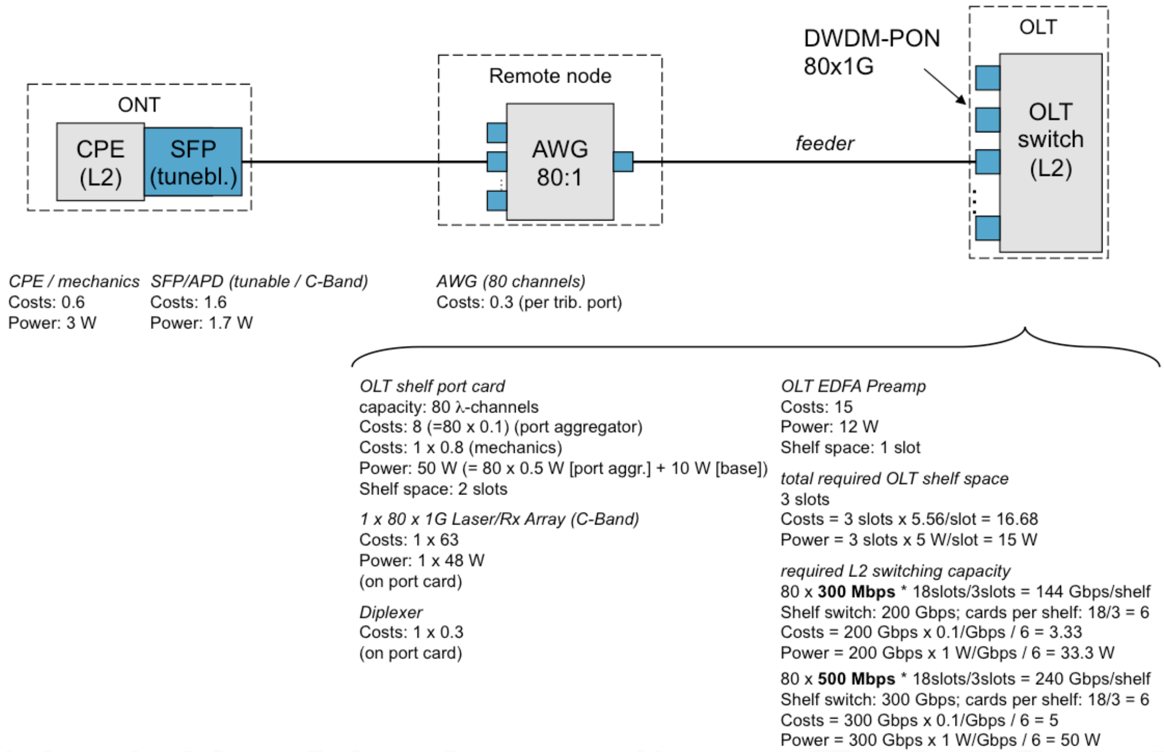


Figure 5-8: Tuneable-based WR-WDM-PON. Analysis for 80 channels version with APDs

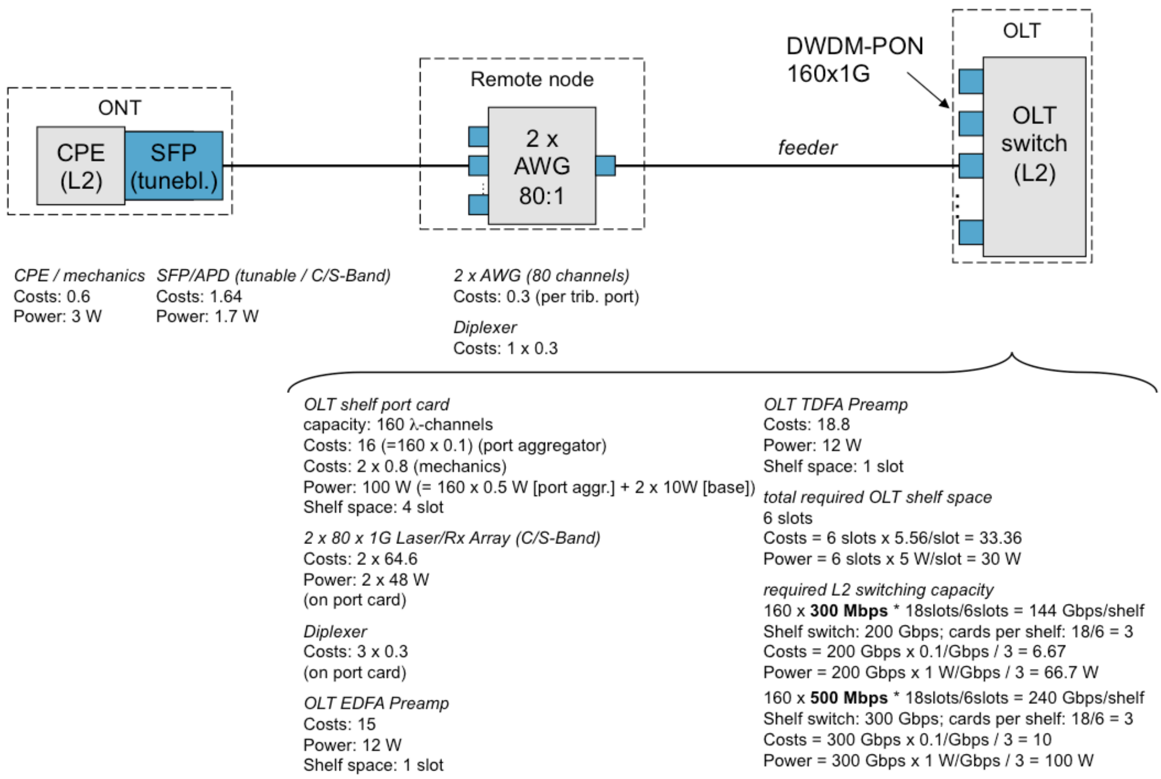


Figure 5-9: Tuneable-based WR-WDM-PON. Analysis for 160 channels version with APDs

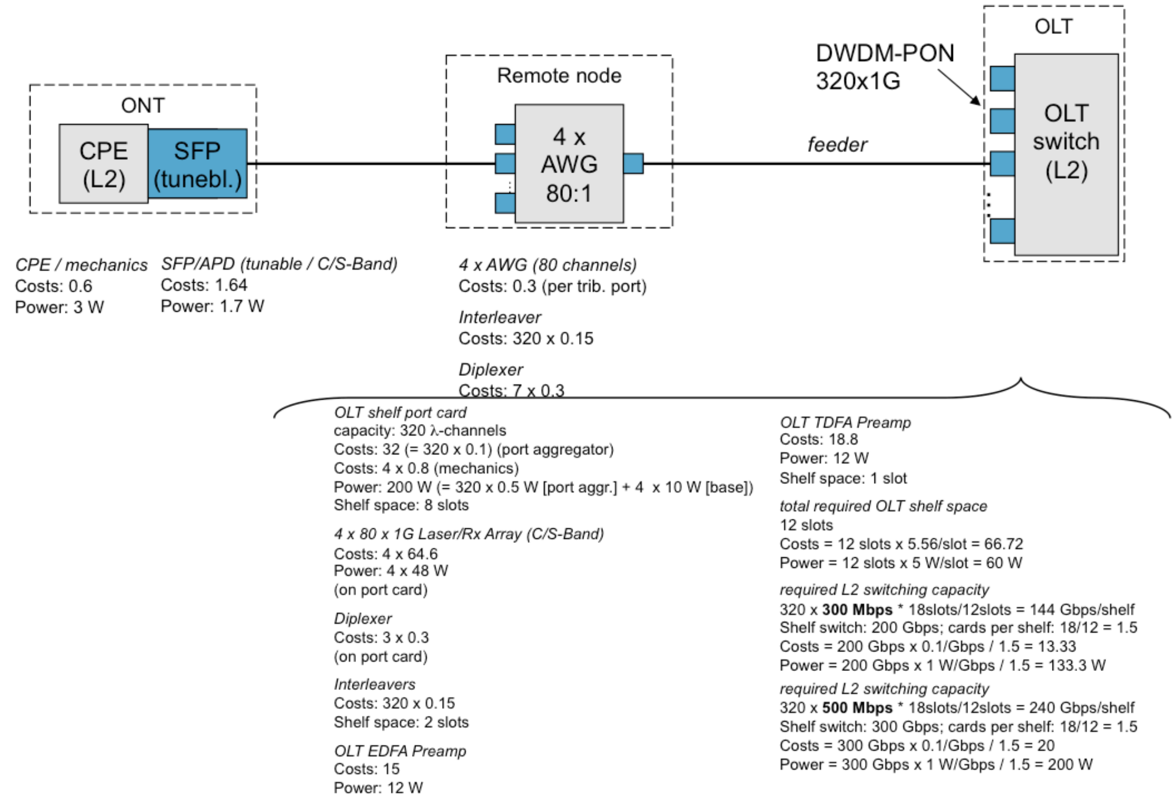


Figure 5-10: Tuneable-based WR-WDM-PON. Analysis for 320 channels version with APDs

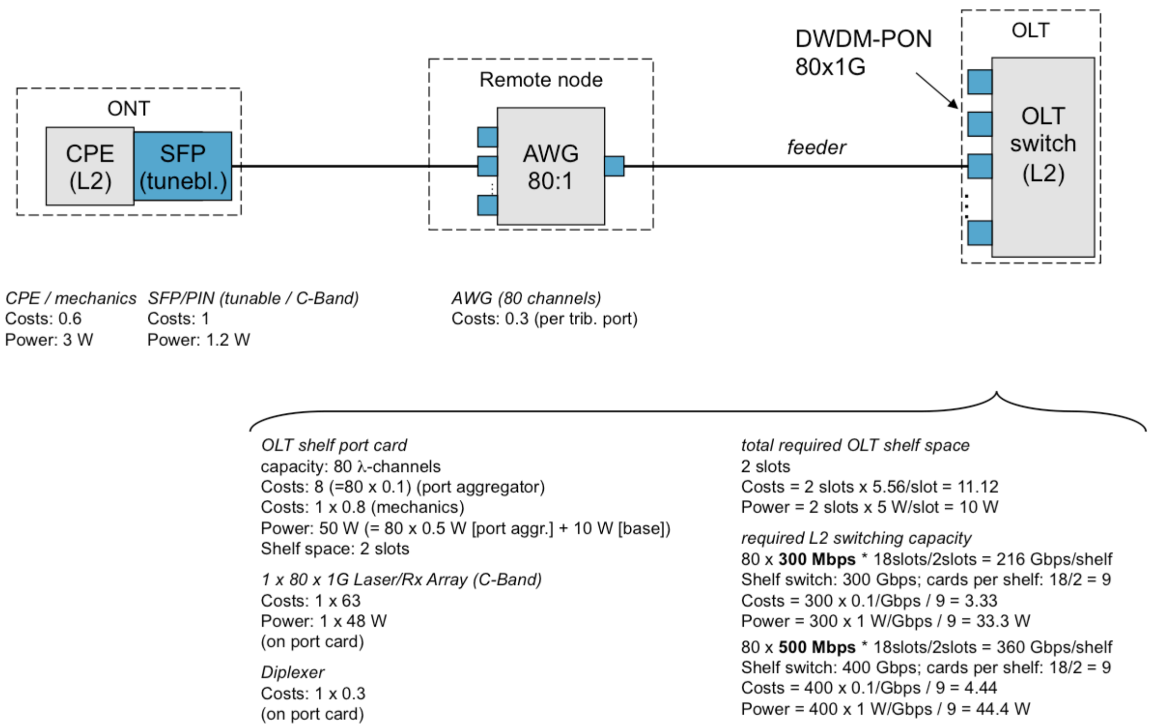


Figure 5-11: Tuneable-based WR-WDM-PON. Analysis for 80 channels version with PIN receivers

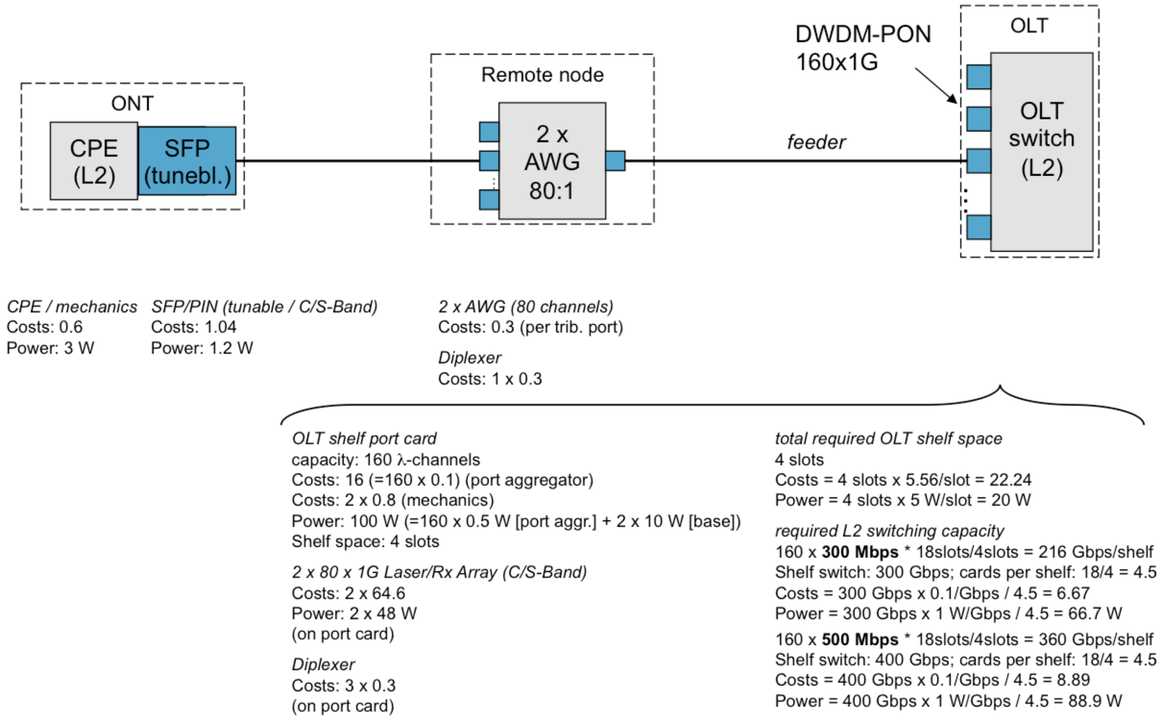


Figure 5-12: Tuneable-based WR-WDM-PON. Analysis for 160 channels version with PIN receivers

The WR-WDM-PON architecture can scale to a higher client count via additional diplexers or interleavers. This also allows combinations with cheap PIN diode receivers or high-performance APD receivers for optimized cost efficiency. The 320-clients configuration using both additional diplexers and interleavers can only be combined with APDs since the PIN receivers lead to a lack in achievable reach. Hence, the analysis has been performed for 5 different configurations (80 and 160 clients with PIN receivers, and 80, 160 and 320 clients with APDs). Also note that in the OLT, multi-channel APD arrays can be replaced by PIN arrays plus pre-amplifiers. At the time being, it is not fully clear yet, which of these two implementations will lead to lower cost. The cost analysis for the tuneable-based WR-WDM-PON is summarized in Table 5-9.

Table 5-9: Cost analysis of tuneable-based WR-WDM-PON

ONT/OLT implementation option	Wavelength-Split	Reach	Sustainable datarate (first mile & feeder) *symmetric*	Client count (feeder)	*Costs per client (w/o feeder fibers)*	Costs ONT	Costs per client remote nodes	Costs per client OLT	Number of clients/20-slot OLT shelf
APD & pre-amp	80 ch	60 km	300/500 Mbps (416/625 Mbps)*	80	*3.84 / 3.86*	2.2	0.3	1.34 / 1.36	480
APD & pre-amp	160 ch	52 km	300/500 Mbps (416/625 Mbps)*	160	*3.92 / 3.94*	2.24	0.3	1.38 / 1.4	480
APD & pre-amp	320 ch	30 km	300/500 Mbps (416/625 Mbps)*	320	*4.13 / 4.15*	2.24	0.46	1.43 / 1.45	480
PIN	80 ch	31 km	300/500 Mbps (416/555 Mbps)*	80	*2.98/3*	1.6	0.3	1.08/1.1	720
PIN	160 ch	23 km	300/500 Mbps (416/555 Mbps)*	160	*3.04/3.06*	1.64	0.3	1.1/1.12	720

*assumes incremental L2 shelf switch dimensioning in 100 Gbps steps

From Table 5-9, it can be seen that a WR-WDM-PON with PIN receivers is clearly cheaper than those versions with APDs. Also, scaling of client count adds a small cost increment as compared to the basic 80-client version. The differences with regard to form factor or compactness (i.e., number of clients per OLT shelf) stem from the use of dedicated pre-amplifiers instead of APD arrays. For APD arrays, the PIN array density can be achieved. Table 5-10 summarizes the respective power consumption analysis.

Table 5-10: Power consumption analysis of tuneable-based WR-WDM-PON

ONT/OLT implementation option	Wavelength-Split	Reach	Sustainable datarate (first mile & feeder) *symmetric*	Client count (feeder)	*Total power consumption per client*	Power cons. ONT	Power cons. per client remote nodes	Power cons. per client OLT	Number of clients/20-slot OLT shelf
APD & pre-amp	80 ch	60 km	300/500 Mbps (416/625 Mbps)*	80	*6.7 / 6.9 W*	4.7 W	0 W	2 / 2.2 W	480
APD & pre-amp	160 ch	52 km	300/500 Mbps (416/625 Mbps)*	160	*6.7 / 6.9 W*			2 / 2.2 W	480
APD & pre-amp	320 ch	30 km	300/500 Mbps (416/625 Mbps)*	320	*6.6 / 6.8 W*			1.9 / 2.1 W	480
PIN	80 ch	31 km	300/500 Mbps (416/555 Mbps)*	80	*5.9/6.1 W*	4.2 W		1.7/1.9 W	720
PIN	160 ch	23 km	300/500 Mbps (416/555 Mbps)*	160	*5.9/6.1 W*			1.7/1.9 W	720

*assumes incremental L2 shelf switch dimensioning in 100 Gbps steps

It can be seen that the PIN versions achieve lower power consumption. In addition, the 320-clients configuration has slightly lower power consumption than the 80/160-client versions. This is due to a more effective sharing of the pre-amplifier between more (interleaved) clients.

WS WDM PON:
In Figure 5-13 the alignment of the WS-WDM-PON with respect to the PCPs is shown. In principle all the general statements regarding wavelength tuning and channel count are also valid for a WS-WDM-PON approach. However, the channel count needs to be adjusted to the given count of the splitters, e.g. 1:32 or 1:64. To increase the splitting or customer count from a nominal value of 1:32 to 1:64 or even 1:128 another splitting stage at PCP5 could be introduced. For high channel count it is preferable to use a band filter at PCP which shows lower loss than a 1:4 splitter (see Figure 5-13).

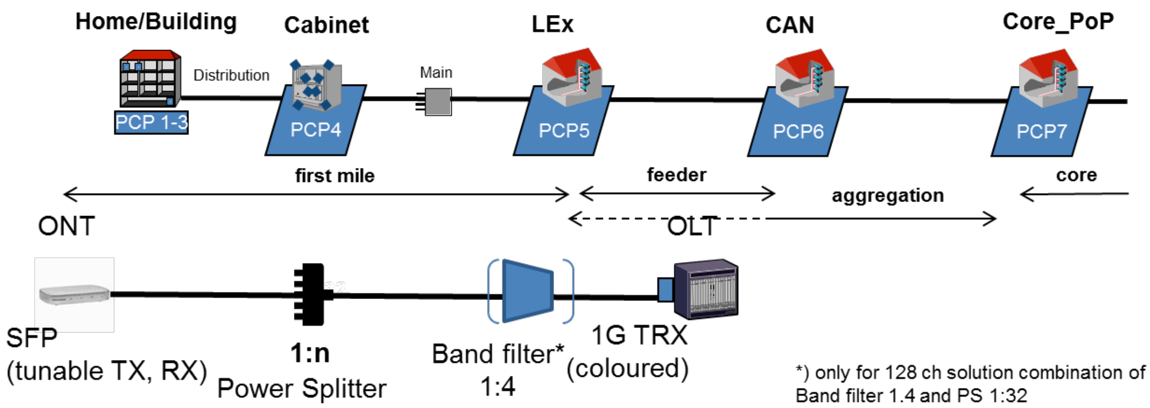


Figure 5-13: Tuneable-based WS-WDM-PON: assignment to PCP sites

Compared to the WR-WDM-PON approach a tuneable filter needs to be inserted at the ONT for wavelength selection. Additionally, due to the higher loss of a splitter based solution compared to the WR-WDM-PON approach (e.g. AWG based) an APD photodiode needs to be used and also for longer reach an additional amplifier at the OLT. The associated costs for a 32, 64 and 128 client count are shown in the Figure 5-14, Figure 5-15 and Figure 5-16, respectively. Figure 5-17 and Figure 5-18 should variants without pre-amplifiers. The change of cost at the ONT and also OLT side due to the adjustment to the client count of the splitter are indicated in red. As obvious from these figures the relative cost of the ONT increases to about 3.2 for a WS-WDM-PON ONT (APD + tuneable Tx+ tuneable filter at Rx) compared to 2.2 for a WR-WDM-PON ONT (APD + tuneable Tx). A key benefit of the WS WDM PON is that it can directly cope with a splitter based deployment in migration scenarios.

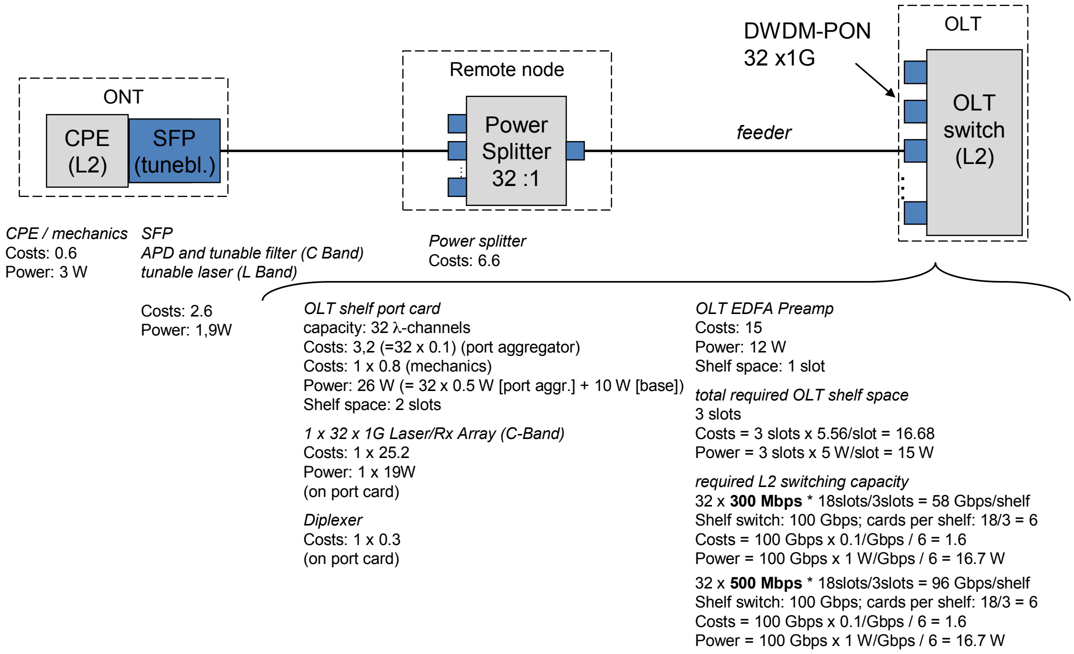


Figure 5-14: WS-WDM-PON with tuneable lasers & filters, APD receivers, preamp., 32 channels

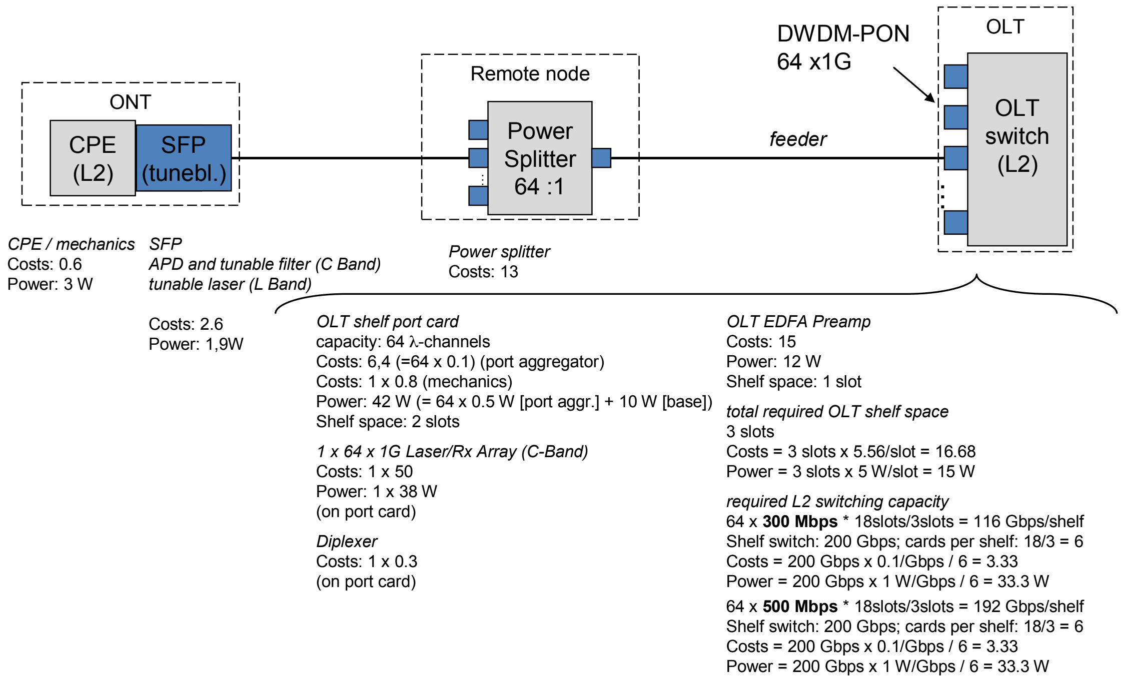


Figure 5-15: WS-WDM-PON with tunable lasers & tuneable filters, APD receivers, preamp., 64 channels

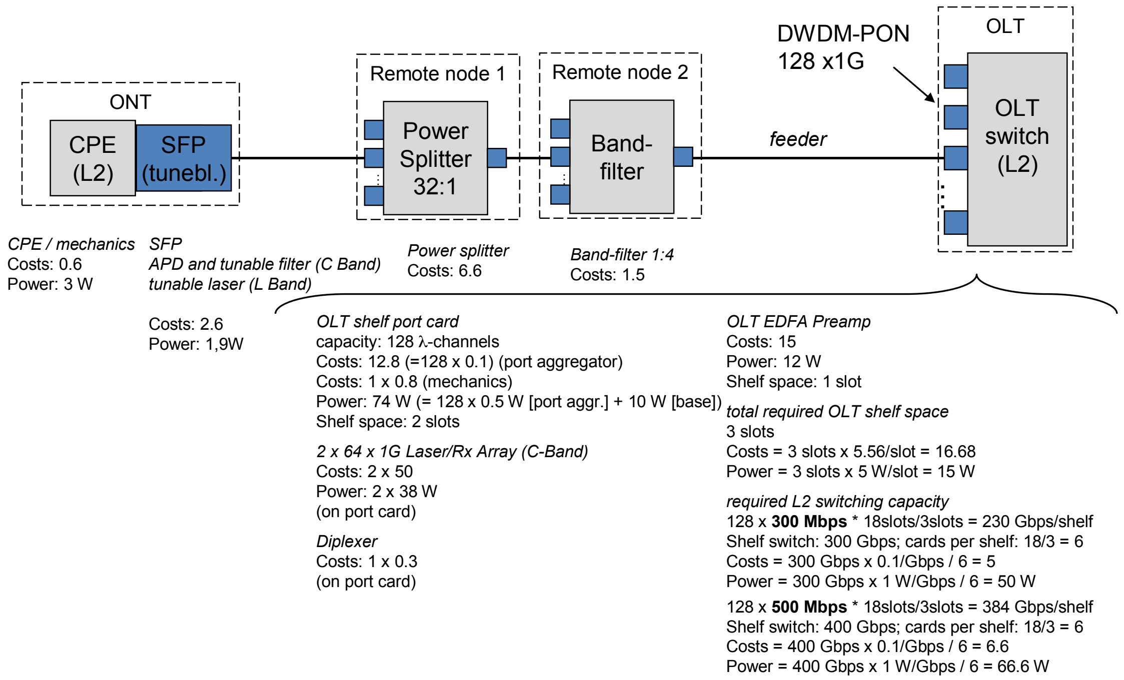


Figure 5-16: WS-WDM-PON with tuneable lasers & filters, APD receivers, preamp.; PS&BF & 128 channels

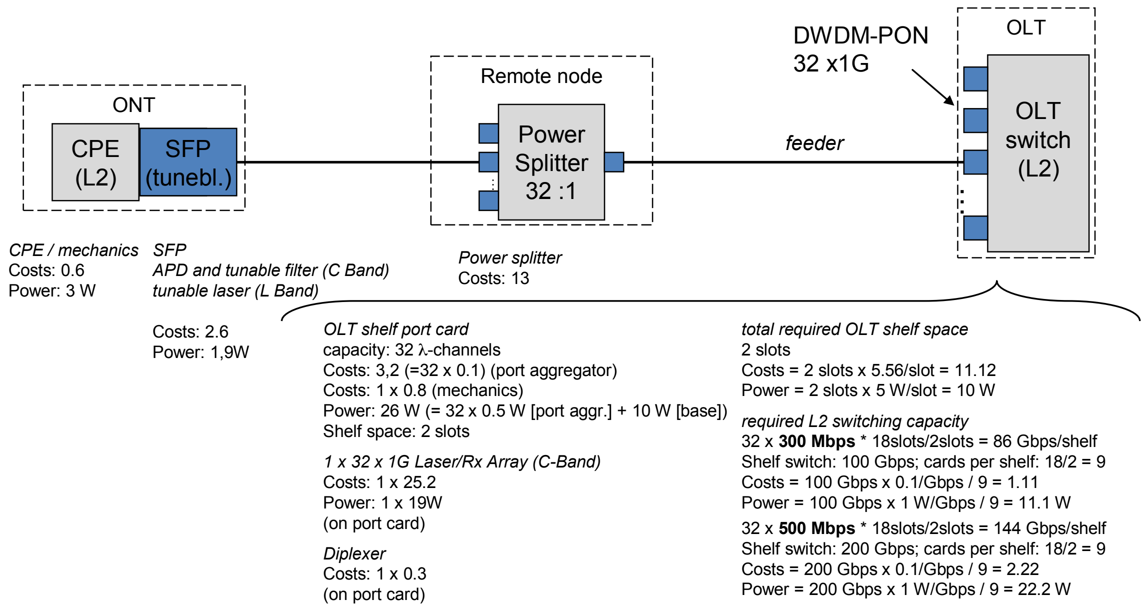


Figure 5-17: WS-WDM-PON with tunable lasers & tuneable filters, APD receivers, 32 channels

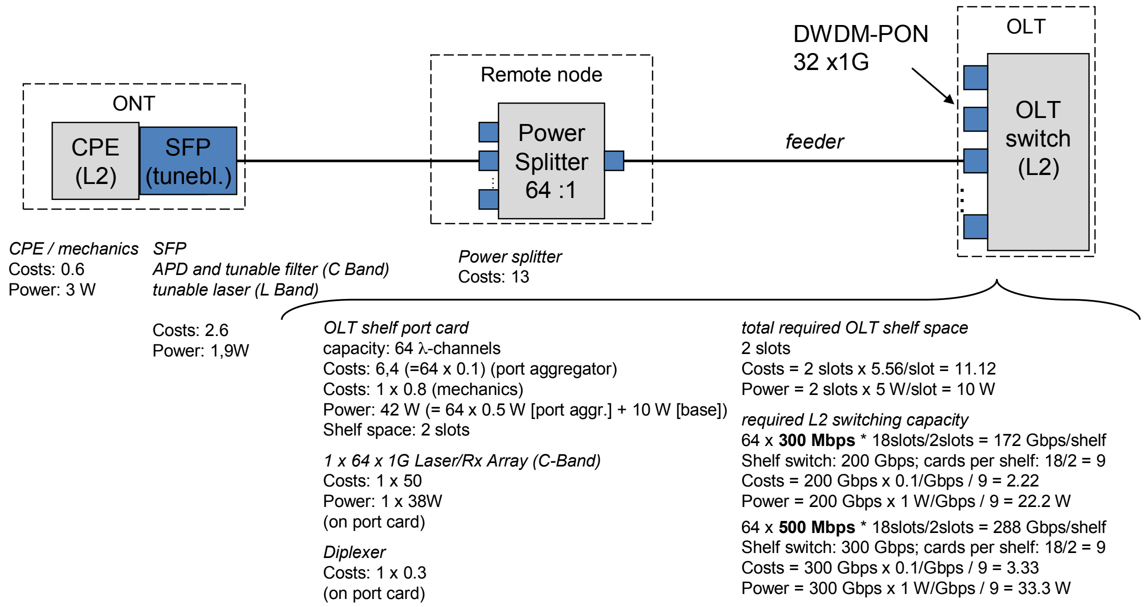


Figure 5-18: WS-WDM-PON with tunable lasers & tuneable filters, APD receivers, 64 channels

Table 5-11 shows the cost, reach and client count for various technical realizations. Table 5-12 shows the corresponding power consumption analysis.

Table 5-11: Cost analysis of tuneable-based WS-WDM-PON

ONT/OLT implementation option	Wavelength-Split	Reach	Sustainable datarate (first mile & feeder) symmetric	Client count (feeder)	*Costs per client (w/o feeder fibers)*	Costs ONT	Costs per client remote nodes	Costs per client OLT	Number of clients/20-slot OLT shelf
APD & pre-amp	32 ch	42 km	300/500 Mbps (Mbps)*	32	*5.37/5.37*	3.2	0.21	1.96/1.96	192
APD & pre-amp	64 ch	20 km	300/500 Mbps (Mbps)*	64	*4.85/4.85*		0.20	1.45/1.45	384
APD & pre-amp & Band filter	128 ch	13km	300/500 Mbps (Mbps)*	128	*4.60/4.61*		0.22	1.18/1.19	768
APD	32 ch	19 km	300/500 Mbps (Mbps)*	32	*4.71/4.75*		0.21	1.30/1.34	192
APD	64 ch	6 km	300/500 Mbps (Mbps)*	64	*4.51/4.52*		0.20	1.11/1.12	384

*assumes incremental L2 shelf switch dimensioning in 100 Gbps steps

Table 5-12: Power consumption analysis of tuneable-based WS-WDM-PON

ONT/OLT implementation option	Wavelength-Split	Reach	Sustainable datarate (first mile & feeder) *symmetric*	Client count (feeder)	*Total power consumption per client*	Power cons. ONT	Power cons. per client remote nodes	Power cons. per client OLT	Number of clients/20-slot OLT shelf
APD & pre-amp	32 ch	42 km	300/500 Mbps (Mbps)*	32	*7.67/7.67 W*	4.9 W	0 W	2.77/2.77 W	192
APD & pre-amp	64 ch	20 km	300/500 Mbps (Mbps)*	64	*7.09/7.09 W*			2.19/2.19 W	384
APD & pre-amp & Band filter	128 ch	13km	300/500 Mbps (Mbps)*	128	*6.67/6.80 W*			1.77/1.90 W	768
APD	32 ch	19 km	300/500 Mbps (Mbps)*	32	*6.97/7.31 W*			2.07/2.41 W	192
APD	64 ch	6 km	300/500 Mbps (Mbps)*	64	*6.65/6.83 W*			1.75/1.93 W	384

*assumes incremental L2 shelf switch dimensioning in 100 Gbps steps

5.2.2 WDM-PON with seeded Reflective Transmitters

In contrast to the previous WR-WDM-PON architecture where the upstream optical carrier is locally generated (e.g. using tuneable lasers), we now present a second variant of the WDM-

PON class of architecture, where the optical carriers are remotely generated and distributed to the ONTs, and where different types of devices can be used to modulate the distributed carrier to create an upstream signal. The basic PCP assignment configuration is shown in Figure 5-19.

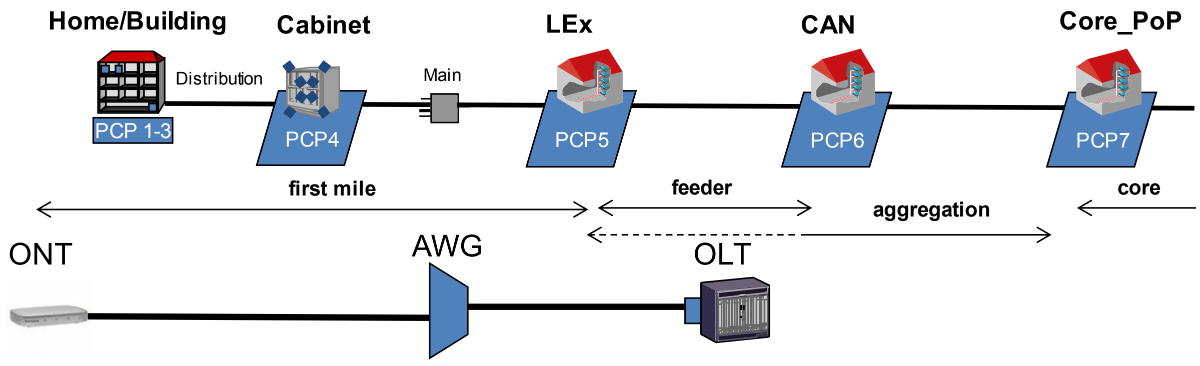


Figure 5-19: Seeded reflective WDM-PON: assignment to PCP sites

Figure 5-20 shows the cost and power model for the 80 channel seeded reflective WDM-PON based on a multi-frequency light source. The multi-frequency laser is used to create the seed carriers which are subsequently routed towards the ONTs, and where a reflective semiconductor optical amplifier (RSOA) is used to modulate the reflective component.

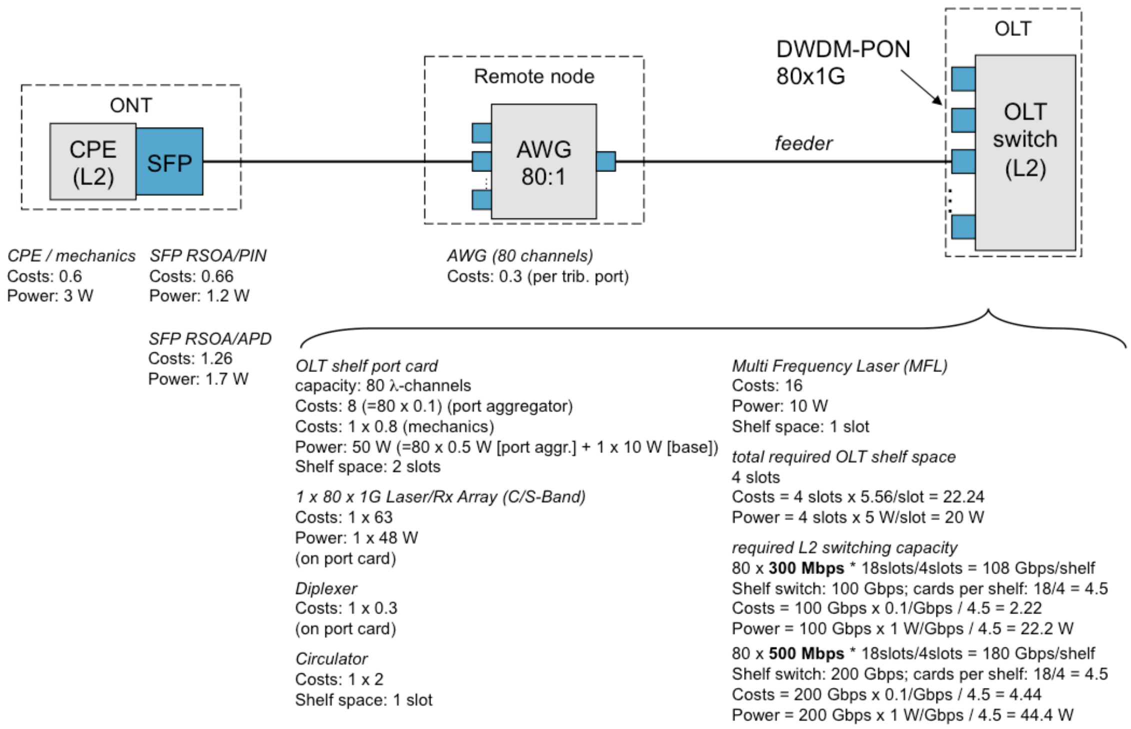


Figure 5-20: Cost and power model for seeded reflective WR-WDM-PON (80 channels)

An alternative variant to the seeded reflective WDM-PON discussed above is the variant based on wavelength reuse, where the downstream wavelength is reused to carry the upstream as well. This offers the advantage of duplicating the number of channels in the allocated wavelength spectrum. The cost and power model for an 80-channel WDM-PON based on wavelength-reuse is shown in Figure 5-21.

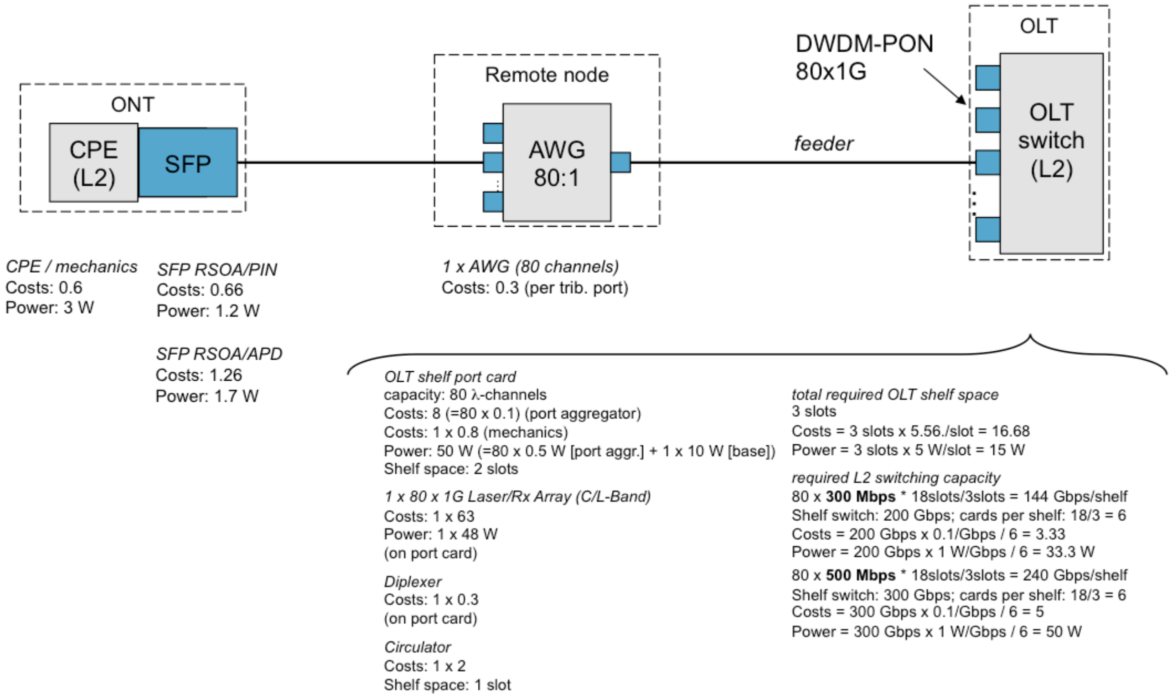


Figure 5-21: Cost and power model for WR-WDM-PON architecture featuring wavelength-reuse (80 channels)

The client-count can be increased further with a slightly more complex remote node consisting of two AWGs and a diplexer to create an analogous wavelength-reuse WDM-PON architecture with 160 channels as shown in Figure 5-22. By means of increasing the client count per feeder fibre, footprint per client can be reduced.

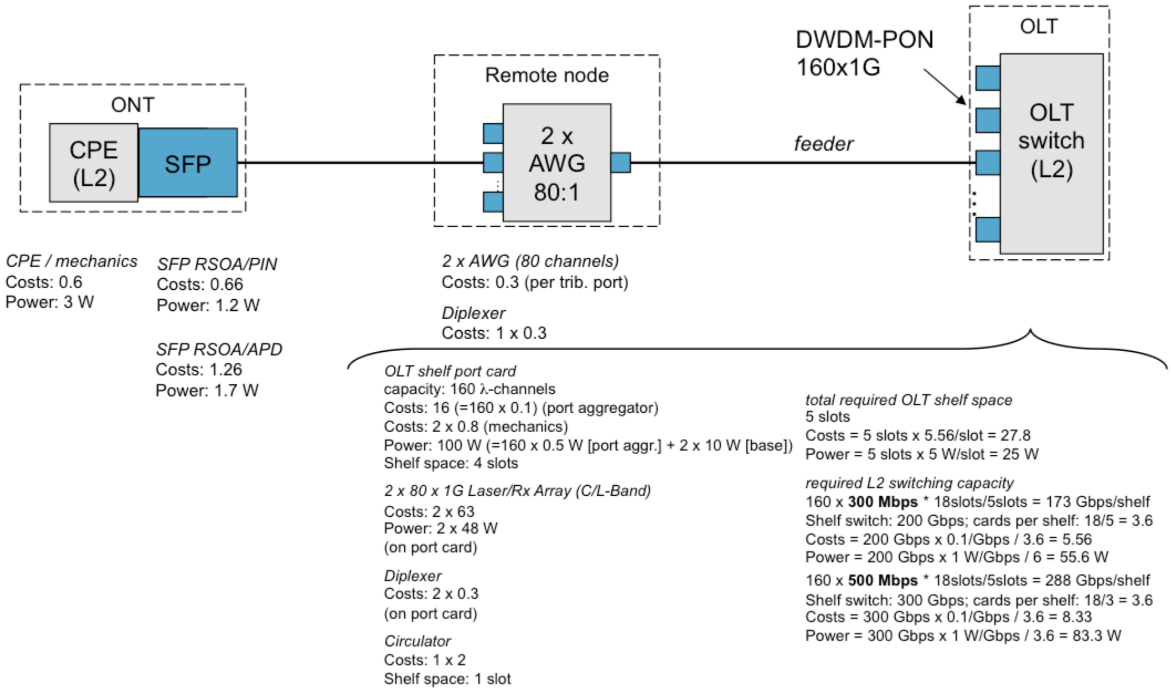


Figure 5-22: Cost and power model for WR-WDM-PON with wavelength reuse (160 channels)

Finally, client-count can be doubled once again to 320 channels by using a more complex remote node containing four AWGs as shown in Figure 5-23. Once again, the wavelength-reuse WDM-PON achieves useful scaling advantages in terms of shelf-space when increasing the channel count to 320.

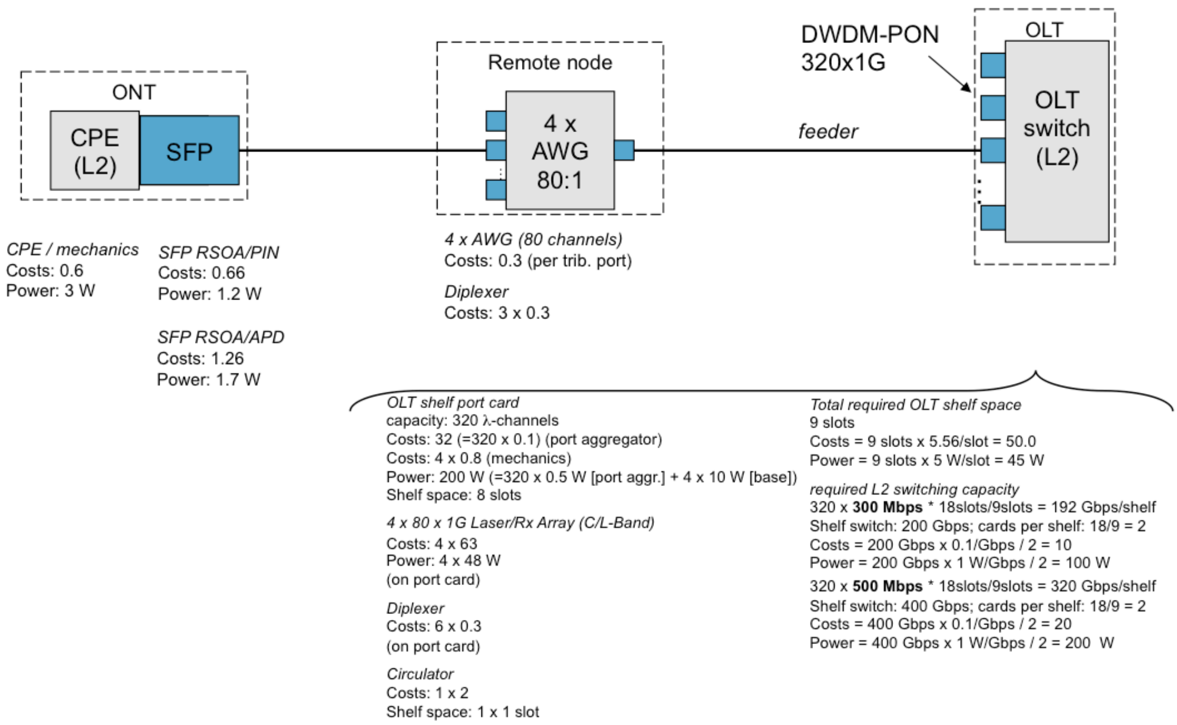


Figure 5-23: Cost and power model for WR-WDM-PON with wavelength reuse (320 channels)

Finally, we consider the cost and power model for a wavelength-reuse WDM-PON featuring 96 channels with 100GHz spacing as shown in Figure 5-24. In this case a 1:48 AWG (instead of a 1:80 AWG) has been considered. A reduction in cost by one-third per channel (for the AWG and OLT Laser/Rx array) was assumed compared to 50GHz technology.

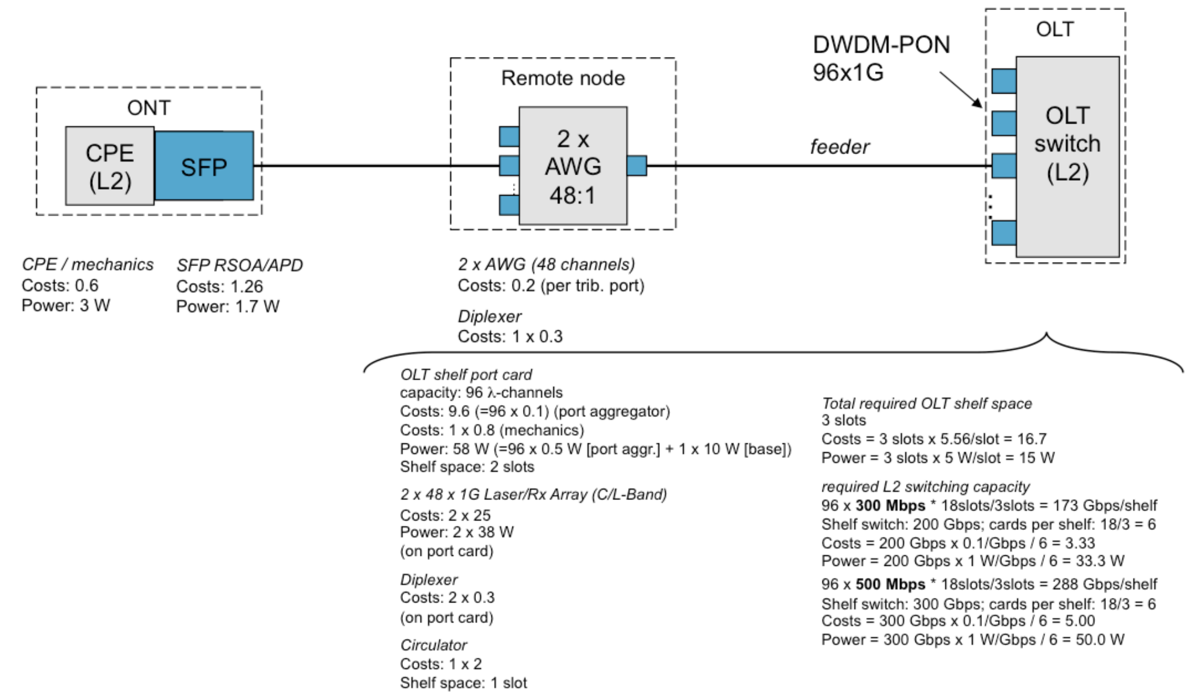


Figure 5-24: Cost and power model for WR-WDM-PON with wavelength reuse (96 channels, 100GHz spacing)

Table 5-13 and Table 5-14 present a summary of the cost, power, reach and footprint results for the considered seeded reflective WDM-PON approaches. The first two solutions in Table 5-13 and Table 5-14 are based on a multi-lambda source placed at the OLT. This solution presents advantages with respect to reach for the APD based ONT while the PIN based solution presents low ONT cost at the expense of reach. From Table 5-13 it can furthermore be deduced that the 96 channel solution based on wavelength reuse and 100GHz spacing is cheaper than other solutions due to the lower cost of 100GHz technology compared to 50GHz. Cost of the wavelength reuse variant is comparable for the 80, 160 and 320 channels variants. In Table 5-14 it can be seen that the power consumption is comparable for all variants.

Table 5-13: Cost analysis of seeded reflective WR-WDM-PON

Implementation-Option	Wavelength-Split	Reach	Sustainable datarate (first mile & feeder) symmetric	Client count (feeder)	Cost per client (w/o feeder fibers)	Costs ONT	Costs per Client remote nodes	Costs per client OLT	Number of clients/20-slot OLT shelf
PIN@ONT MFL@ONT	80 ch	28 km	300/500 Mbps (277/555 Mbps)*	80	2.99/3.02	1.26	0.3	1.43/1.46	360
APD@ONT MFL@ONT	80 ch	57 km	300/500 Mbps (277/555 Mbps)*	80	3.59/3.62	1.86			360
APD@ONT wavelength_reuse@OLT	80 ch	34 km	300/500 Mbps (416/625 Mbps)*	80	3.34/3.36			1.18/1.2	480
APD@ONT wavelength_reuse@OLT	160 ch	28 km	300/500 Mbps (347/520 Mbps)*	160	3.28/3.3		0.3	1.12/1.14	576
APD@ONT wavelength_reuse@OLT	320 ch	16 km	300/500 Mbps (312/625 Mbps)*	320	3.26/3.29		0.3	1.10/1.13	640
100GHz, APD@ONT wavelength_reuse@OLT	96 ch	34 km	300/500 Mbps (347/520 Mbps)*	96	2.92/2.94		0.2	0.86/0.88	576

*assumes incremental L2 shelf switch dimensioning in 100 Gbps steps

Table 5-14: Power consumption analysis of seeded reflective WR-WDM-PON

Implementation-Option	Wavelength-Split	Reach	Sustainable datarate (first mile & feeder) *symmetric*	Client count (feeder)	*Total power consumption per client*	Power cons. ONT	Power cons. Per client remote nodes	Power cons. per client OLT	Number of clients/20-slot OLT shelf
PIN@ONT MFL@ONT	80 ch	28 km	300/500 Mbps (277/555 Mbps)*	80	6.1/6.4 W	4.2 W	0 W	1.9/2.2 W	360
APD@ONT MFL@ONT	80 ch	57 km	300/500 Mbps (277/555 Mbps)*	80	6.6/6.9 W	4.7 W			360
APD@ONT wavelength_reuse@OLT	80 ch	34 km	300/500 Mbps (416/625 Mbps)*	80	6.5/6.7 W			1.8/2 W	480
APD@ONT wavelength_reuse@OLT	160 ch	28 km	300/500 Mbps (347/520 Mbps)*	160	5.9/6.1 W			1.7/1.9 W	576
APD@ONT wavelength_reuse@OLT	320 ch	16 km	300/500 Mbps (312/625 Mbps)*	320	6.4/6.7 W			1,7/2.0 W	640
100GHz, APD@ONT wavelength_reuse@OLT	96 ch	34 km	300/500 Mbps (347/520 Mbps)*	96	6.6/6.8 W			1.9/2.1 W	576

*assumes incremental L2 shelf switch dimensioning in 100 Gbps steps

In Figure 5-24 and Figure 5-25 we present variants of WS-WDM-PON based seeded reflective transmitters and wavelength reuse. Despite limited reach the variants show that WDM-PON based on seeded reflective transmitter can be used in areas where compatibility requirements with the legacy GPON are strict. The figures show both a low channel count and a high channel count variant where the for high channel count it is preferable to use a band filter at PCP which shows lower loss than a 1:4 splitter (see Figure 5-13).

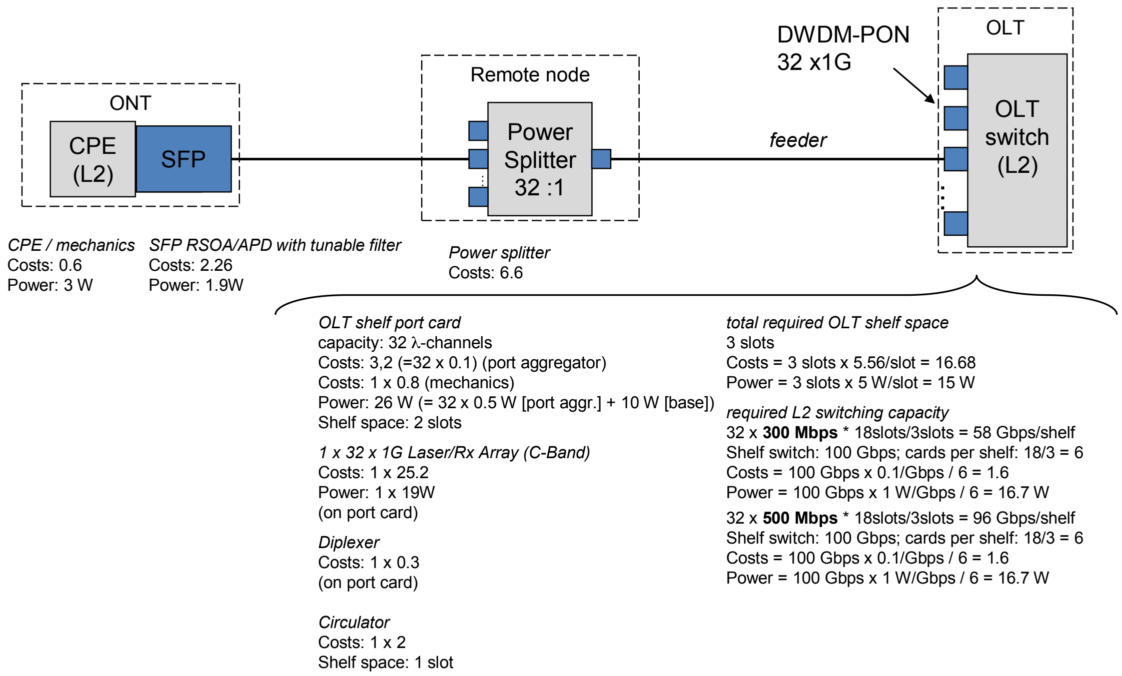


Figure 5-25: Cost and power model for WS-WDM-PON with wavelength reuse (32 channels)

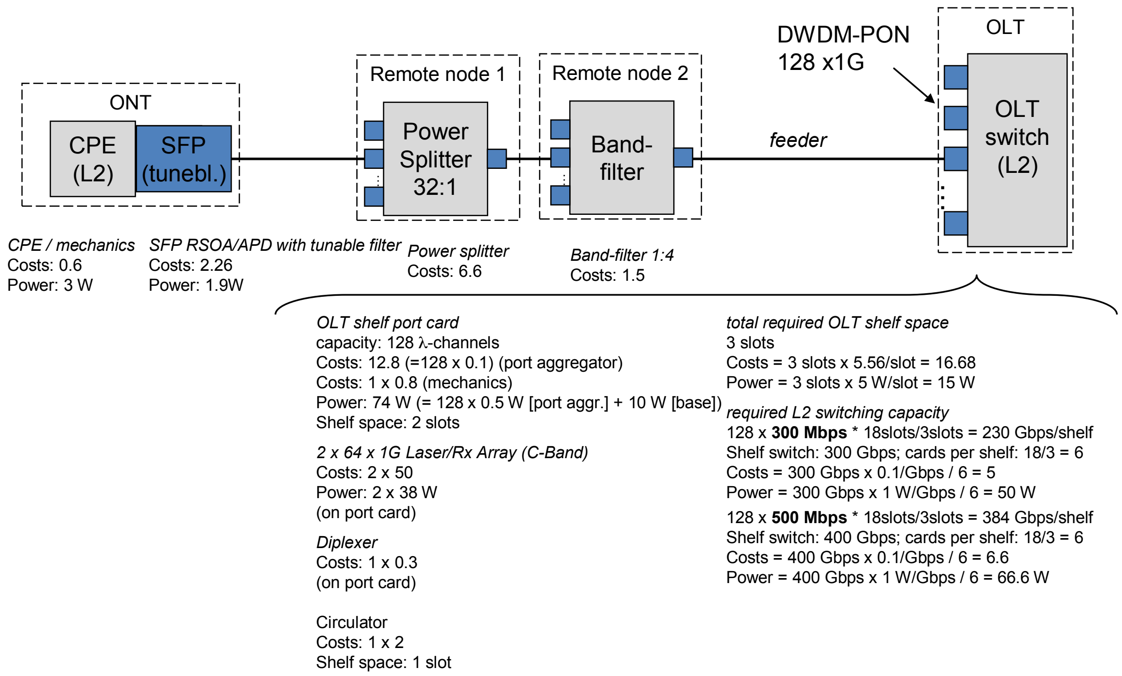


Figure 5-26: Cost and power model for WS-WDM-PON with wavelength reuse (128 channels)

Table 5-15 and Table 5-16 show the summary of the cost and power consumption analysis for the two proposed system variants.

Table 5-15: Cost analysis of seeded reflective WS-WDM-PON

ONT/OLT implementation option	Wavelength-Split	Reach	Sustainable datarate (first mile & feeder) symmetric	Client count (feeder)	*Costs per client (w/o feeder fibers)*	Costs ONT	Costs per client remote nodes	Costs per client OLT	Number of clients/20-slot OLT shelf
APD	32 ch	10 km	300/500 Mbps (Mbps)*	32	*4.63/4.63*	2.86	0.21	1.56/1.56	192
APD & Band filter	128 ch	6 km	300/500 Mbps (Mbps)*	128	*4.15/4.17*		0.22	1.07/1.09	768

*assumes incremental L2 shelf switch dimensioning in 100 Gbps steps

Table 5-16: Power analysis of seeded reflective WS-WDM-PON

ONT/OLT implementation option	Wavelength-Split	Reach	Sustainable datarate (first mile & feeder) *symmetric*	Client count (feeder)	*Total power consumption per client*	Power cons. ONT	Power cons. per client remote nodes	Power cons. per client OLT	Number of clients/20-slot OLT shelf
APD	32 ch	10 km	300/500 Mbps (Mbps)*	32	*7.30/7.30 W*	4.9 W	0 W	2.40/2.40 W	192
APD & Band filter	128 ch	6 km	300/500 Mbps (Mbps)*	128	*6.58/6.71 W*			1.68/1.81 W	768

*assumes incremental L2 shelf switch dimensioning in 100 Gbps steps

5.2.3 UDWDM-PON

The third and final main variant of the WR-WDM-PON architectures we are considering is based on a coherent UDWDM-PON (Co-UDWDM-PON) approach. Here, we analyse the heterodyne solution currently being commercially developed by NSN. This approach combines the advantages of allowing single-fibre working, sharing a single laser in the ONT between the upstream TX and RX local oscillator, and providing multi-channel transceivers for the OLT (which, as compared with dedicated single-channel transceivers allows a lower CapEx, lower power consumption, and also a better form factor).

Due to its potentially very high ODN-loss budget, many different ODN configurations over a broad range of client counts are possible. However, when combined with realistic (urban area) fibre loss and EOL penalties for fibre repair and in-house cabling as defined in WP2, several ODN configurations can be discarded because of a lack of suitable reach. This holds for an ODN, which is exclusively based on power splitters/combiners for client count >128. Hence a high client count needs WDM pre-filtering, followed by power splitting. Even in site-consolidation scenarios, this approach is fully acceptable since there is no reason why legacy infrastructure (which is very likely to be based on 1:32 power splitting) should be combined via further power splitters/combiners, instead of being multiplexed in the wavelength domain. Hence, we have analysed Co-UDWDM-PON configurations with WDM mux/demux (in both OLT and RN), and power split in subsequent remote nodes. We focused in particular on a client count of around 320, since this is the area for a very high client-count × reach product. When EOL penalties are also considered, the reach drops severely for a higher client count. On the other hand, for a small client count, the Co-UDWDM-PON may no longer be a cost-efficient solution (see the respective cost analysis). Hence, there is an interesting trade-off here, which needs to be carefully considered. The basic Co-UDWDM-PON configuration and its assignment to the PCP sites are shown in Figure 5-27.

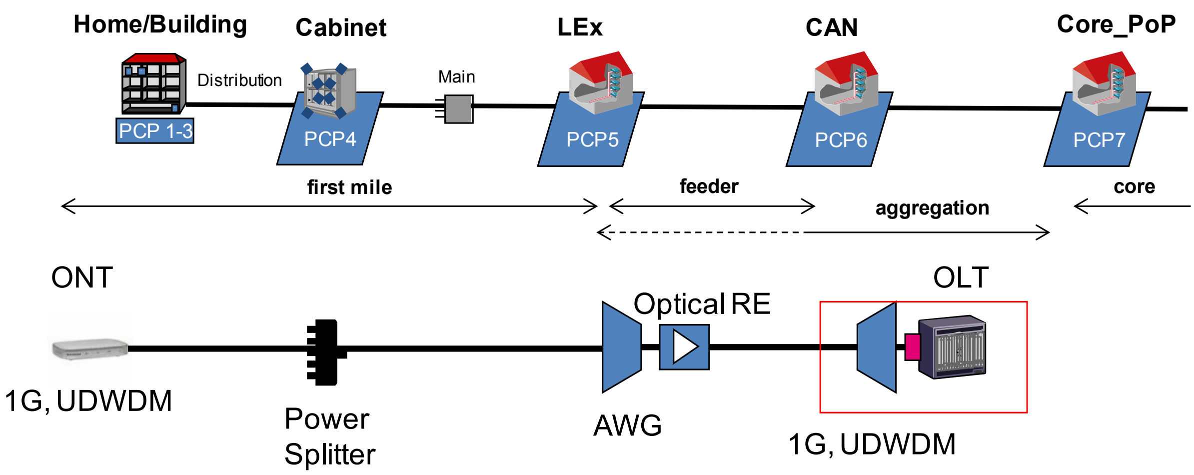


Figure 5-27: Coherent UDWDM-PON: assignment to PCP sites

We have performed a detailed relative cost and power-consumption analysis for various different configurations of the Co-UDWDM-PON architecture variant, with different combinations of AWG port count and power-splitter port count investigated. Figure 5-28 shows the analysis for the combination of 1:40 (100 GHz) AWGs and 1:8 power splitters.

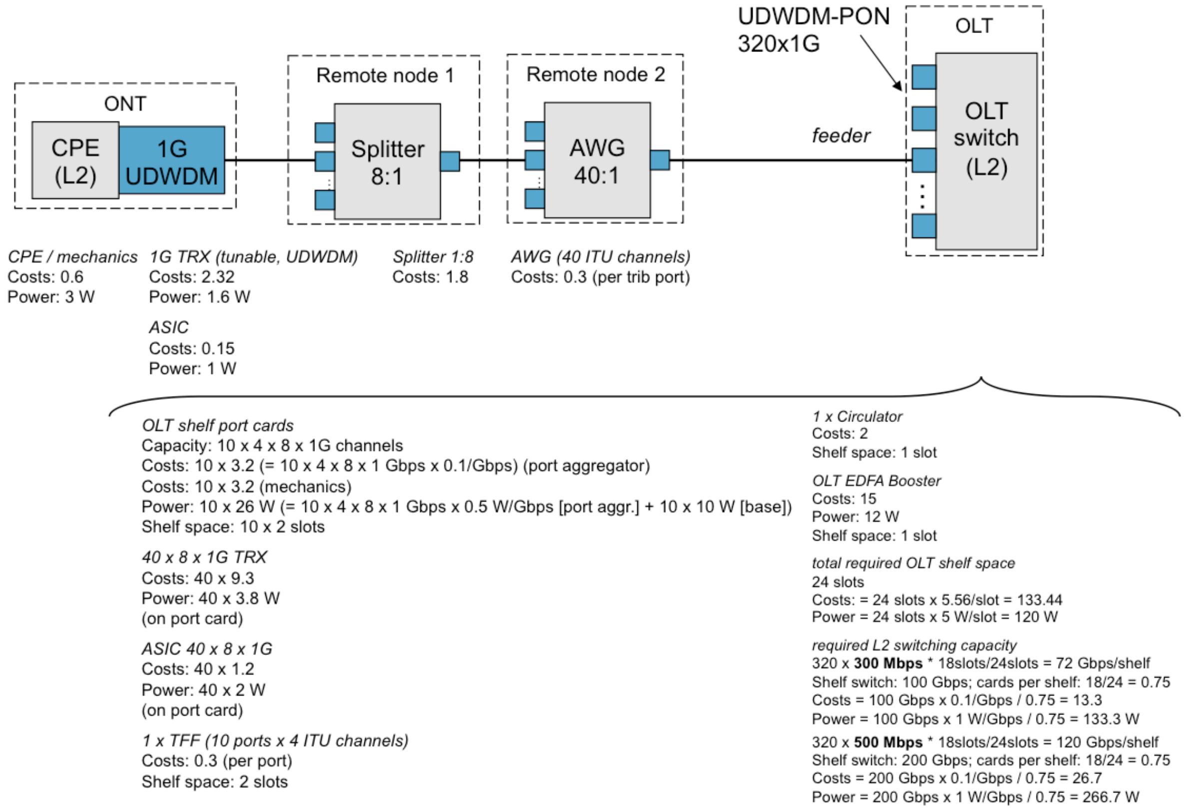


Figure 5-28: Co-UDWDM-PON: analysis for 320-clients version

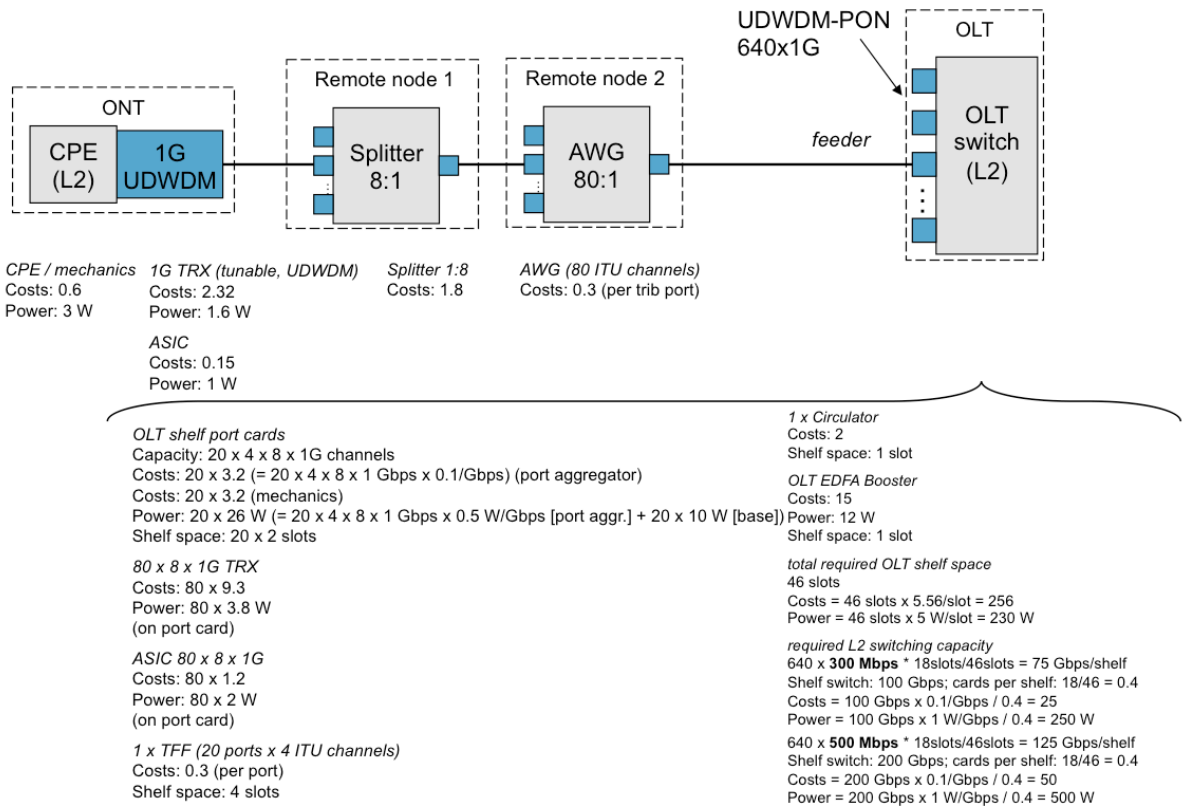


Figure 5-29: Co-UDWDM-PON: analysis for 640-clients version

There is a significant difference in the achievable reach for different combinations of the passive fan-out components, however leading to the same client count. For example, the combination of 1:80 AWGs followed by 1:8 power splitters will have a lower insertion loss for 640 clients as compared to the combination of 1:20 AWG filters and 1:32 power splitters. This is shown in more detail in the reach analysis. The effects on the per-client cost and power consumption are small, as can be seen from Table 5-17 and Table 5-18, respectively.

Table 5-17: Cost analysis of Co-UDWDM-PON

Implementation Option	Power-Split	Waveband-Split	Reach	Sustainable Datarate (first mile & feeder) *symmetric*	Client count (feeder)	*Cost per client (w/o feeder fiber)*	Costs ONT	Costs per client remote nodes	Costs per client OLT	Number of clients/20-slot OLT shelf
1:32 / 20x4 ITU-λ	1:32	20	29 km	300/500 Mbps (390/780 Mbps)*	640	*5.32 / 5.36*	3.07	0.22	1.99 / 2.03	256
1:32 / 20x4 ITU-λ With Reach Extender	1:32	20	82 km	300/500 Mbps (390/780) Mbps*	640	*5.38 / 5.42*		0.32	1.99 / 2.03	256
1:8 / 40 ITU-λ	1:8	40 ch	59 km	300/500 Mbps (416/833 Mbps)*	320	*5.36 / 5.4*		0.26	2.03 / 2.07	240
1:8 / 80 ITU-λ	1:8	80 ch	48 km	300/500 Mbps (390/780 Mbps)*	640	*5.32 / 5.36*		0.26	1.99 / 2.03	256

*assumes incremental L2 shelf switch dimensioning in 100 Gbps steps

From Table 5-17, it can be seen that the cost does not heavily depend on either the client count or on the exact configuration of the passive components. It increases slightly with decreasing client count (due to less sharing of components), and also with a higher relative amount of WDM filtering vs. power switching (because power splitter ports are cheaper than WDM filter ports).

Table 5-18: Power consumption analysis of Co-UDWDM-PON

Implementation Option	Power-Split	Waveband-Split	Reach	Sustainable Datarate (first mile & feeder) *symmetric*	Client count (feeder)	*Total power consumption per client*	Power consumption ONT	Power consumption per client remote node	Power consumption per client OLT	Number of clients/20-slot OLT shelf
1:32 / 20x4 ITU-λ	1:32	20	29 km	300/500 Mbps (390/780 Mbps)*	640	*5.32 / 5.36*	5.6 W	0 W	2.3 / 2.7 W	256
1:32 / 20x4 ITU-λ With Reach Extender	1:32	20	82 km	300/500 Mbps (390/780) Mbps*	640	*5.28 / 5.32*		0.2 W	2.3 / 2.7 W	256
1:8 / 40 ITU-λ	1:8	40 ch	59 km	300/500 Mbps (416/833 Mbps)*	320	*5.36 / 5.4*		0 W	2.4 / 2.8 W	240
1:8 / 80 ITU-λ	1:8	80 ch	48 km	300/500 Mbps (390/780 Mbps)*	640	*5.32 / 5.36*		0 W	2.3 / 2.7 W	256

*assumes incremental L2 shelf switch dimensioning in 100 Gbps steps

From Table 5-18 it can be additionally seen that the different combinations of the passive fan-out components do not have an impact on the power consumption. This is clear, since to a first approximation changing the passive components does not change (any operating points of) the active transceivers. There is, however, a small difference with regard to the total fan-out or client count. This can be explained by the slightly different sharing aspect of the required booster amplifier in the OLT amongst the different numbers of clients. Compared to WR-WDM-PON, the per-client end-to-end power consumption of the Co-UDWDM-PON architecture is higher. This is due to the necessity of digital signal processing (DSP) for the coherent intradyne transceivers, together with the related DAC (OLT only) and ADC (ONT and OLT).

Since both power consumption and cost are not heavily impacted by the different fan-out configurations, these configurations can be designed according to the needs with regard to reach and support of legacy infrastructure.

5.3 HYBRID WDM/TDM-PON

The second class of architectures studied is the hybrid WDM/TDM-PON. Two variants are considered, the passive and the semi-passive hybrid WDM/TDM-PON.

5.3.1 Passive hybrid WDM/TDM-PON

The first analysed variant of a hybrid WDM/TDM-PON consists of only passive components (e.g. AWG and splitters) deployed in the outside plant. The most common solution consists of several TDM-PONs embedded within a WDM-PON system. In order to be able to provide a high bandwidth and high customer count, we have considered a DWDM system with 40 or 80 bi-directional channels, each of which offer a *symmetric* bandwidth of 10 Gbit/s. As such, a 10G burst-mode transmitter is required at the ONT (user) side, while another 10G burst-mode receiver is also needed at the OLT. It should be noted that the requirement of 10G burst-mode receivers acts as one of the main cost drivers for the passive hybrid WDM/TDM-PON architecture.

Figure 5-30 shows the basic passive hybrid WDM/TDM-PON configuration and its assignment to each PCP site. It can be seen that its ODN configuration is exactly the same as the one of Co-UDWDM. Therefore, the passive hybrid WDM/TDM-PON has the same ODN-loss budget as Co-UDWDM-PON which has been analyzed in the previous section.

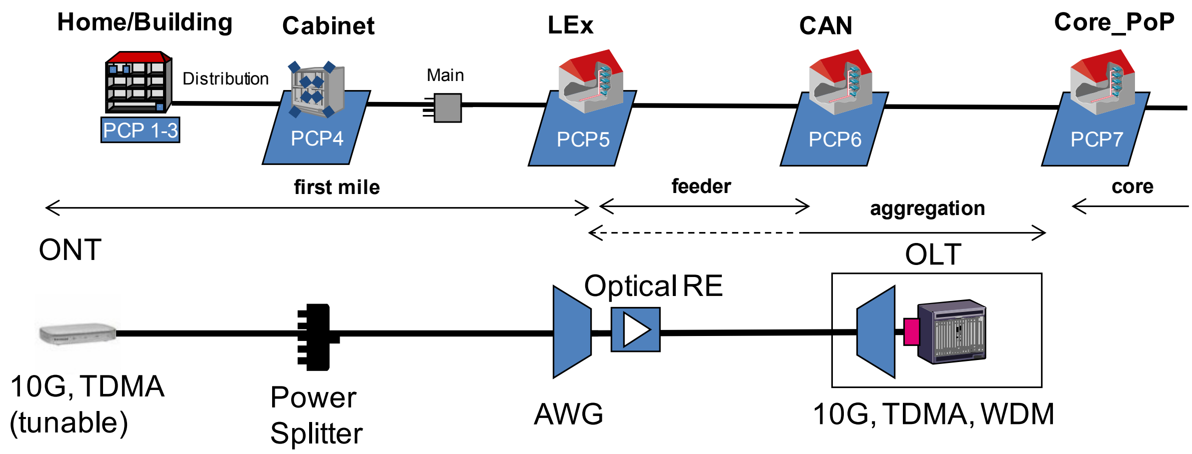


Figure 5-30: Passive hybrid WDM/TDM-PON: assignment to each PCP site

Figure 5-31 shows the analysis for the combination of 1:40 (wavelength spacing: 100 GHz) AWGs and 1:16 or 1:32 power splitters. Figure 5-32 shows the analysis for a 1:80 AWG configuration. One splitter corresponds to one embedded 10 Gbit/s TDM-PON.

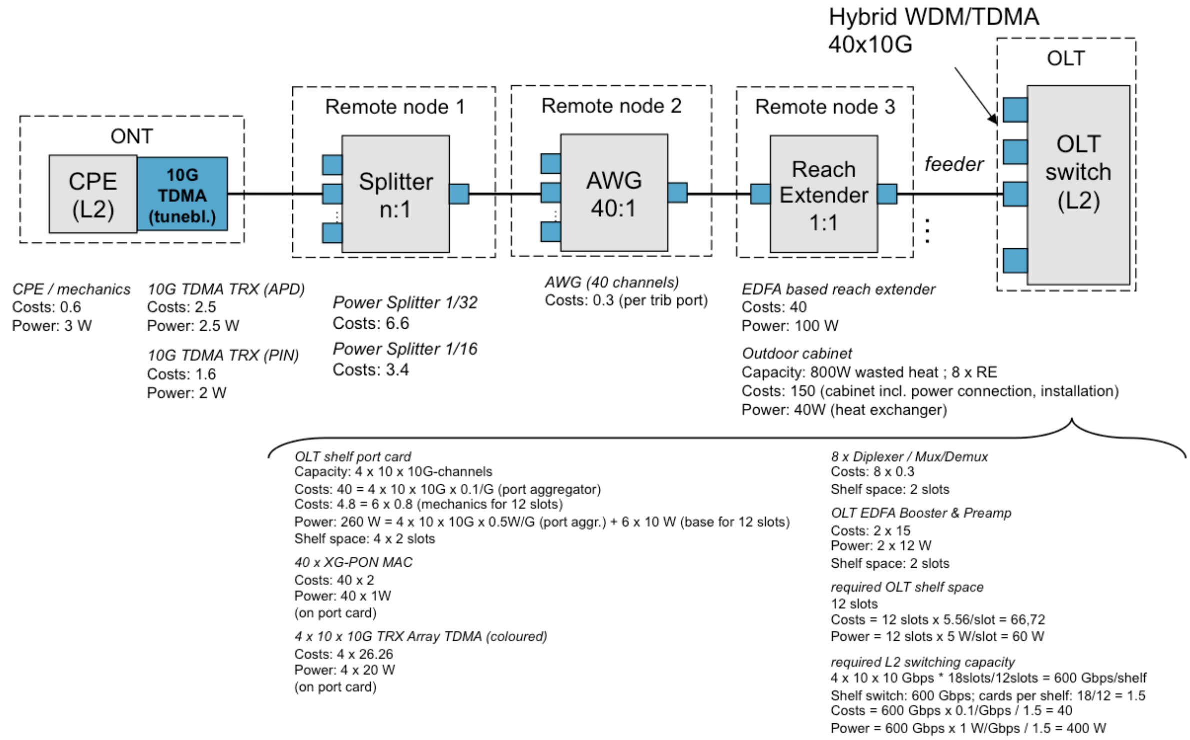


Figure 5-31: Passive hybrid WDM/TDM-PON: analysis for the configuration with 640/1280 clients per feeder

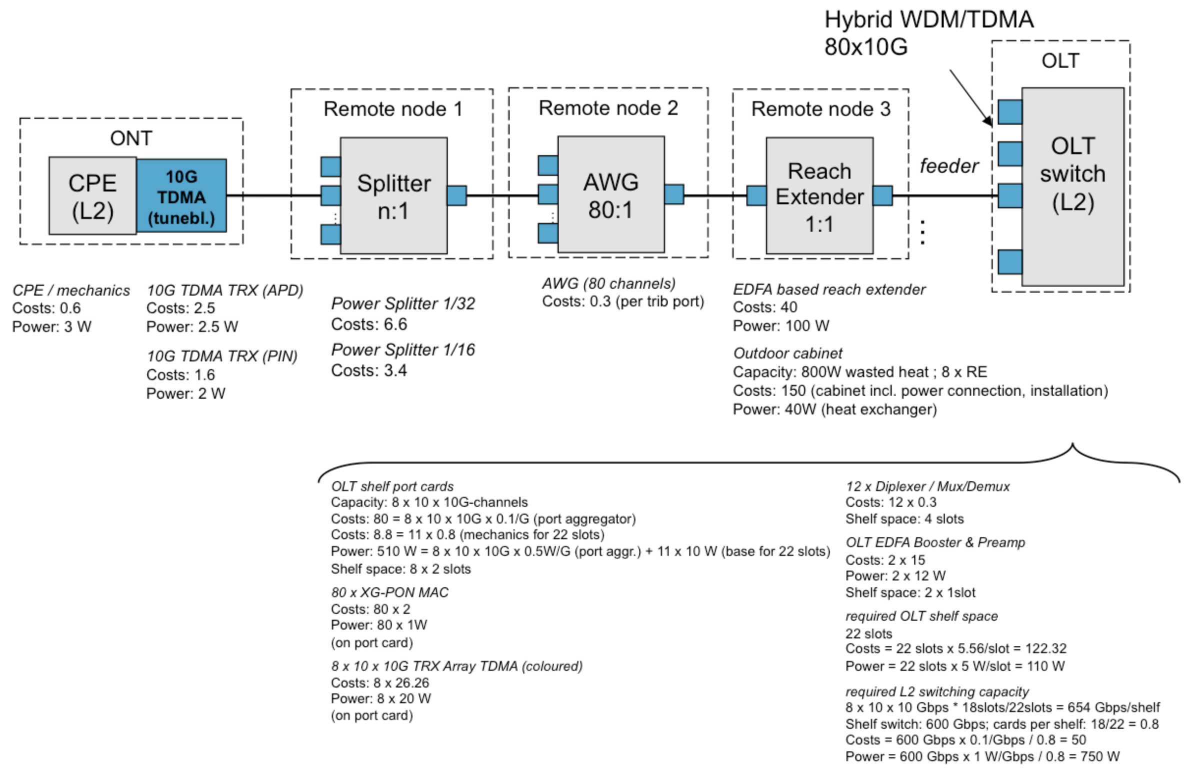


Figure 5-32: Passive hybrid WDM/TDM-PON: analysis for the configuration with 1280/2560 clients per feeder

Different combinations of AWG port count and power-splitter port count have been investigated to provide alternative configurations of this type of architecture variant. Table

5-20 and Table 5-19 summarize the results of power consumption and cost for the passive hybrid WDM/TDM-PON.

In contrast to the Co-UWDM-PON, different combinations of the fan-out counts of passive components have a high impact on both cost and power consumption. From Table 5-19, it can be seen that the cost per client depends on the fan-out count of power splitter. As well the cost-per-client variation at the OLT, the remote-node cost on a per-user basis also varies with the power-splitting ratio.

Table 5-19: Cost analysis of passive hybrid WDM/TDM-PON

Power-Split	λ-split AWG	Reach	Sustainable datarate (first mile & feeder) *Down-/up-link*	Client count (feeder)	*Cost per client (w/o feeder fibers)*	Costs ONT	Costs per client remote nodes	Costs per client OLT	Number of clients/20-slot OLT shelf
1:16 (APD@ONT; PAB@OLT)	40 ch	27 km	625/312 Mbps	640	*3.92*	3.1	0.24	0.58	960
1:16 (APD@ONT; PAB@OLT)	80 ch	16 km		1,280	*3.88*	3.1	0.24	0.54	1,024
1:16 (PIN@ONT; PAB@OLT; RE)	80 ch	30 km		1,280	*3.02*	2.2	0.28	0.54	1,024
1:16 (APD@ONT; PAB@OLT; RE)	80 ch	60 km		1,280	*3.92*	3.1	0.28	0.54	1,024
1:32 (APD@ONT; PAB@OLT)	40 ch	17 km	312/156 Mbps	1,280	*3.62*	3.1	0.22	0.3	1,920
1:32 (APD@ONT; PAB@OLT)	40 ch	70 km		1,280	*3.66*	3.1	0.26	0.3	1,920
1:32 (PIN@ONT; PAB@OLT; RE)	80 ch	20 km		2,560	*2.72*	2.2	0.24	0.28	2,048
1:32 (APD@ONT; PAB@OLT; RE)	80 ch	50 km		2,560	*3.62*	3.1	0.24	0.28	2,048

From Table 5-20, we can further see that the larger the fan-out count of the splitter is, the lower is the power consumption on a per-user basis. It is because the power consumption per client at the OLT side depends strongly on the splitting ratio of power splitter. In addition, the maximum sustainable data-rate per user decreases as the power-splitting ratio increases, such that with a 1:32 or higher power-split, the average bandwidth per user can no longer exceed 500 Mbit/s.

Table 5-20: Power consumption analysis of passive hybrid WDM/TDM-PON

Power-Split	Wavelength-Split	Reach	Sustainable datarate (first mile & feeder) *Down-/up-link*	Client count (feeder)	*Total power consumption per client*	Power cons. ONT	Power cons. per client remote nodes	Power cons. per client OLT	Number of clients/20-slot OLT shelf
1:16 (APD@ONT; PAB@OLT)	40 ch	27 km	625/312 Mbps	640	*6.9 W*	5.5 W	0 W	1.4 W	960
1:16 (APD@ONT; PAB@OLT)	80 ch	16 km		1,280	*6.8 W*	5.5 W	0 W	1.3 W	1,024
1:16 (PIN@ONT; PAB@OLT; RE)	80 ch	30 km		1,280	*6.4 W*	5 W	0.1 W	1.3 W	1,024
1:16 (APD@ONT; PAB@OLT; RE)	80 ch	60 km		1,280	*6.9 W*	5.5 W	0.1 W	1.3 W	1,024
1:32 (APD@ONT; PAB@OLT)	40 ch	17 km	312/156 Mbps	1,280	*6.2 W*	5.5 W	0 W	0.7 W	1,920
1:32 (APD@ONT; PAB@OLT; RE)	40 ch	70 km		1,280	*6.3 W*	5.5 W	0.1 W	0.7 W	1,920
1:32 (PIN@ONT; PAB@OLT; RE)	80 ch	20 km		2,560	*5.65 W*	5 W	0.05 W	0.6 W	2,048
1:32 (APD@ONT; PAB@OLT; RE)	80 ch	50 km		2,560	*6.15 W*	5.5 W	0.05 W	0.6 W	2,048

In supporting a sustainable data-rate per-user of 500 Mbit/s and a client count of 640, the passive hybrid WDM/TDM-PON architecture exhibits both a lower cost and lower power consumption as compared with the Co-UDWDM-PON. Furthermore, the passive hybrid WDM/TDM-PON has additional flexibility in terms of dynamic bandwidth allocation among the users connecting to the same power splitter. Its high-speed burst-mode operation allows a peak data-rate of 10 Gbit/s per user, which is hard to reach in the types of WDM-PON discussed in the previous section.

Another variant of passive hybrid WDM/TDM-PON architectures to provide flexible architectures are with Super OLT configuration. The fully flexible passive hybrid WDM/TDM-PON uses a Super-OLT with N × M-channel (e.g., 80-channel) WDM arrays and N feeder fibres which contain 1: k power splitters each. Each wavelength of each array can go to any AWG (where it is routed to the respective output port). This allows switching off and re-configuring any wavelengths. The respective local part is done in the L2 switch. The OLT contains 2N × 1: N power splitters, 2N × M-channel (X GHz) 1: N WSS, and 2N optical amplifiers (EDFAs). The remote nodes RN1n contain M-channel (X GHz) AWGs (so do the OLT TRX arrays). Each feeder and TRX array potentially has the same wavelengths, and there is no possibility to assign more than one wavelength to an ONT. The primary goal is to potentially shut down complete TRX arrays (overnight or so). Figure 5-33 gives the system architecture of fully flexible passive hybrid WDM/TDM-PON.

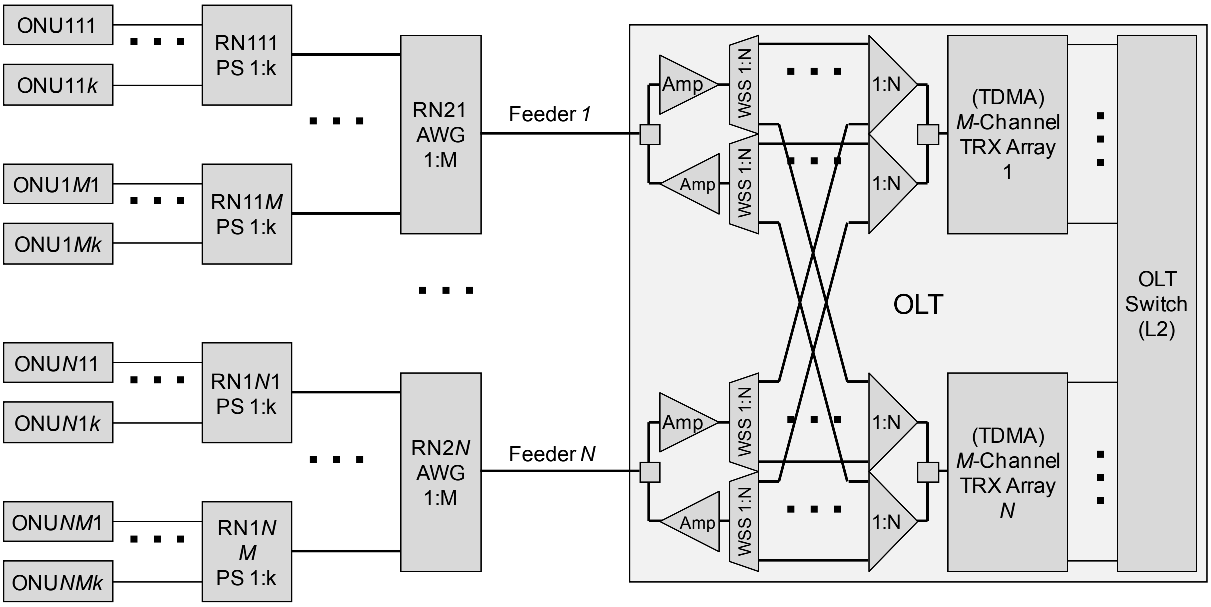


Figure 5-33: The fully flexible passive hybrid WDM/TDM-PON

Figure 5-34 gives the system concepts of the fully flexible passive hybrid WDM/TDM-PON.

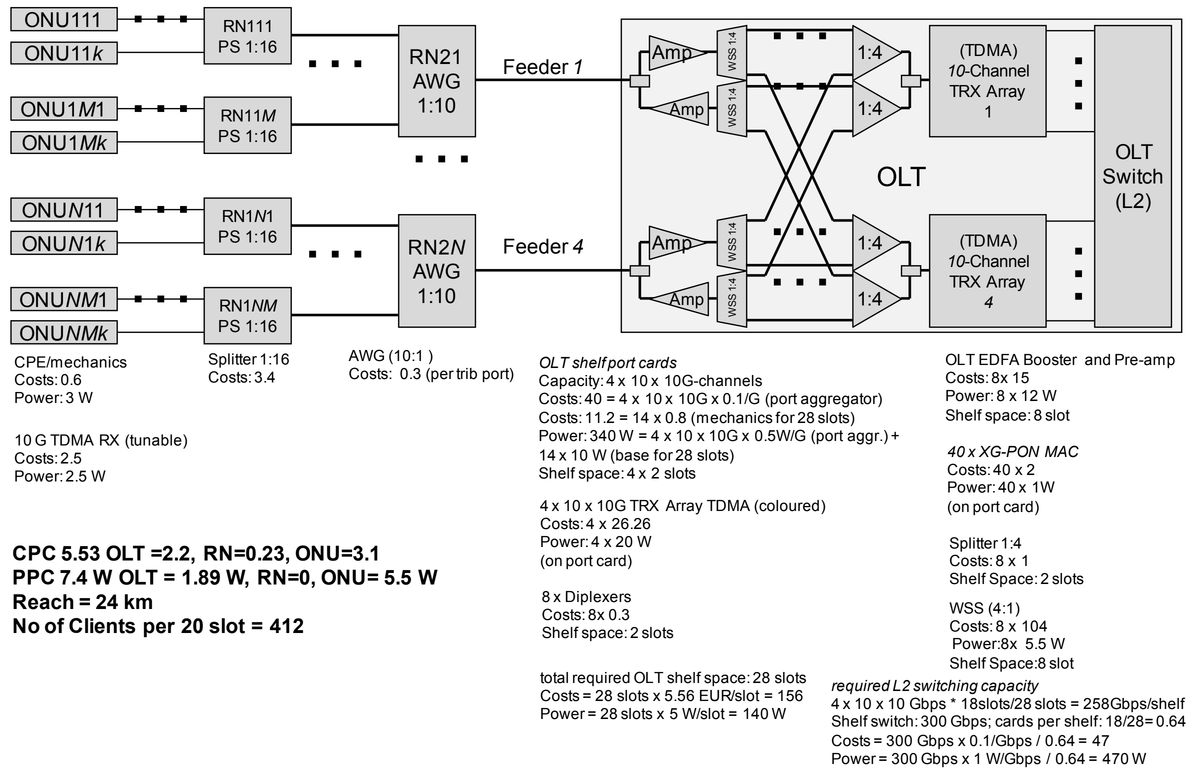


Figure 5-34: System concepts of fully flexible passive hybrid WDM/TDM-PON

Table 5-21 gives the cost comparison of flexible passive hybrid WDM/TDM-PON for an 80-channel and 40-channel configuration. The configuration with 80 channels comes at a higher cost and lower form factor.

Table 5-21: Cost analysis of fully flexible (FF) passive hybrid WDM/TDM-PON

Configuration	RN1	Power-Split	Reach	Sustainable datarate (first mile & feeder) *Down-/up-link*	Client count (feeder)	*Cost per client (w/o feeder fibers)*	Costs ONT	Costs per client remote nodes	Costs per client OLT	Number of clients/20-slot OLT shelf
FF (1:4 WSS at OLT)	1:10 AWG	1:16	24 km	625/312 Mbps	160	5.33	3.1	0.23	2.2	412
FF (1:8 WSS at OLT)	1:10 AWG	1:16	24 km	625/312 Mbps	160	6.5		0.23	3.17	384

Table 5-22 gives the power consumption analysis of flexible passive hybrid WDM/TDM-PON for an 80-channel and 40-channel configuration. There is no significant difference between the power consumption figures of the 80-channel and 40-channel configurations.

Table 5-22: Power consumption analysis of fully flexible (FF) passive hybrid WDM/TDM-PON

Configuration	RN1	Power-Split	Reach	Sustainable datarate (first mile & feeder) *Down-/up-link*	Client count (feeder)	*Power per client (w/o feeder fibers)*	Power ONT	Power per client remote nodes	Power per client OLT	Number of clients/20-slot OLT shelf
FF (1:4 WSS at OLT)	1:10 AWG	1:16	24 km	625/312 Mbps	160	*7.4 W*	5.5 W	0 W	1.89 W	412
FF (1:8 WSS at OLT)	1:10 AWG	1:16	24 km	625/312 Mbps	160	*7.48 W*		0 W	1.98 W	384

5.3.2 *Semi-passive hybrid WDM/TDM-PON*

In this section, we analyze a second variant of a hybrid WDM/TDM-PON, the semi-passive hybrid WDM/TDM-PON. A semi-passive hybrid WDM/TDM-PON basically aims to provide partial flexibility (PF) in the network. The flexibility can sit either in the remote node 2 or at the OLT. Semi-passive hybrid WDM/TDM-PON aims to provide flexibility by employing an active element like WSS in the remote node 2. Note that in Chapter 2, we referred to the semi-passive hybrid WDM/TDM-PON as a wavelength-routed (or wavelength-switched) hybrid WDM/TDM-PON.

Figure 5-35 shows the basic semi-passive hybrid WDM/TDM-PON configuration and its assignment to each PCP site.

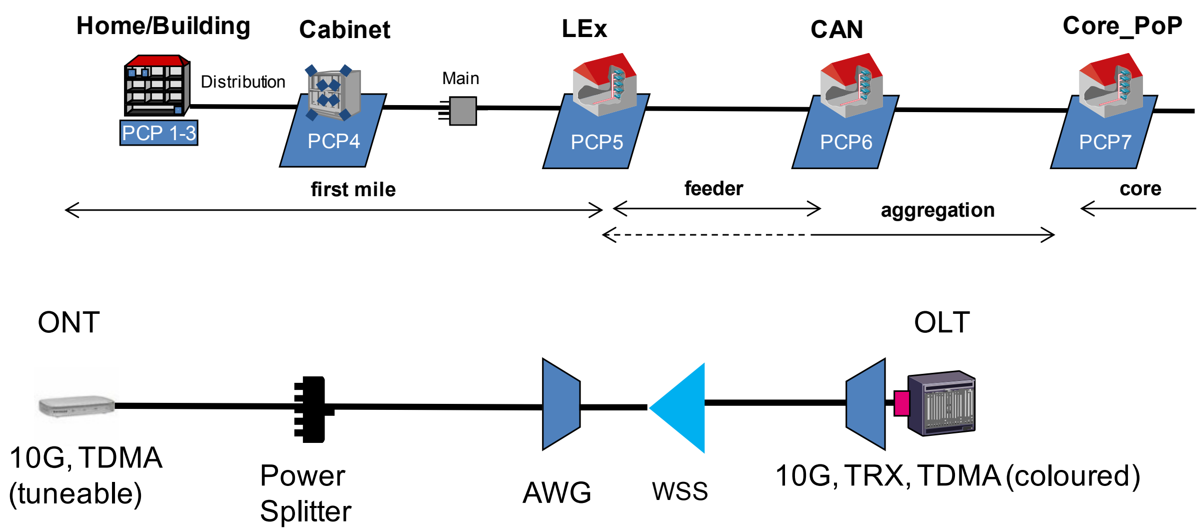


Figure 5-35: Semi-passive hybrid WDM/TDM-PON: assignment to each PCP site

The important advantages of the semi-passive hybrid WDM/TDM-PON are as follows:

- Network planning: The urban scenario will require less reach and more splitting ratio whereas rural scenario will require more reach and less splitting ratio. Thus, the PS with variable splitting ratio is required. The WSS can be used to configure different number of wavelength feed at the input of Remote node 2 and thus will enable Power Splitter (PS) with different splitting ratio (assuming same bandwidth demand per customer). Also, the NGOA architecture should have the provision for narrowband services, and thus the concept of different bandwidth feed will ease the network planning according to the scenario and requirement.
- Network migration: To support network migration, network should have dynamic capability to route 10 G and/or 1 G channel towards PS as and when customers are willing to migrate. Also, note that at the input of the PS, we can have different types of channels, and thus all customers behind the PS need not migrate at the same time.
- Network extensibility: If during the network design, the customer base is low, and then gradually more users add up, then we can accommodate all new users by assigning a proper wavelength to them. A WSS will help in easy wavelength routing. Thus, use of WSS will reduce Operational Expenditures.

The semi-passive hybrid WDM/TDM-PON makes use of the C (downstream) and L (upstream) bands, which are accessible via a cyclic AWG. At remote node 2, we assume a cascaded configuration of WSS and AWGs. To compensate for the insertion loss of WSS, we have used EDFA based amplifiers. Two 4:1 WSS are used: each for downstream and upstream. The WSSs are used in combination with 10:1 cyclic AWGs. The AWGs are of 10-skip-0 configuration. Both AWG and WSS used are of 50 GHz configuration. To keep the cost of WSS low, we have assumed no special functionality like broadcast etc. Note that on an average at the input port of an AWG, we will have 20 wavelength channels. These 20 wavelength channels are split in two wavelength channels per AWG output port. However, at high traffic demands, even each AWG can be fed with all 80 channels. Note that in Long Reach PON, there will be different traffic scenarios for home (domestic) and business premises. Normally, the peak traffic rate at domestic premises is in the night whereas in business premises it is closer to the morning hour. Thus re-routing the traffic from some network parts to another network part will lead to improvements in the PON performance. Remote node 1 is considered to be a simple power splitter. At the ONT, tuneable transceivers are assumed. Presently, the transceivers are tuneable over 4 nm or so, but we expect that cheap transceivers will become available that will be tuneable over the entire C band in the next few years. Figure 5-36 gives the system concepts of a semi-passive hybrid WDM/TDM-PON.

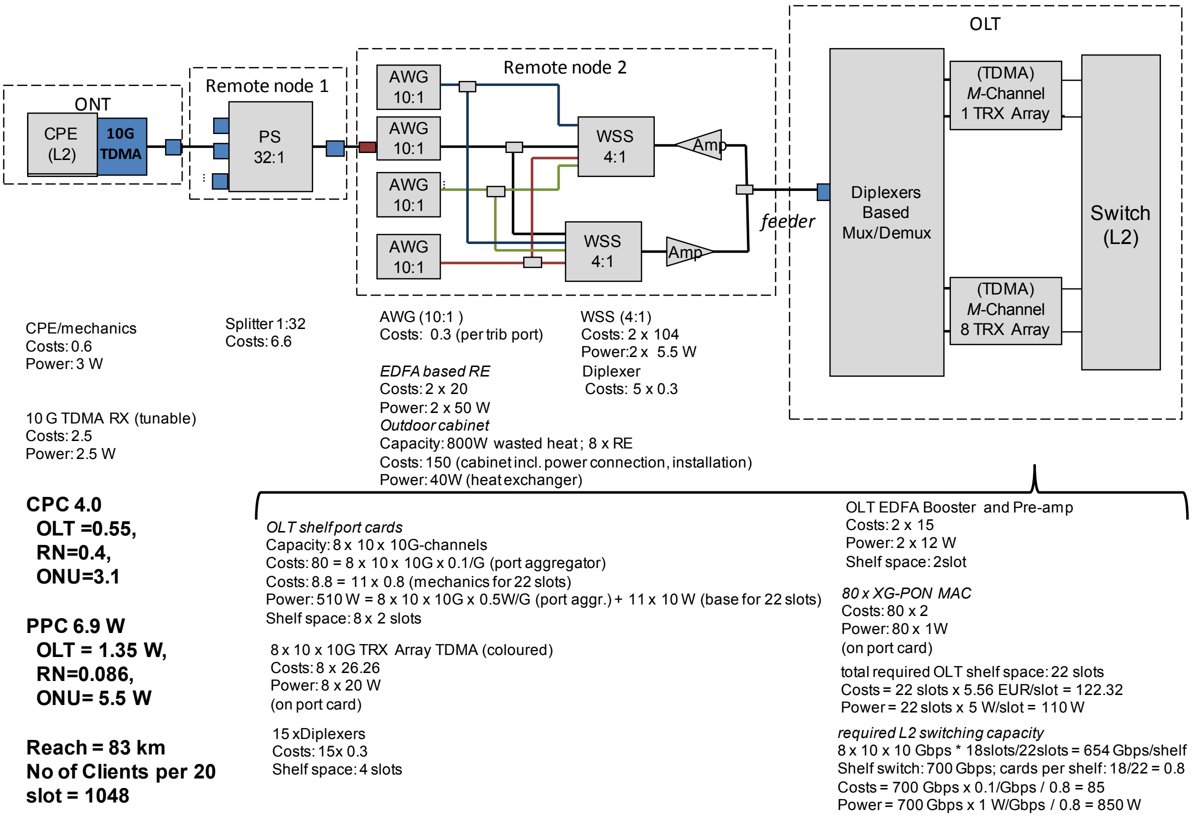


Figure 5-36: System concepts of semi-passive hybrid WDM/TDM-PON with 1:4 WSS, 1:10 AWG, and 1:32 PS.

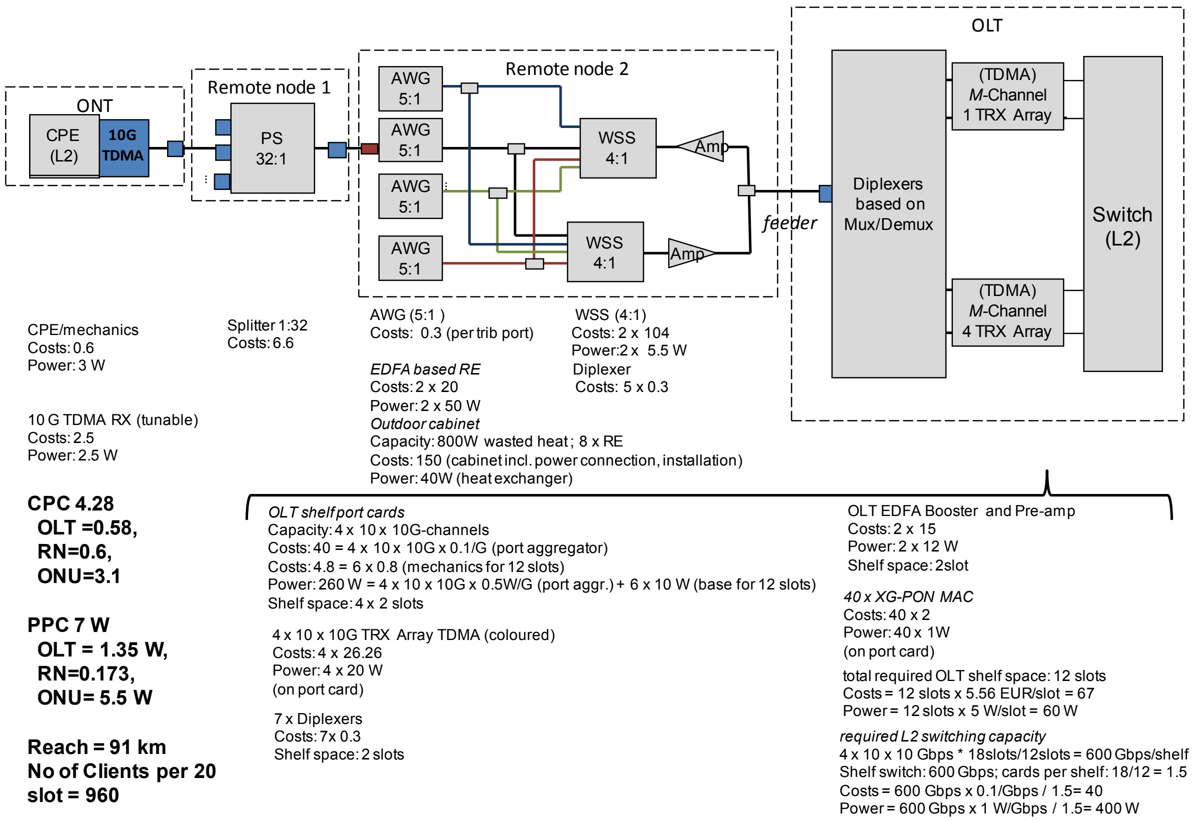


Figure 5-37: System concepts of semi-passive hybrid WDM/TDM-PON with 1:4 WSS, 1:5 AWG, and 1:32 PS.

Table 5-23 gives the cost comparison of a semi-passive hybrid WDM/TDM-PON for an 80-channel and 40-channel configuration. There is no significant cost difference between both the configurations; however the 40-channel configuration is slightly more costly and with a smaller form factor.

Table 5-23: Cost analysis of partially flexible (PF) semi-passive hybrid WDM/TDM-PON

Configuration	RN1	Power-Split	Reach	Sustainable datarate (first mile & feeder) *Down-/up-link*	Client count (feeder)	*Cost per client (w/o feeder fibers)*	Costs ONT	Costs per client remote nodes	Costs per client OLT	Number of clients/20-slot OLT shelf
PF (80 channels)	1:4 WSS, 1:10 AWG,	1:32	83 km	625/312 Mbps	1280	*4.0*	3.1	0.4	0.55	1048
PF (40 channels)	1:4 WSS, 1:5 AWG,	1:32	91 km	625/312 Mbps	640	*4.28*		0.6	0.58	960

Table 5-24 gives the power consumption analysis of the semi-passive hybrid WDM/TDM-PON for 80-channel and 40-channel configurations. The 40-channel configuration also has a slightly higher power consumption. The power and cost figures of the 40-channel configurations are slightly higher as it has a lower customer base. Employing an EDFA in remote node 2 gives higher reach figures.

Table 5-24: Power consumption analysis of partially flexible (PF) semi-passive hybrid WDM/TDM-PON

Configuration	RN1	Power-Split	Reach	Sustainable datarate (first mile & feeder) *Down-/up-link*	Client count (feeder)	*Power per client (w/o feeder fibers)*	Power ONT	Power per client remote nodes	Power per client OLT	Number of clients/20-slot OLT shelf
PF (80 channels)	1:4 WSS, 1:10 AWG,	1:32	83 km	625/312 Mbps	1280	*6.9 W*	5.5 W	0.086 W	1.35 W	1048
PF (40 channels)	1:4 WSS, 1:5 AWG,	1:32	91 km	625/312 Mbps	640	*7 W*		0.173 W	1.35 W	960

5.4 NEXT-GENERATION AON

Ethernet has become the ubiquitous service delivery technology that can be supported over any transport network, with Gigabit Ethernet initially finding deployment in backbone network links. Higher bandwidth 10 Gigabit Ethernet is now replacing 1Gb as the backbone network standard, and has also begun to migrate down to high-end server systems, with 100 Gigabit Ethernet standards also now approved (June 2010). We note that the IEEE Gigabit fibre standards 1000BASE-LX10 and 1000BASE-BX10 were part of a larger group of protocols known as Ethernet in the First Mile.

As indicated in deliverable D3.1 [3] the NG AON (see section 2.3) architecture comes in a multitude of configurations when applied from the home to the core network. However, in the context of the pure access part of the OASE architectural scope there are three solutions: 1) AON homerun; 2) AON active star with/without WDM on the feeder fibre; and 3) hybrid PtP Ethernet over PtP WDM-PON. Together they can be applied in fibre-rich to fibre-poor scenarios, and in networks operated as open access networks to fully-vertical business models. If only looking to the pure access scenario, the third solution has a large overlap with the WDM-PON solutions covered in the previous section, but in the context of a NG AON architecture it has less focus on long-reach and a high number of wavelengths, i.e. it is used in a more distributed scenario, which is optimized towards a larger degree of local traffic patterns. In which case, here we concentrate on solutions (1) and (2).

5.4.1 AON homerun

An AON homerun architecture (also called point-to-point Ethernet) is illustrated in Figure 5-38. Each subscriber link has a dedicated fibre connection from the home ONT to the OLT at the LEx or CAN, therefore it requires a number of fibres at least the same as the number of connected subscribers.

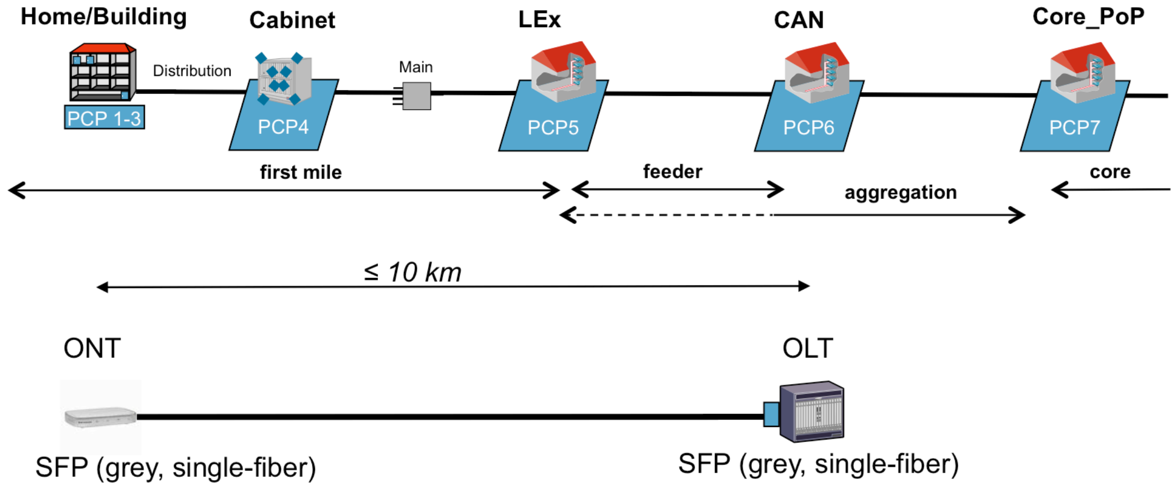


Figure 5-38: AON homerun: assignment to PCP sites

A detailed analysis of the cost and power consumption figures for the AON homerun solution can be found in Figure 5-39, with the results summarized in Table 5-25 and Table 5-26.

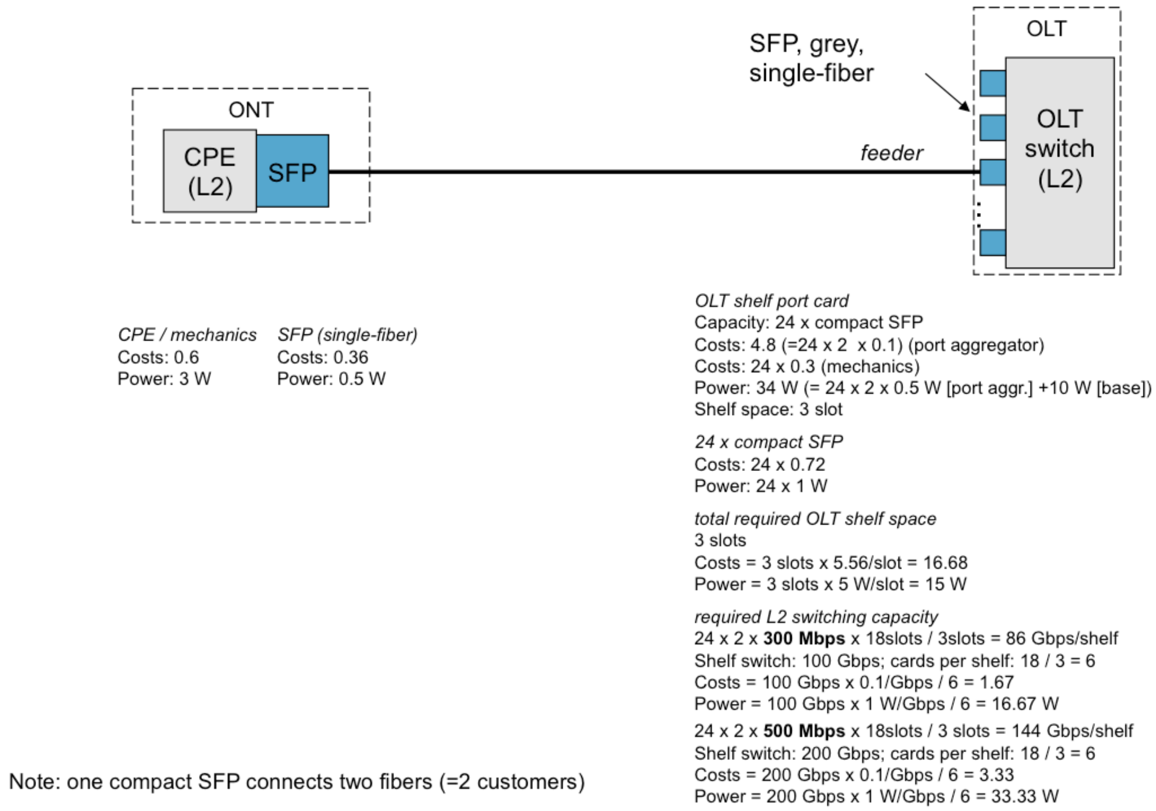


Figure 5-39: Detailed cost and power calculation of AON homerun network equipment

Table 5-25: Cost analysis of AON homerun

Reach	Sustainable datarate (first mile & feeder) *symmetric*	Client count (feeder)	*Costs per client (w/o feeder fibers)*	Costs ONT	Costs per client OLT	Number of clients/ 20-slot OLT shelf
10 km	300/500 Mbps (347/694 Mbps)*	1	*1.95 / 1.98*	0.96	0.99 / 1.02	288

*assumes incremental L2 shelf switch dimensioning in 100 Gbps steps

Table 5-26: Power consumption analysis of AON homerun

Reach	Sustainable Datarate (first mile & feeder) *symmetric*	Client count (feeder)	*Total power consumption per client*	Power cons. ONT	Power cons. per client OLT	Number of clients/ 20-slot OLT shelf
10 km	300/500 Mbps (347/694 Mbps)*	1	*5.4 / 5.7 W*	3.5 W	1.9 / 2.2 W	288

*assumes incremental L2 shelf switch dimensioning in 100 Gbps steps

The cost calculation above only considers the network equipment and components, with the cost of the feeder fibre infrastructure and related civil work not included. In comparison to other access solutions offering the same sustainable bandwidth, both network equipment cost and the power consumption per-line are low for the AON homerun solution, as compared to competing solutions. These evaluations are based on current existing products, so it is reasonable to expect that the system performance, power consumption, port density etc. of Ethernet equipment will be still further improved over the coming years.

In a node-consolidation oriented NGOA scenario, the consolidated CANs are utilized as the first access node location and accommodate a large number of customers, with the CANs located, for example, 20 to 40 km from the end-users depending on degree of node consolidation [2]. For the AON homerun solution, the long reach distance is technically not a problem, with currently available components and equipment able to support up to 120 km reach distance. However, due to the point-to-point topology, the reach is limited by economical factors when considering the deployment of fibre infrastructures. This is particularly true for brownfield fibre deployment, where the available duct space is limited, with the more subscribers connected to the CAN, the more duct space and installation is needed for fibre. When running out of duct space, additional civil work (e.g. digging, trenching, etc.) may be required, which is generally quite costly, especially over long distances. Therefore it is not practical to have an Ethernet point-to-point solution over a long reach distance in this case. This issue can either be fixed by using the Ethernet over point-to-point WDM-PON concept, or using an active remote-node solution as described in the next section. All these alternatives can dramatically reduce number of fibres deployed in the field.

We note that this techno-economic aspect will behave differently from case to case depending on the different business models and deployment strategies adopted. For instance, in a green field fibre deployment area, where no existing ducts or other infrastructure exists, all architectures will need civil works, so that the economic difference between deploying PtP fibre infrastructure and the other more fibre-lean architectures will be less.

5.4.2 Active Star

The active star architecture relates to the use of an active remote node (ARN) topology, where upstream data from a group of end-users is first aggregated in an active node, where active equipment, e.g. Ethernet switches are located. Subsequent to the ARN, the uplink of Ethernet switches are further aggregated into either a single or a few feeder fibres towards the CAN. For a pure Ethernet active star architecture, the number of subscribers per feeder fibre is limited by the maximum transmission capacity of optical transceivers. For example, a 100 Gbit/s transceiver can support a maximum of 200 subscribers with 500 Mbit/s for each of them on one feeder fibre. However, by making use of WDM technologies this number can be further improved to match the OASE NGOA requirements.

There are two active star architectures using WDM backhaul technology that we are considering:

a) Ethernet active star with WDM PtP backhauling, Figure 5-40(a)
b) Ethernet active star with WDM-PON backhauling, Figure 5-40(b), as also partly described in the next section 5.5

The main difference between those two architectures is that in the WDM-PtP backhauling active remote node architecture Figure 5-40(a), AWGs are collocated with switches in the first ARN, hence each active node is then PtP connected to CAN. Whereas, in the WDM-PON backhaul architecture the CAN connects the active nodes via PtMP links by the introduction of a passive AWG at an intermediate passive node, see Figure 5-40(b), (i.e. an additional passive remote node between the active remote node and the CAN.) The remote nodes in Figure 5-40(b) can be located flexibly from the building basement to the CAN (PCPs 3 to 6); whereas the Figure 5-42 is assumed to have its RNs located at only the LEx and CAN (PCPs 5&6). Another difference between these two WDM backhaul architectures is that in the WDM-PON backhaul architecture 10 Gbit/s transceivers are used together with a 40-wavelength channel WDM system, whereas in the WDM-PtP backhaul architecture higher speed transceivers are suggested (e.g. 40 Gbit/s or 100 Gbit/s) together with fewer wavelength channels (e.g. 4 or 8 wavelengths).

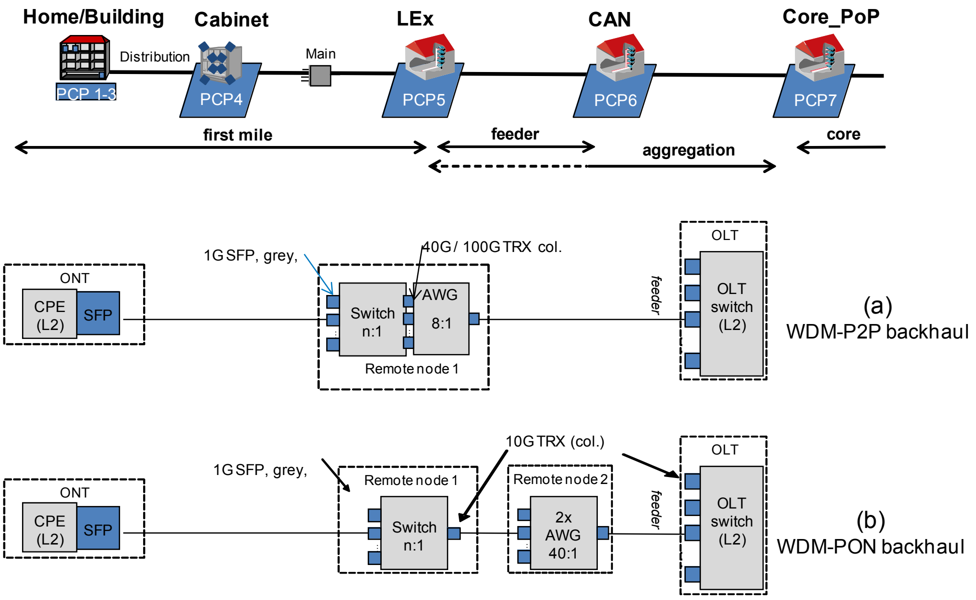


Figure 5-40: Ethernet active remote node with (a) WDM-PtP backhaul; and (b) in a WDM-PON backhaul context. Assignment to PCP sites.

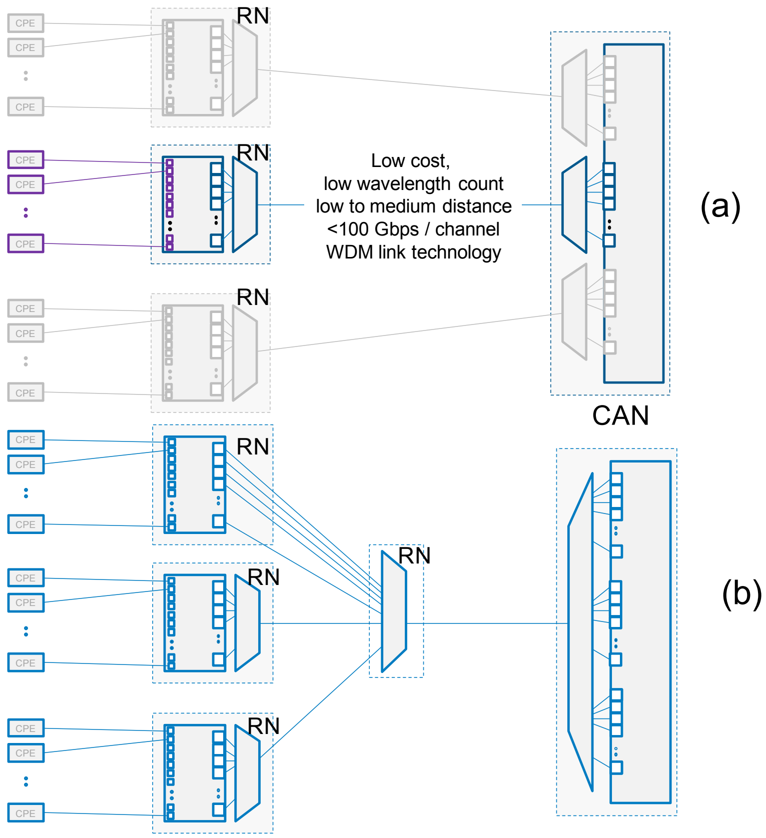


Figure 5-41: Tree diagrams of Ethernet active remote node with (a) WDM PtP backhaul; and (b) WDM-PON backhaul

The Ethernet active star with WDM PtP backhaul architecture is relatively simple in terms of the complexity of the optical system (and how it affects costs) due to the lower channel counts per feeder fibre. This architecture also has easier service upgrade/migration scalability. However the main disadvantage of the solution is that it requires a relatively higher number of feeder fibres as compared to the WDM-PON backhauling solution of Figure 5-41(b). The impact of this is hard to judge since it is highly dependent on whether the fibre is deployed in a green or brown field scenario, and whether the fibre infrastructure is operated as an open access or vertical physical infrastructure provider (PIP).

In robustness scenarios or scenarios with a high degree of local traffic patterns, the architectures of Figure 5-40 can be exchanged with an optical ring or mesh by inter-connecting the active remote nodes, where the load dynamics can either be handled on the optical level (e.g. via ROADMs) or at the electrical layer (e.g. on the Ethernet layer). A dynamic optical layer can then stretch all the way to PCP7 as indicated in the architectural reference picture in Figure 5-40. The latter scenario has implications on the energy efficiency due to a lower use of OE (optical and electrical) conversion.

The cost and power consumption results for the Ethernet active star with WDM-PON backhauling can be found, as appropriate, in Table 5-27 and Table 5-28 respectively in the following section. We note that a more detailed comparison and analysis between different Ethernet active star scenarios in the context of the WDM PtP backhaul architecture will be further studied in the future deliverable D5.3.

5.5 WDM-PON BACKHAUL

In contrast to node-consolidation achieved by increasing the passive reach length in the access between ONT and OLT, an alternative strategy to achieve a lower TCO is by simplifying the metro network, and introducing long reach passive systems from the local exchange to an aggregation node higher up in the network. This strategy is enabled by the WDM-PON backhauling class of architecture that we analyse here. If active hybrid concepts based on WDM-PON backhaul are treated as integrated access systems, both long reach and large client count can be achieved. However, these performance advantages come at the penalty of requiring active remote nodes in the local exchange. This trade-off needs to be addressed by complete TCO calculations.

Here we consider a 10-Gbit/s WDM-PON backhaul system combined with four different technologies in the first mile, i.e. Ethernet PtP, GPON, XG-PON and WDM-PON, as indicated in Figure 5-42. We assume a 10-Gbit/s 40-channel WDM-PON system. This is a dual-fibre system based on two 40-channel AWGs at the remote node and 8 x 10G transceiver arrays assumed on the OLT-side.

The cost and power models for the first mile systems have already been described in previous sections. Note, however, that the systems have been dimensioned to comply with the OASE data-rate requirements, which means that, for example, the power splitter within the first-mile G-PON system should be in the range of 1:4 to 1:8.

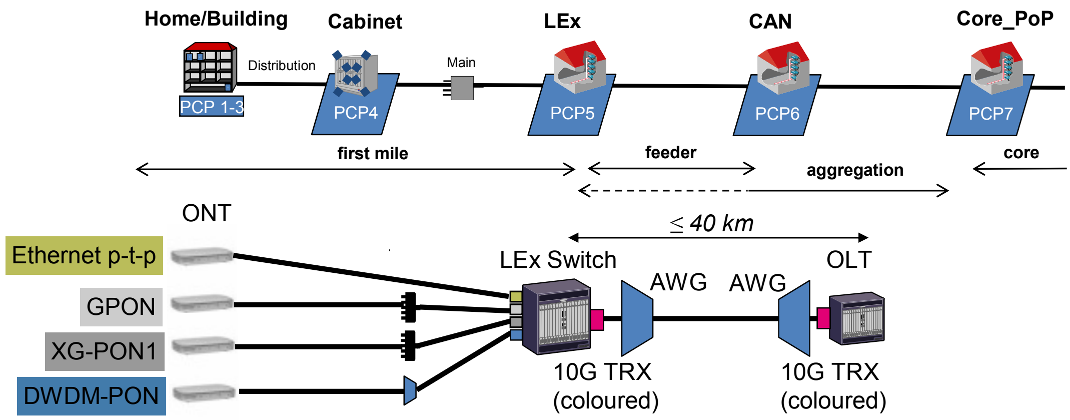


Figure 5-42: Considered system configurations based on WDM-PON backhauling: assignment to PCP sites

5.5.1 *Hybrid active Ethernet-PtP-in-WDM-PON*

The cost and power model for the hybrid active Ethernet-PtP-in-WDM-PON is shown in Figure 5-43. Assuming each remote node is served by one 10-Gbit/s uplink channel, the first remote node is configured for either 20 or 33 clients depending on whether the sustainable bandwidth is 500 Gbit/s or 300 Gbit/s.

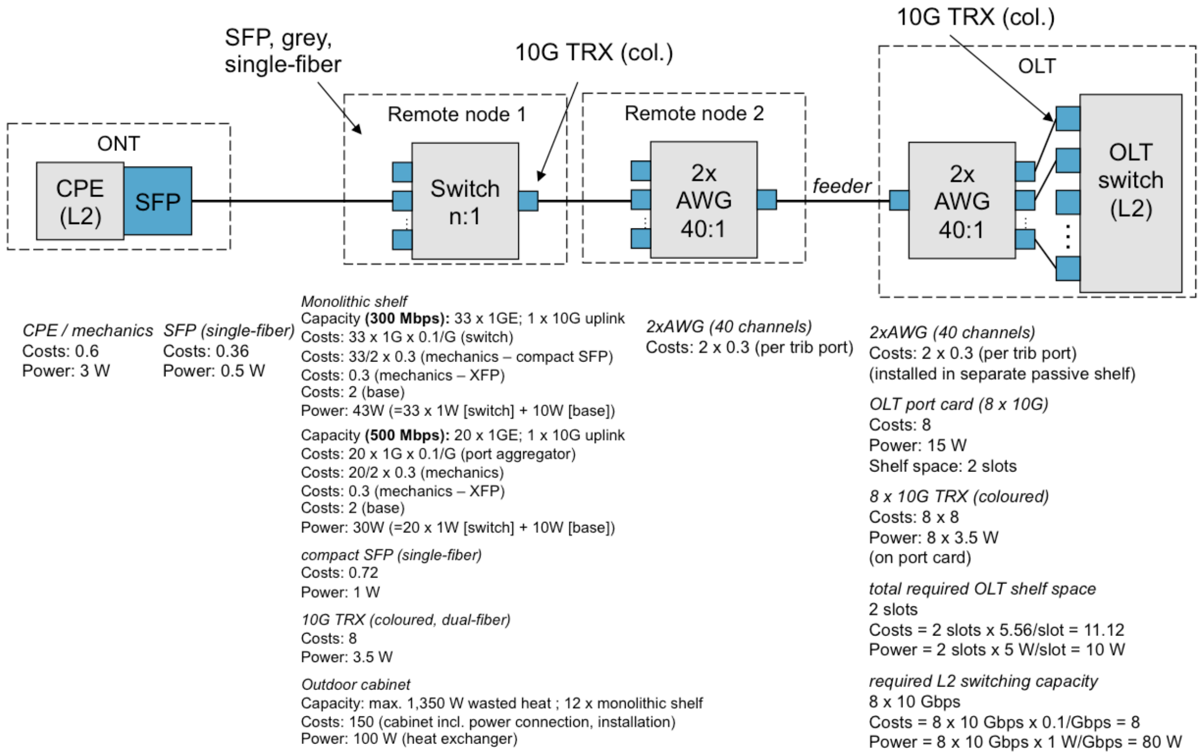


Figure 5-43: Cost and power model for hybrid active Ethernet-PtP-in-WDM-PON

5.5.2 Hybrid active G-PON-in-WDM-PON

The cost and power model for hybrid active G-PON-in-WDM-PON is shown in Figure 5-44. Here, we assume there are four G-PON ports per first remote node without any overbooking of the downstream capacity. Three G-PON splitting ratios have been considered (1:4, 1:8 and 1:32). The 1:4 split complies with the requirement for a sustainable data-rate of 500 Gbit/s, while the 1:8 and 1:32 splits comply with the requirement of 300 Gbit/s.

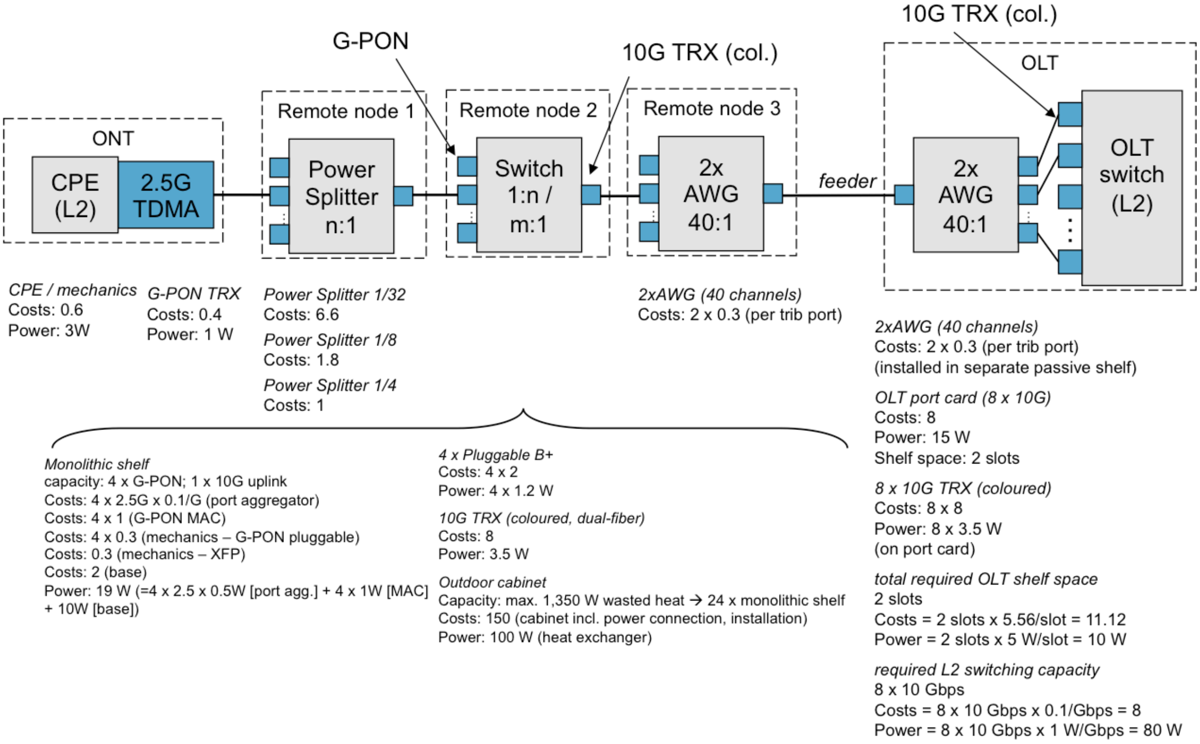


Figure 5-44: Cost and power model for hybrid active G-PON-in-WDM-PON

5.5.3 Hybrid active Ethernet XG-PON-in-WDM-PON

The cost and power model for the hybrid active XG-PON-in-WDM-PON variant is shown in Figure 5-45. Here, we again assume that there are four XG-PON ports and four 10-Gbit/s uplink ports per first remote node without any overbooking of the downstream capacity. In this case, two XG-PON splitting ratios have been considered (1:16 and 1:32). The 1:16 split complies with the requirement for a sustainable data rate of 500 Gbit/s, whilst the 1:32 split complies with the requirement of 300 Gbit/s.

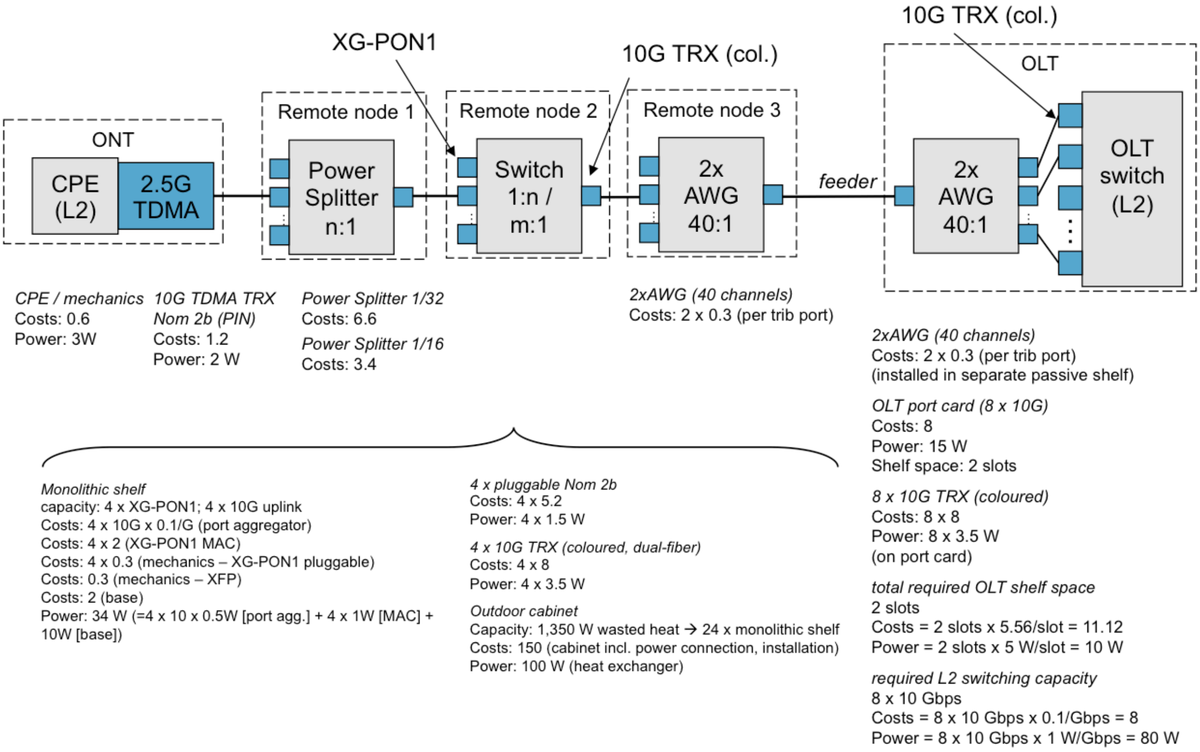


Figure 5-45: Cost and power model for hybrid active XG-PON-in-WDM-PON

5.5.4 Hybrid active DWDM-PON-in-WDM-PON

The cost and power model for the hybrid active DWDM-PON-in-WDM-PON architecture variant is shown in Figure 5-46. In this case, an 80-channel WDM-PON system is considered for the first-mile, with two configurations of the second remote node considered. One has an overbooking factor of two providing a 500 Gbit/s sustainable downstream rate, and the other configuration features an overbooking factor of four, providing a 250 Gbit/s sustainable downstream rate. This corresponds to either four or two 10-Gbit/s uplink channels per second remote node.

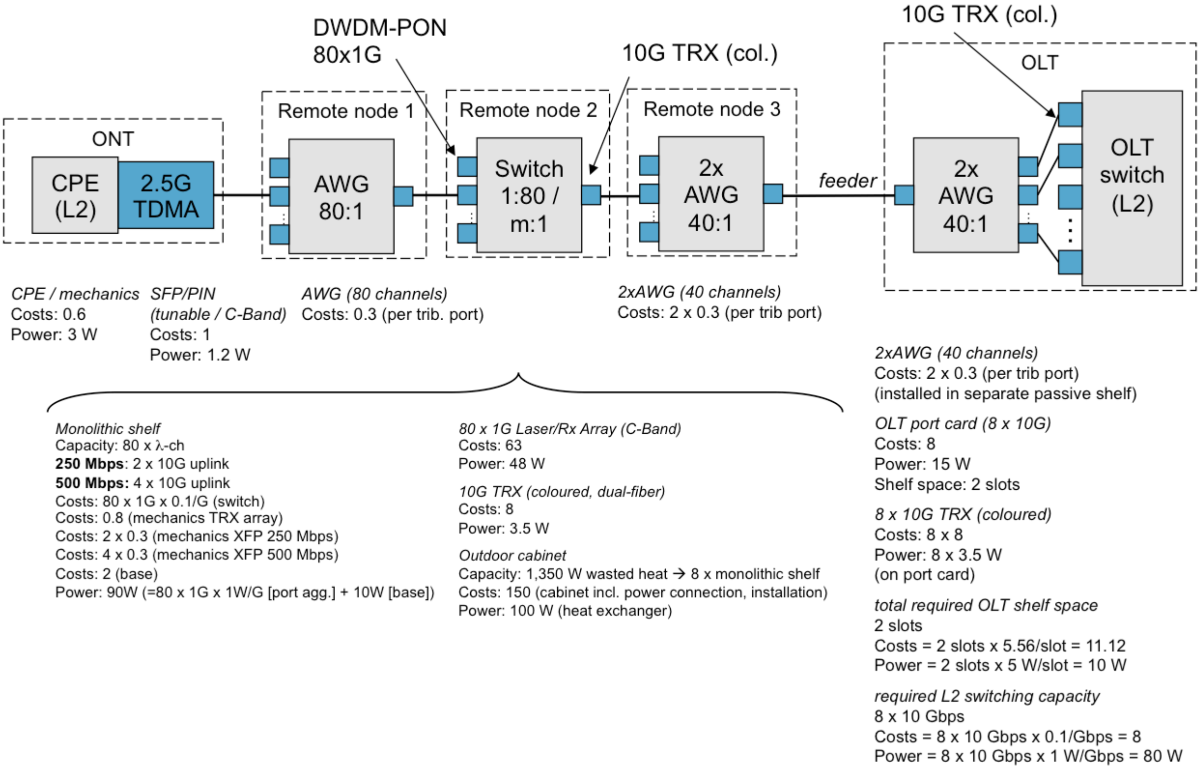


Figure 5-46: Cost and power model for hybrid active DWDM-PON-in-WDM-PON

5.5.5 WDM-PON backhaul Summary

Table 5-27 and Table 5-28 summarise the complete assessment of reach, client count per feeder fibre, sustainable data-rate, cost, and power for the system configurations based on the WDM-PON backhauling architecture class. The different drop alternatives are color coded with Ethernet PtP (yellow), G-PON (grey), XG-PON (dark grey) and WDM-PON (blue).

Table 5-27: Cost analysis of configurations based on WDM-PON backhauling

Power/ Wavelength split ODN	Ethernet Port-Aggregation (LEx)	Wavelength-Split (dual-fiber XFP)	Reach	Sustainable datarate (down-/uplink)	Client count (feeder)	*Cost per client (w/o feeder fibers)*	Costs ONT	Costs per client remote nodes	Costs per client OLT	Number of clients/20-slot OLT shelf	Number of clients/44U rack
1:1	33:1	40 ch	40 km	300 Mbps	660	*2.64*	0.96	1.32	0.36	2,376	7,128
1:1	20:1	40 ch	40 km	500 Mbps	400	*3.34*		1.78	0.6	1,440	4,320
1:4	16:1	40 ch	40 km	625/312 Mbps	320	*3.94*	1	2.2	0.74	1,152	3,456
1:8	32:1	40 ch	40 km	312/156 Mbps	640	*2.58*		1.2	0.38	2,304	6,912
1:32	128:1	40 ch	40 km	78/39 Mbps	2560	*1.56*		0.46	0.1	9,216	27,648
1:16	16:1	40 ch	40 km	312/156 Mbps	320	*3.94*	1.8	1.4	0.74	1,152	3,456
1:32	32:1	40 ch	40 km	156/78 Mbps	640	*2.98*		0.8	0.38	2,304	6,912
1:80	40:1	40 ch	40 km	250 Mbps	800	*3.58*	1.6	1.68	0.3	2,880	8,640
1:80	20:1	40 ch	40 km	500 Mbps	400	*4.08*		1.88	0.6	1,440	4,320

Table 5-28: Power consumption analysis of configurations based on WDM-PON backhauling

Power/ Wavelength split ODN	Ethernet Port-Aggregation (LEx)	Wavelength-Split (dual-fiber XFP)	Reach	Sustainable datarate	Client count (feeder)	*Total power consumption per client*	Power cons. ONT	Power cons. per client remote nodes	Power cons. per client OLT	Number of clients/outdoor cabinet	Number of clients/20-slot OLT shelf	Number of clients/44U rack
1:1	33:1	40 ch	40 km	300 Mbps	660	*6.2 W*	3.5 W	2.2 W	0.5 W	396	2,376	7,128
1:1	20:1	40 ch	40 km	500 Mbps	400	*6.9 W*		2.6 W	0.8 W	240	1,440	4,320
1:4	16:1	40 ch	40 km	625/312 Mbps	320	*7 W*	4 W	2 W	1 W	464	1,152	3,456
1:8	32:1	40 ch	40 km	312/156 Mbps	640	*5.5 W*		1 W	0.5 W	928	2,304	6,912
1:32	128:1	40 ch	40 km	78/39 Mbps	2560	*4.45 W*		0.25 W	0.2 W	3,712	9,216	27,648
1:16	32:1	40 ch	40 km	312/156 Mbps	320	*6.9 W*	5 W	0.9 W	1 W	896	1,152	3,456
1:32	64:1	40 ch	40 km	156/78 Mbps	640	*6 W*		0.5 W	0.5 W	1,792	2,304	6,912
1:80	40:1	40 ch	40 km	250 Mbps	800	*6.6 W*	4.2 W	2 W	0.4 W	400	2,880	8,640
1:80	20:1	40 ch	40 km	500 Mbps	400	*7 W*		2 W	0.8 W	400	1,440	4,320

6. Qualitative assessment of selected technical criteria

In this section we provide additional detail on the resilience, security, upgradeability, and mobile backhaul requirements which NGOA systems will have to satisfy. Quantifying adherence to these requirements is not so obvious; in which case we do not provide any additional quantitative analysis of the systems as to how they satisfy these additional requirements. Indeed, our expectation is that each system will satisfy these base requirements, so that on their own they won't act as a differentiating factor between the various system variants; as long as each requirement is satisfied.

6.1 RESILIENCE

Resilience in NGOA systems is a critical feature, such that architectures and systems need to be designed to have inherent fail-safe and robust features to ensure high reliability (4 nines or >99.99%) between ONT and OLT. When considering high resilient systems designs both the links between nodes, as well as the system equipment within nodes needs to be studied. For the system equipment, suitable doubling of critical components (i.e. 100% redundancy) can be adopted as an appropriate strategy so as to build-in additional resilience, as well as the use of 'software-defined' approaches, so that equipment can be 'reprogrammed' in the event of individual component failures and maintain a degree of ongoing operation. For the links between nodes the obvious solution is to have a parallel link configuration between nodes, i.e. dual parenting. This is already predominantly the case between PCPs 6 and 5. Up to now, relatively little doubling exists between PCPs 5 and 4, but as bandwidth increases, node consolidation takes place, and total aggregated traffic continues to increase significantly, suitable inherent back-up strategies are becoming ever more necessary so as to avoid complete and widespread service failure or outages - an unacceptable situation, both from a QoS, QoE, and SLA perspective, as well as from safety considerations (e.g. emergency services, tele-medicine, e-security etc.), the link between PCPs 5 and 4 is also becoming an ever more important issue for the same reasons as for the feeder fibre between PCPs 6 and 5.

In all the architectures considered in the OASE project, topological resilience solutions with dual optical fibre deployments down to the RN (i.e. between PCPs 6 and 5) are already assumed. For the final link between PCPs 5 and 4, all-optical resilience solutions will depend on many techno-economic factors, since it is the most expensive aspect of the NGOA network. We note that a wireless back-up solution for the final-drop may eventually be the most cost-effective and reliable method to achieve the required resilience. However, such wireless technology solutions lie outside the scope of the OASE project. Instead, we present viable all-optical alternatives, which will flexibly integrate into the NGOA optical methodology of the designs presented in this project. To that end, we note that the resilience concepts considered here are relatively generic to NGOA designs, and can be straightforwardly adapted to each of the main architectures and system variants considered in this Deliverable. This means that we don't expect the resilience techniques and design methodologies presented here to act as an explicit differentiator between the systems and architecture variants. We present these methodologies for completeness, since they are necessarily a key feature for future NGOA design, and it is important to demonstrate their effectiveness and the possibility of their inclusion in our OASE system variants.

We note that in WP3, which is studying NGOA design aspects from a more architectural perspective, one aspect of resilience that has been studied there is to locate multiple OLTs at different geographic locations. In this case, rather than simply doubling the OLT at the same head-end location, each OLT is instead located at a different geographic position (PCP6), with different (diversified) feeder fibres connecting the diversified OLTs at their different PCP6 locations to the same RN. This provides additional NGOA resilience, but at the architectural level. However, we are not considering this architectural doubling aspect here, but rather more at the system level. Hence, when we discuss, for example, dual OLTs, they could either be in the same geographic location or at different PCP6's. For some system concepts, this doesn't tend to affect the intrinsic physical OLT system design (as described in this deliverable), but a different network management & control software scheme will be required for these two different resilience/diversification approaches. For some concepts, such as for WDM-PON, there will be implications on the system design and required hardware/ components depending on how resilience is arranged. Hence, the case of WDM-PON requires a more detailed discussion.

Due to the protocol agnosticism of WDM PON, resilience can be implemented in both the wavelength/wavelength-adaptation layer and the PON client layer, respectively. In case of an Ethernet client layer, existing protocols such as G.8031 (Ethernet linear protection), G.8032 (Ethernet ring protection switching) and 802.3ad (Ethernet link aggregation) can be leveraged. In the combined WDM PON wavelength/wavelength-adaptation layer, several PON-specific resilience mechanisms can be implemented. G.984.1 lists protection and dual-parenting options for both the entire PON segment and the feeder fibre section.

Regarding component doubling, protection configurations include the option to duplicate the OLT transceiver array. Figure 6-1: (A) shows the configuration for a non-duplicated transceiver array; figure 6-1: (B) shows the respective configuration with duplicated transceiver arrays.

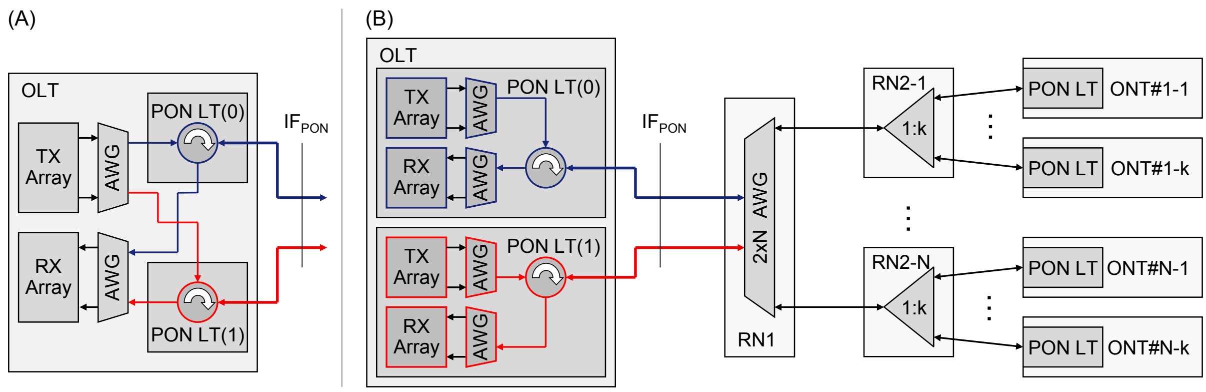


Figure 6-1: 2:N-AWG protection with (A) non-duplicated transceiver array and (B) duplicated transceiver array

Figure 6-1: shows an ODN where wavelengths are first de-/multiplexed in a 2:N AWG. Then groups of densely spaced wavelengths are further split/combined by power splitters. This is a hybrid wavelength-routed/wavelength-selected ODN.

For dual parenting of the link between PCPs 6 and 5, the base configuration for feeder fibre resilience is shown in figure 6-2. Two PON LTs are connected to two feeder fibres in the OLT. Dual parenting can be similarly configured. In the RN (or BN), the two feeder fibres 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 an important aspect of WDM PON standardization.

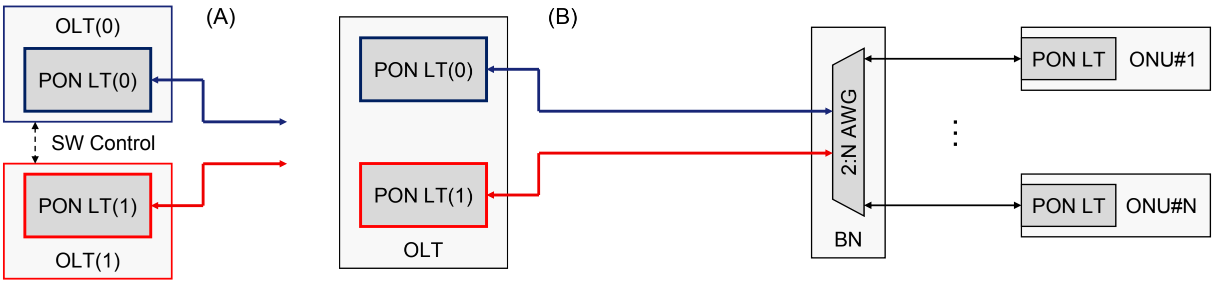


Figure 6-2: 2:N-AWG-based protection of feeder fibre

When switching from one feeder fibre 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 fanout 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 fibre port would remain dark if the ONTs retained their original working wavelengths. The second feeder fibre 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 WDM PON, seed light, which includes broadband light sources or multi-frequency “comb” sources, is switched onto the respective feeder fibre 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.

Resilience for WDM PON can also be optionally 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 6-3. It is based on adding/dropping (groups of) wavelengths in the respective RNs by means of group add/drop filters (G*n* in figure 6-3). RNs are resiliently connected to the OLT(s), protecting the feeder fibres. Several RNs can be passively traversed. For rings with a large number of remote nodes, either a subset of the remote nodes must be active nodes with lumped amplifiers, e.g., EDFAs, or a very high loss budget must be available. These active remote nodes may include the function of reconfigurable optical add/drop multiplexers (ROADMs) to support flexible dynamic wavelength assignment. In addition, the legacy G-PON/XG-PON could co-exist in this configuration through either transparently transmitted or wavelengths converted to the DWDM grid at the active remote 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).

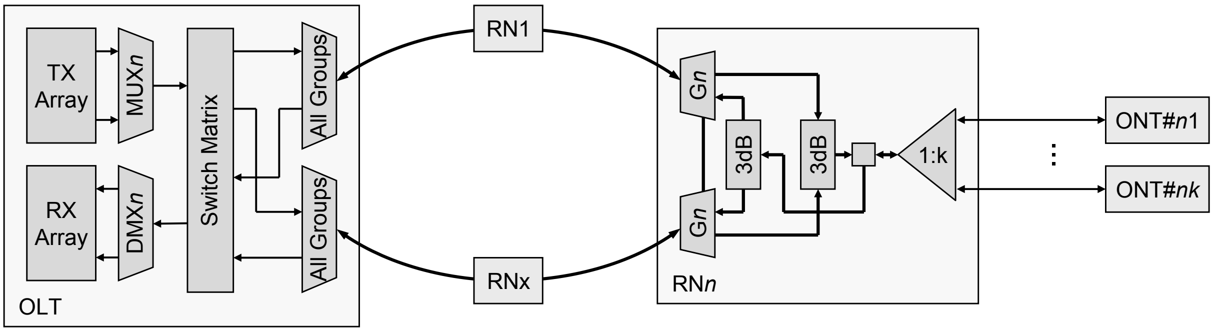


Figure 6-3: Ring protection

The ring protection shown in figure 6-3 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 protection shown in figure 6-3 can also be extended to chains of remote nodes that are connected to two OLTs (dual parenting) in an "open ring" structure. Between the OLTs, signalling or centralized management must be established.

Protection along the entire end-to-end PON network, including the link between PCPs 5 and 4 is also possible. In this case, a WS WDM PONs can support all resilience concepts described in G.984.1. An example, including two protection cases (entire PON segment, feeder fibre section only), is shown in figure 6-4. Here LT denotes line termination.

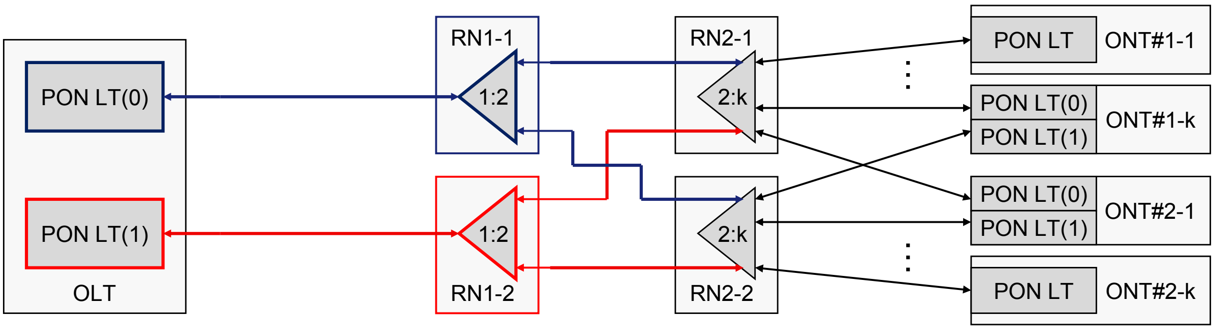


Figure 6-4: Protection for wavelength-selected WDM PON

An additional solution for feeder fibre protection is to use 2:1 power splitters and 1:N AWGs. This configuration is a derivative of the scheme shown in figure 4a/G.984.1, where the AWG replaces the x:N power splitter for WR WDM PON. The additional 2:1 power splitter used for resilience also adds insertion loss.

AWG-based remote nodes support an additional protection mode by adding a second 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.

6.2 Security

Security is getting more relevant in NGOA networks that potentially offer new levels of open access. The most important aspects cover security against the following issues:

- Malicious users. This includes security against hacking (unauthorized access) as well as against intentional attacks which potentially affect the whole PON or access system. The latter includes jamming of the respective access system, e.g., by so-called crosstalk attacks.
- Rogue ONTs. This covers malfunctioning ONTs, and consequently the attempt to limit their effects as much as possible.

Some of the system concepts need to employ encryption and authentication to protect against unauthorized access and eavesdropping. This is true for the NGOA solution where a user potentially could receive other users' traffic. This is not an issue for system concepts where the medium is dedicated to one user, as in for example point-to-point AON. In any NGOA solution, security against unauthorized access and eavesdropping will (have to) be provided by encryption. This is the consensus approach also in (pre-) standardization bodies like FSAN.

A standardized encryption system is the advanced encryption standard (AES) which was developed in 2000 by the National Institute of Standards and Technology (NIST) [8]. The algorithm was developed by Joan Daemen and Vincent Rijmen, and is also known as the Rijndael-Algorithm. It was investigated cryto-analytically in detail and is commonly regarded as relatively safe.

AES uses a block length of 128 bits, the key length is 128, 192 or 256 bits. Therefore, three variants exist, AES-128, AES-192 and AES-256. Proprietary variants can have longer key lengths (e.g., 1024, 2048). The algorithm can be implemented in transport systems (e.g., WDM transponders, access systems), see Figure 6-5:.

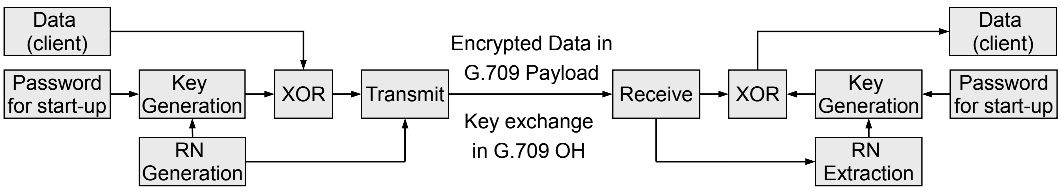


Figure 6-5: Implementation of AES (here: using G.709/OTN framing). RN: Random Number.

AES requires a key which must be exchanged securely, e.g. the Diffie-Hellman key exchange can be used, even over an unsecure channel [9]. Here, both ends transmit one message each to generate a secret key. The task of generating this key from the two messages is known as the Diffie-Hellman-Problem, and it is regarded as non-attackable. Even if an eavesdropper intercepts both messages, he or she is generally not able to generate the key. However, the Diffie-Hellman key exchange can be attacked by changing the two messages; in which case additional means like message authentication codes can be used.

AES (using Diffie-Hellman key exchange) should be complemented by secure access to the access equipment. Dedicated security root access for security settings can be provided. The respective passwords are generated onboard the access cards or systems and sent to the remote systems via secure (encrypted) in-band channels. In this way, unauthorized access is made highly difficult.

Regarding jamming (or crosstalk attacks) and rogue ONTs, a significant difference exists between AON, PONs with power splitters, and purely WDM-filtered PONs (WR-WDM-

PONs). The sole reason is the crosstalk suppression of the WDM filters used. In many WDM-PON approaches, these filters are (cyclic) AWGs. Typical AWGs have total crosstalk suppression (i.e., rejection of crosstalk from all other channels) of >20 dB. Hence, crosstalk attacks and effects of malfunctioning (rogue) ONTs are suppressed in a filtered ODN by at least 20 dB. This suppression may already be big enough to suppress any crosstalk effects (e.g., increased BER). In almost any case, it will help prevent damage to other channel transceivers. For hybrid WDM/TDM PON, the users after a power splitter will be affected by a rogue user, but since the number of users after a power splitter typically is less than for GPON/EPON/XGPON, there are less security concerns for hybrid WDM/TDM PON compared to other TDM technologies such as GPON/EPON/XG-PON etc.

6.3 UPGRADEABILITY

In rolling out a NGOA system network, alongside the techno-economic issues of deploying a cost-effective and financially-sustainable network architecture, there are the technical issues of ensuing compatibility with legacy infrastructure, and also leaving open the possibility of future technical upgrades; i.e. a "dead-end" technology solution should generally be avoided. Here we discuss some of the critical aspects associated with upgradeability, which tend to be common to all the OASE candidate systems discussed. We make the distinction between upgradeability and migration (which is considered in greater detail in WP3), by first acknowledging that a continuous spectrum between upgrading at one end, and migration at the other end, does indeed tend to exist. However, whereas a system upgrade will often be associated with the addition of extra cards, or changing the fan-out at a PCP etc., migration is associated with major changes which are more architectural in nature. In such a way, the following upgradeability criteria are not expected to act as differentiators between the various system variants. However, they are highly relevant to NGOA system design, and are currently being actively considered within key industry fora, such as FSAN. Specific technical upgradeability aspects we consider here can be thought of as broadly system considerations, e.g. legacy ODN compatibility; as well as more sub-systems/component factors, e.g. co-existence with OTDR (optical time-domain reflectometry) monitoring systems, and transceiver interfaces.

6.3.1 Legacy ODN compatibility

In terms of NGOA compatibility with existing ODN infrastructure, of great importance are structural aspects, concerning whether or not the ODN is shared and for shared structures the location of power splitters and/or other passive components. These aspects of ODN compatibility are handled in greater detail in WP3. Beyond compatibility aspects relating to pure structural differences of the ODN, an important aspect for WDM-based systems, which will be discussed more in detail here, is the spectrum allocation.

Spectrum allocation of WDM-PON systems is expected to work over either or both of the C- and L-bands, as defined in G.Sup39 clause 5.2. Upstream and downstream can be in separate spectral regions or share the same spectral band. In addition, the S-band may also be used for channel-count increase, or in order not to use the C-band in co-existence scenarios. WDM-PON can exploit the intrinsic cyclic nature of the AWG to extend the operational wavelength range without increasing RN loss, complexity and cost. Athermal cyclic 100 GHz AWGs are commercially available for the O, E, S, C, L, U and extended U bands. Narrower spacing of 50 GHz is technically possible and would be produced as soon as market demand appears. In the wavelength-selected (WS) approach, channel spacing can be determined by a tuneable optical filter in the ONT or via coherent detection with a tuneable local oscillator.

Cyclic AWGs are used to establish the wavelength in most wavelength-routed (WR) approaches. They are suitable for a wavelength plan with upstream and downstream transmission in separate bands. Acyclic AWGs are suitable for the case that the upstream and downstream wavelengths are nominally the same (WR-WDM-PON with wavelength reuse).

Schemes having nominally the same upstream and downstream wavelengths can achieve higher channel counts for the same spectrum, but need to budget for or mitigate impairments due to reflections and backscatter in the ODN. This can be done by considering a certain path penalty, or by implementing special modulation schemes like IRZ/RZ.

Figure 6-6 suggests the wavelength ranges for WDM-PON (gray lines) for four co-existence scenarios. The values in Figure 6-6 assume 15-nm guardbands between adjacent wavelength ranges for different systems, and the presence of legacy-PON ONT wavelength-blocking filters (WBFs) which need not be modified or replaced. Figure 6-6 also indicates the number of WDM channels available, assuming a cyclic AWG with 50 GHz spacing.

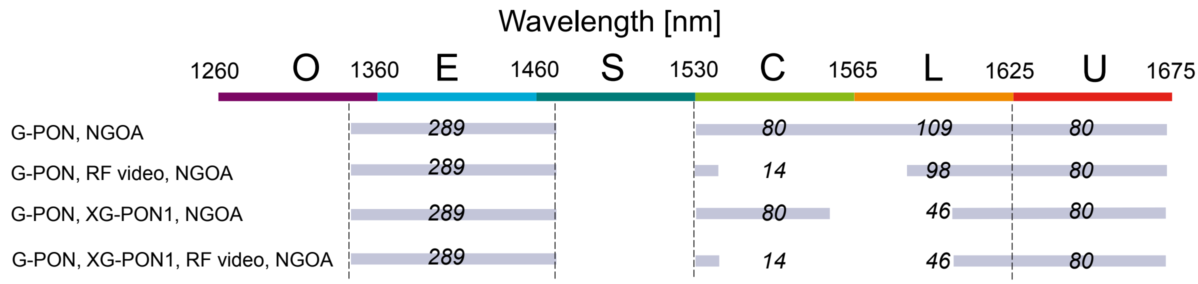


Figure 6-6: Wavelengths and max. 50-GHz channel count for WDM-PON

ITU-T G.694.1 defines the optical frequency grid for optical transport systems. These frequencies are used by WR-WDM-PON systems that rely on acyclic AWGs or other wavelength splitter technologies at the RN.

Table 6-1 defines a channel grid used to multiplex the upstream and downstream wavelengths in the WR case using a cyclic AWG. An AWG that is compliant with this grid can also provide many more channels in other cycles (i.e. orders of the free-spectral range) of the AWG that fall in the adjacent bands, possibly by using additional wavelength-band splitters.

Table 6-2 shows a bandwidth plan for cyclic AWGs.

Table 6-1: Frequency grid for 24/48/96 channel cyclic AWGs

		Downstream			Upstream		
Minimum channel spacing	GHz	194.7	97.35	48.675	200	100	50
Minimum central frequency	THz	187.034	187.034	187.034	192.0	192.0	192.0
	nm	1602.88	1602.88	1602.88	1561.42	1561.42	1561.42
Maximum central frequency	THz	190.733	190.831	190.879	195.8	195.9	195.95
	nm	1571.79	1570.98	1570.59	1531.12	1530.33	1529.94
Number of channels		24	48	96	24	48	96

Table 6-2: Nominal central frequencies of reference channel and channel spacing for various orders of AWG

Refractive order, *M*	Nominal center frequency (THz) of reference channel, $f_{0,M}$	Nominal wavelength of reference channel, (nm)	Nominal channel spacing, $\Delta f_{M,CS}$ (GHz) in order *M*, for nominal channel spacing in order 0	
			50 GHz	100 GHz
-2	183.962	1629.64	47.3500	94.7000
-1	188.981	1586.36	48.6750	97.3500
0	194.000	1545.32	50.0000	100.0000
1	199.019	1506.35	51.3250	102.6500
2	204.038	1469.30	52.6500	105.3000
3	209.057	1434.02	53.9750	107.9500
4	214.076	1400.40	55.3000	110.6000
5	219.095	1368.32	56.6250	113.2500
6	224.114	1337.68	57.9500	115.9000
7	229.133	1308.38	59.2750	118.5500
8	234.152	1280.33	60.6000	121.2000

Both plans rely on 100 GHz frequency spacing, with 50 GHz as an option. Some types of ONTs, e.g. those based on RSOAs, support flexible frequency spacing, which enables migration from less dense to denser wavelength spacing without needing to change the ONT.

Spectrum allocation of hybrid WDM/TDM PON systems is also expected to work over either or both of the C- and L-bands. For hybrid WDM/TDM PON since one channel is shared by 16 users, the need to exploit other bands (e.g. O, E, S) are minimal. Upstream and downstream can be in separate spectral regions or share the same spectral band. Hybrid WDM-PON can exploit the intrinsic cyclic nature of the AWG/WSS to extend the operational wavelength range without increasing RN loss. Since hybrid WDM/TDM PON supports large customer number, the power consumption and cost of the added components is minimal. Narrower spacing of 50 GHz is technically possible for both AWG and WSS and would be produced as soon as market demand appears. For wavelength switched hybrid WDM/TDM PON, the ONTs are assumed to be equipped with tuneable filters over a whole L band.

6.3.2 Migration (allow co-existing generations)

For different NGOA architectures there are different challenges for the migration from legacy architectures. Different migration scenarios for the different architectures will be discussed in greater detail in WP3. For AON there is no compatibility with the legacy GPON ODN. For hybrid WDM/TDM PON migration from already deployed GPON may be fairly easy with seamless migration steps. For WDM-PON and in particular to wave-length routed variants migration challenges will be discussed here with somewhat more detail.

This section describes two basic co-existence methods for WDM-PON: 1) power splitter ODN; and 2) wavelength-filtered ODN. It describes co-existence for one legacy PON generation only. Single-fibre WDM1r and WDM1rn filters according to ITU-T G.984.5 can be used for C-band WDM PON co-existence with G-PON. Modification of the WDM1r filter (denoted as WDMx hereinafter) at the CO is required for co-existence with XG-PON1 and for the case where the existing WDM1r is not compatible with the selected NG-PON2 bandplan.

Method 1 – Power splitter ODN

Figure 6-7 shows an example of a co-existence scenario with legacy PON and RF video, which is suitable for the WS architecture. The existing passive splitter in the field remains unchanged. Legacy ONTs already contain filters to reject NG-PON2 wavelengths, and WS ONTs reject legacy wavelengths.

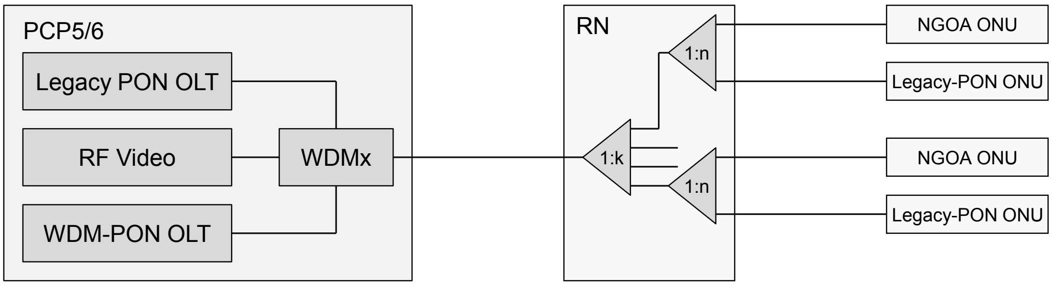


Figure 6-7: Method-1 co-existence: power splitter ODN

Method 2 – (Partially) Wavelength-Filtered ODN

This method is supported by both WR and WS architectures. As illustrated in Figure 6-8, this method can add a WDM filter to the legacy power-split RN in order to separate NG-PON2 from legacy signals. This avoids the insertion loss of the power splitter in the WDM PON path, but at the cost of an additional loss penalty in the legacy ODN. Alternatively, a power splitter can also be used. In addition, one or multiple ports of the AWG may form sub-branches to support WS type ONTs with subsequent power splitters. This is also an example of co-existence between WR- and WS-WDM-PONs.

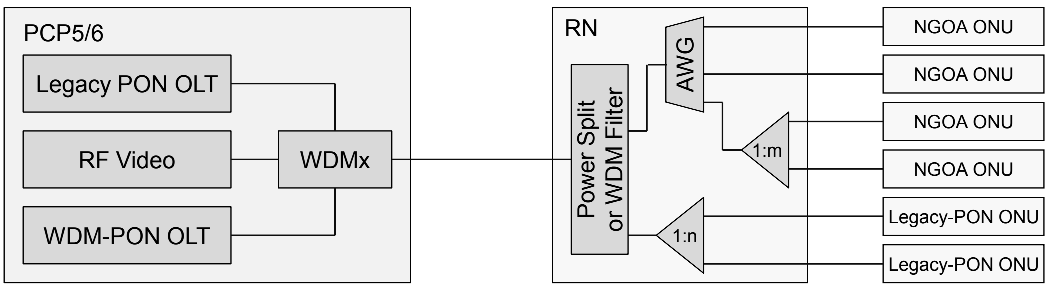


Figure 6-8: Method-2 co-existence: (partially) wavelength filtered ODN

Another important aspect that needs to be considered is the compatibility with OTDR. In the case of WR systems, it is possible to use other FSR orders of the AWG in the OTDR band (1625-75 nm). Since the OTDR band is quite wide, it would be possible to filter one part of this band to the legacy part of the ODN, and another part to NGOA systems. In the case of WS systems operating in a power splitter ODN, traditional OTDR can be supported, whilst for WR-WDM-PON, tuneable OTDRs must be used. We note that such tuneable OTDRs are already commercially available. Although tuneable OTDRs may add a certain cost penalty, this is expected to be negligible once the respective OTDRs are produced in numbers. On the other hand, tuneable OTDRs within a WR infrastructure will also allow unambiguous per-ONT monitoring and thus can help in saving a useful amount of OpEx.

In the case of migrating WDM-PON into co-existence scenarios, several steps need to be taken:

1. The WDM1r filter at the CO may need to be modified or replaced.
2. Depending on architecture, filters at existing RNs may need to be modified or added, and AWGs may also need to be installed.
3. The WDM-PON band plan must be chosen to be compatible with the WBFs that already exist in the legacy ONTs. Otherwise, legacy-ONT WBFs may have to be modified.
4. For WS-WDM-PON, all signals are available at all drop locations. Therefore, there is no specific step required to modify the ODN.
5. For WR-WDM-PON, an AWG (or an alternative WDM filter) is needed in the RN to assign the proper wavelength to each ONT.
6. Service outage times depend on installation or modification of filters, and potential rearrangement of the distribution fibres.

It can be seen that the steps 1, 2, 3 (if the band plan is chosen respectively), and 5 all lead to actions that will tend to affect service availability. In addition, it must also be noted that customer-by-customer migration may also lead to repeated truck rolls.

6.3.3 Interfaces (flexible & agnostic interfaces)

Transceiver interfaces should be analyzed separately for ONTs and the OLT when it comes to flexibility considerations. The main rational is that in most WDM-PON/hybrid WDM/TDM PON approaches, OLT interfaces are integrated within multi-channel transceivers for cost, power-consumption, and form-factor reasons. This makes OLT adaptation to client-specific requirements potentially more difficult as compared with per-ONT adaptation. In this latter case, change of interface specifications leads to simple adaptation on a per-ONT basis. Therefore, it is to be expected that differentiated ONT variants will become available, just from cost reasons alone. For multi-channel OLT transceiver arrays, the trade-off between the added costs for having differentiated variants versus the added cost for a single one-fits-all model must be considered.

From today's perspective, it is difficult to evaluate the costs associated with having different variants of the OLT because integrated multi-channel transceivers are only now being developed. No differentiated-cost data for a real-world (PON or access-related) multi-channel transceivers is thus available. The data that are available so far from components vendors, such as Oclaro, suggest that the two main variant options for multi-channel OLT transceiver PICs (photonic integrated circuits) are most likely to consist of the following:

1. An array (e.g., with 32…48 bi-directional channels) that is kept as transparent as possible in the (electro-) optical domain. This may include an inherent readiness for bit-rates up to at least ~11 Gbit/s. It may also allow a certain freedom with regard to the modulation scheme. For cost reasons, generalised complex I+Q modulation capability is regarded unlikely; but variants such as OOK, ODB or DBPSK may be implemented. This will almost certainly require per-channel external modulation, or techniques like CML (chirp-managed lasers, a special modulation technique which leads to ODB-like modulation). External modulators can be implemented cost-effectively as EAM (electro-absorption modulators). These modulators cover modulation schemes like ODB that has been proven in the EU FP7 project C-3PO. Any bit-rate or protocol adaptation is performed in the electronic domain, and may include pre-distortion, equalization or similar tasks. In general, this requires a certain degree of openness with regard to the supported Baud rates.
2. Choice between two PICs, where the first one follows a strict design-to-cost approach with restrictions on the per-channel bit rate and performance specifications like power

budget, jitter etc. This PIC will most likely be designed to support 1.25 Gbit/s per channel, i.e., support of GbE PHYs. The restrictions may likewise hold for the electronics that can be optimised for both cost and power-consumption while supporting multiple GbE services. A second PIC variant may then support business and other premium customers with higher bit rates in the range of 10 Gbit/s.

At the time being, there is no clear industry consensus regarding these two options.

6.3.4 Future proofness (future traffic patterns)

In general, future traffic growth in terms of per-client bandwidth demand and traffic patterns is difficult to predict. From the past 100 years we know that offered bandwidth has always been consumed. Regarding bandwidth, the question remains if high sustainable bandwidth or ultra-high bursty (but lower sustainable mean) bandwidth will be required. In addition, at the time being, traffic patterns (e.g., locality of traffic) are also difficult to predict.

From past network development (which refers from local to core networks), we also know that the simpler "big-pipe" Ethernet (and later WDM) approach was preferred over the more sophisticated ATM approach.

From these developments, one may conclude that any future-proof access solution should provide a certain transparent "big-pipe" transport capability. In addition, it is hard at best to see how shared approaches like TDMA or OFDMA shall scale to accumulated bit rates of well beyond 100 Gbit/s, sustained per-client bit rates of >1 Gbit/s, or bursty per-client bit rates of ≥10 Gbit/s. For the latter, it must be considered that the end-to-end transmission equipment, including client-side interfaces, must support these bit rates. From today's perspective, this may lead to severe problems with regard to both, cost and power consumption.

From this, one can further conclude that a massive parallelization in the WDM domain will be required in any case. As an alternative, point-to-point solutions may also be considered.

6.4 MOBILE BACKHAUL AND FRONTHAUL

Regarding future support of mobile networks, one has to differentiate between mobile backhaul and mobile fronthaul.

Mobile backhaul refers to the connection of the mobile base stations (BS, in 2G and 3G networks) or eNodeBs in LTE (LTE-A). Today, a mixture of copper, fibre, and point-to-point radio is used for mobile backhaul, with fibre-based backhaul clearly increasing, see Figure 6-9. It is commonly expected that backhaul bit rates will quickly approach 1 Gbit/s at least in certain urban areas.

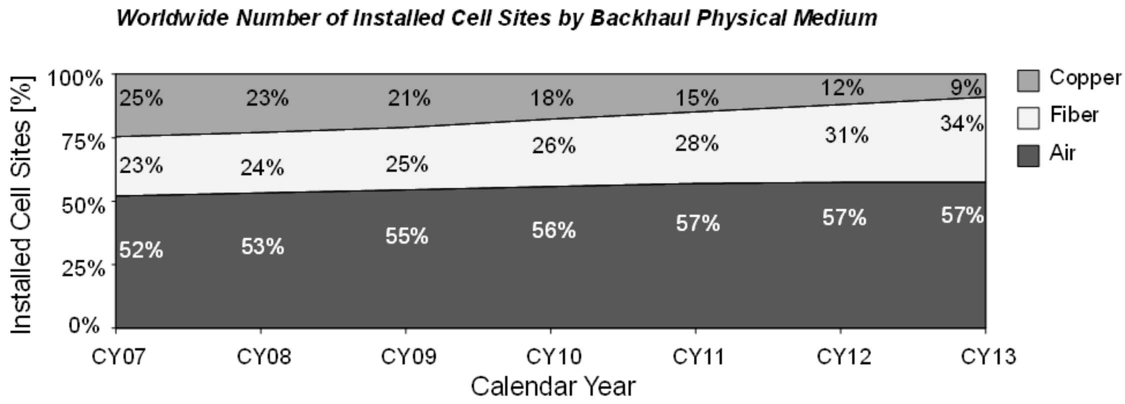


Figure 6-9: Mobile backhaul (source: Infonetics Microwave Equipment 2009)

Mobile fronthaul refers to (near-) future LTE scenarios where the electronics (the base band units, BBUs) of several eNodeBs are concentrated in a common site (in a so-called BBU hotel). The remote antenna sites (remote RF units, RRUs) are connected to the BBUs via ultra-fast fibre fronthaul. These links will run digital I/Q samples of the radio signals which then only requires relatively simple electronics at the RRUs. This can be done using protocols like CPRI. Today, CPRI already covers bit rates up to 9.83 Gbit/s, and it is expected that this bit rate will massively increase in the future, see Figure 6-10.

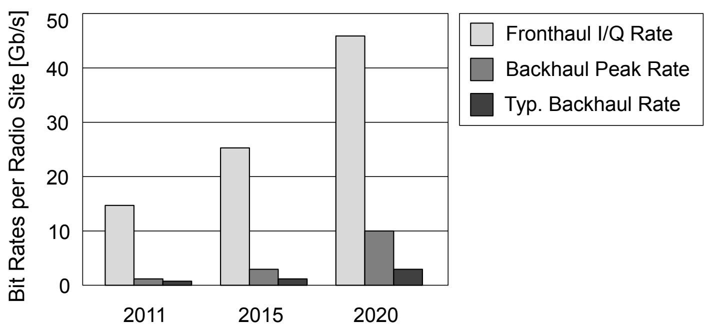


Figure 6-10: Mobile fronthaul development (source: NSN/FSAN 2011)

According to NSN/FSAN, fronthaul bit rates may exceed 40 Gbit/s by 2020, at least for certain urban areas. Obviously, such bit rates can only be accepted with high-speed point-to-point and WDM-PON links. They are far beyond the scope of PONs with per-wavelength multiple-access schemes like TDMA, OFDMA etc. Further, it has to be considered that LTE-A will require severe delay and delay variation specifications. Again, these can only be supported by point-to-point and WDM-PON links without TDMA or similar schemes.

The requirements for the Frame Delay (FD), Frame Delay Variation (FDV) and Frame Loss Ratio (FLR) according to MEF 22, Ethernet Based Mobile Backhaul, are listed in the following table.

High (H)	Medium (M)	Low (L)
FD = 20ms FDV = 4ms FLR = 10^{-5} Availability = 99.999%	FD = 50ms FDV = 10ms FLR = 10^{-4} Availability = 99.99%	FD = 100ms FDV = 10ms FLR = 10^{-4} Availability = 99.99%

The requirements with regard to bit rates and FD, FDV indicate that point-to-point or WDM-PON techniques must be used if convergence between wireline access and wireless back- and fronthaul is the goal. In addition, the development towards micro-, pico- and femto-cells (which is required to enable high wireless access in densely populated areas) makes it more unlikely that a point-to-point fibre infrastructure can be realized in all cases. Then, the only solution with a partly shared fibre infrastructure is WDM-PON. An example of such a converged solution is shown in Figure 6-11.

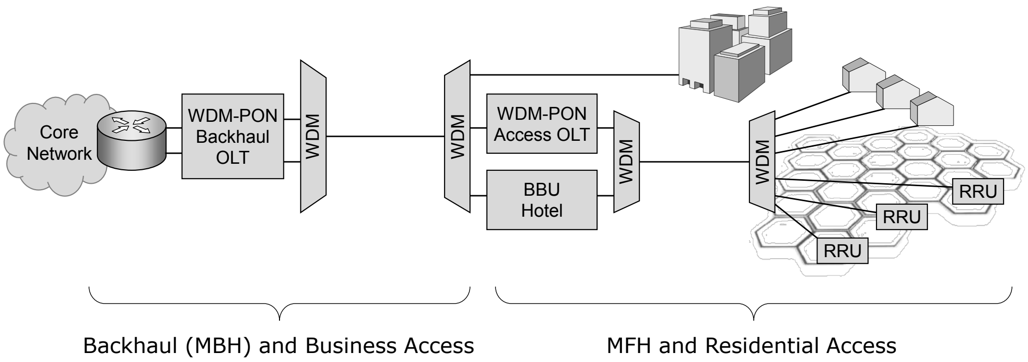


Figure 6-11: Combined mobile backhaul, mobile fronthaul, and residential and business access

With regard to the general applicability of WDM-PON for converged wireline access and wireless front- and backhaul, it has to be noted that very high bit rates will be required in fronthaul beyond 2020. These bit rates (which can exceed 40 Gbit/s per RRU) require a certain optical bandwidth. In the case of the (coherent) UDWDM-PON, this will require a massive increase of the channel grid which is to be used for fronthaul. Since this prohibits the shared use of OLT transceivers, much of the cost-effectiveness of this solution which can be realized for residential access will not be applicable for wireless fronthaul.

7. Summary

In this chapter, we present a summary of the key outcomes for the four architecture classes and their system variants discussed in the previous chapter, presenting their important performance characteristics in quantitative terms of: reach; client-count; guaranteed & peak data-rates; and power consumption. These represent the quantitative critical performance parameters (i.e. technical requirements) as identified and discussed in Chapters 3 and 4, respectively. Together, the results presented here allow us to perform a quantitative assessment of the relative merits of each architecture class and its variants, with the results being fed into WP5, to provide the raw techno-economic data for use in the WP5 analysis.

A summary of the performance analysis for the different NGOA concepts is shown in Table 7-1 with respect to reach, client-count, guaranteed and peak data-rate per client. Power consumption and footprint parameters are shown in

Table 7-2 and Table 7-3, respectively.

Table 7-1: Performance parameters of selected NGOA system concepts

System concept	Reach	Client Count (Feeder)	Guaranteed Data rate	Peak data rate down-/uplink
G-PON	35/44 km (1:4; B+/C+) 27/36 km (1:8; B+/C+) 11/20 km (1:32; B+/C+) 60 km (RE)	4 (1:4) 8 (1:8) 32 (1:32)	625 / 312 Mbit/s (1:4) 312 / 156 Mbit/s (1:8) 78/39 Mbit/s (1:32)	2.5/1.25 Gbit/s
XG-PON 1	26 km (1:16; Nom2b) 35 km (1 :16 ; Ext2) 18 km (1:32; Nom2b) 27 km (1 :32) ; Ext2) 60 km (RE)	16 (1:16) 32 (1:32)	625 / 156 Mbit/s (1:4) 312 / 78 Mbit/s (1:8)	10/2.5 Gbit/s
Ethernet p-t-p	10 km	1	300 and 500 Mbit/s* sym.	1 Gbit/s sym.
DWDM-PON (tuneable lasers)	60 km (80 λ; APD@ONT & pre-amp@OLT) 52 km (160 λ; APD@ONT & pre-amp@OLT) 30 km (320 λ; APD@ONT & pre-amp@OLT) 31 km (80 λ; PIN@ONT) 23 km (160 λ; PIN@ONT)	80, 160, 320 (APD@ONT & pre-amp@OLT) 80, 160 (PIN@ONT)	300 and 500 Mbit/s* sym.	1 Gbit/s sym.
DWDM-PON (seeded reflective transmitters; multi-frequency-laser@OLT)	57 km (80 λ; APD@ONT) 28 km (80 λ; PIN@ONT)	80	300 and 500 Mbit/s* sym.	1 Gbit/s sym.
DWDM-PON (seeded reflective transmitters; wavelength-reuse@OLT)	34 km (80 λ; APD@ONT) 28 km (160 λ; APD@ONT) 16 km (320 λ; APD@ONT)	80 160 320	300 and 500 Mbit/s* sym.	1 Gbit/s sym.
DWDM-PON (seeded reflective transmitters; wavelength-reuse@OLT; 100 GHz spacing)	34 km (96 λ; APD@ONT)	96	300 and 500 Mbit/s* sym.	1 Gbit/s sym.
Passive hybrid WDM/TDM-PON	27 km (1:16 / 40 λ; APD@ONT) 16 km (1:16 / 80 λ; APD@ONT) 30 km (1:16 / 80 λ; PIN@ONT; RE) 60 km (1:16 / 80 λ; APD@ONT; RE) 17 km (1:32 / 40 λ; APD@ONT) 20 km (1:32 / 80 λ; PIN@ONT; RE) 50 km (1:32 / 80 λ; APD@ONT; RE)	640 (1:16 / 40 λ) 1,280 (1:16 / 80 λ) 1,280 (1:32 / 40 λ) 2,560 (1:32 / 80 λ)	625/312 Mbit/s (1:16) 312/156 Mbit/s (1:32)	10/5 Gbit/s
Fully flexible passive hybrid WDM/TDM-PON	24 km (1:16 / 1:10 AWG / 1:4 WSS) 24 km (1:16 / 1:10 AWG / 1:8 WSS)	160	625/312 Mbit/s	10/5 Gbit/s

Semi-passive hybrid WDM/TDM-PON	83 km (1:32 / 1:10 AWG / 1:4 WSS) 91 km (1:32 / 1:5 AWG / 1:4 WSS)	1280 (1:32 / 1:10 AWG / 1:4 WSS) 640 (1:32 / 1:5 AWG / 1:4 WSS)	625/312 Mbit/s	10/5 Gbit/s
UDWDM-PON	59 km (1:8 / 40 λ) 48 km (1:8 / 80 λ) 27 km (1:32 / 20 λ) 82 km (1:32 / 20 λ) with Reach Extender	320 (1:8 / 40 λ) 640 (1:8 / 80 λ) 640 (1:32 / 20 λ)	300 and 500 Mbit/s* sym.	1 Gbit/s sym.
Active Remote Node and WDM-PON backhaul (40 λ@10 Gbit/s; dual fibre)	40 km	320 (G-PON 1:4) (XG-PON1 1:16) 640 (G-PON 1:8) (XG-PON1 1:32) 660 (Eth. p-t-p, 300 Mbit/s) 400 (Eth. p-t-p, 500 Mbit/s) 800 (DWDM-PON, 250 Mbit/s) 400 (DWDM-PON, 500 Mbit/s	625 / 312 Mbit/s (G-PON 1:4) (XG-PON1 1:16) 312 / 156 Mbit/s (G-PON 1:8) (XG-PON1 1:32) 300 and 500 Mbit/s sym. (Eth. p-t-p) 250 and 500 Mbit/s sym. (DWDM-PON)	2.5/1.25 Gbit/s (G-PON) 10/2.5 Gbit/s (XG-PON1) 1 Gbit/s sym. (Eth. p-t-p) 1 Gbit/s sym. (DWDM-PON)

Table 7-2: Power consumption parameters of selected NGOA system concepts

System concept	Power consumption per connected customer (100% system utilization)			OLT power consumption per 11U shelf	OLT power consumption per 44U rack
	ONT	Remote Node	OLT (incl. Shelf, L2 switch)		
G-PON (2020) (2020) (2011)	4 W 4 W 5 W	1.6 W (1:4 with RE) 0.8 W (1:8 with RE) 0.3 W (1:32 with RE)	2 W (1:4) 1 W (1:8) 0.5 W (1:32)	0.58 kW 0.58 kW 1.15 kW	2.3 kW 2.3 kW 4.6 kW
XG-PON 1 (2020) (2020) (2011)	5 W 5 W 6.5 W	0.6 W (1:16 with RE) 0.3 W (1:32 with RE) 0.4 W (1:32 with RE)	1.4 W (1:16) 0.7 W (1:32) 1.1 W (1:32)	1.2 kW 1.2 kW 1.86 kW	4.8 kW 4.8 kW 7.43 kW
Ethernet p-t-p	3.5 W		1.9 W (300 Mbit/s) 2.2 W (500 Mbit/s)	0.55 kW (300 Mbit/s) 0.63 kW (500 Mbit/s)	2.2 kW (300 Mbit/s) 2.53 kW (500 Mbit/s)
DWDM-PON (tuneable lasers)	4.7 W (APD) 4.2 W (PIN)		2 W (with pre-amp@OLT; 300 Mbit/s) 2.2 W (with pre-amp@OLT; 500 Mbit/s) 1.7 W (without pre-amp@OLT; 300 Mbit/s) 1.9 W (without pre-amp@OLT; 500 Mbit/s)	0.96 kW (with pre-amp@OLT; 300 Mbit/s) 1.06 kW (with pre-amp@OLT; 500 Mbit/s) 1.22 kW (without pre-amp@OLT; 300 Mbit/s) 1.37 kW (without pre-amp@OLT; 500 Mbit/s)	3.84 kW (with pre-amp@OLT; 300 Mbit/s) 4.22 kW (with pre-amp@OLT; 500 Mbit/s) 4.9 kW (without pre-amp@OLT; 300 Mbit/s) 5.47 kW (without pre-amp@OLT; 500 Mbit/s)
DWDM-PON (seeded reflective transmitters; multi-frequency-laser@OLT)	4.7 W (APD) 4.2 W (PIN)		1.9 W (300 Mbit/s) 2.2 W (500 Mbit/s)	0.68 kW (300 Mbit/s) 0.79 kW (500 Mbit/s)	2.74 kW (300 Mbit/s) 3.17 kW (500 Mbit/s)

DWDM-PON (seeded reflective transmitters; wavelength-reuse@OLT)	4.7 W (APD)		1.8 W (300 Mbit/s; 80 λ) 2 W (500 Mbit/s; 80 λ) 1.7 W (300 Mbit/s; 160 λ) 1.9 W (500 Mbit/s; 160 λ) 1.7 W (300 Mbit/s; 320 λ) 2.0 W (500 Mbit/s; 320 λ)	0.86 kW (300 Mbit/s; 80 λ) 0.96 kW (500 Mbit/s; 80 λ) 0.98 kW (300 Mbit/s; 160 λ) 1.1 kW (500 Mbit/s; 160 λ) 1.1 kW (300 Mbit/s; 320 λ) 1.28 kW (500 Mbit/s; 320 λ)	3.46 kW (300 Mbit/s; 80 λ) 3.84 kW (500 Mbit/s; 80 λ) 3.92 kW (300 Mbit/s; 160 λ) 4.38 kW (500 Mbit/s; 160 λ) 4.35 kW (300 Mbit/s; 320 λ) 5.12 kW (500 Mbit/s; 320 λ)
DWDM-PON (seeded reflective transmitters; wavelength-reuse@OLT; 100 GHz spacing)	4.7 W (APD)		1.9 W (300 Mbit/s) 2.1 W (500 Mbit/s)	1.1 kW (300 Mbit/s) 1.21 kW (500 Mbit/s)	4.38 kW (300 Mbit/s) 4.84 kW (500 Mbit/s)
Passive hybrid WDM/TDM-PON	5.5 W	0.1 W (1:16 / 80 λ with RE) 0.05 W (1:32 / 80 λ with RE)	1.4 W (1:16 / 40 λ) 1.4 W (1:16 / 80 λ) 0.7 W (1:32 / 40 λ) 0.6 W (1:32 / 80 λ)	1.34 kW (1:16 / 40 λ) 1.33 kW (1:16 / 80 λ) 1.34 kW (1:32 / 40 λ) 1.33 kW (1:32 / 80 λ)	5.38 kW (1:16 / 40 λ) 5.32 kW (1:16 / 80 λ) 5.38 kW (1:32 / 40 λ) 5.32 kW (1:32 / 80 λ)
Fully flexible passive hybrid WDM/TDM-PON	5.5W		1.75 W (1:16 / 1:10 AWG / 1:4 WSS) 1.77 W (1:16 / 1:10 AWG / 1:8 WSS)	0.8 kW (1:16 / 1:10 AWG / 1:4 WSS) 0.75 W (1:16 / 1:10 AWG / 1:8 WSS)	3.2 kW (1:16 / 1:10 AWG / 1:4 WSS) 3.0 W (1:16 / 1:10 AWG / 1:8 WSS)
Semi-passive hybrid WDM/TDM-PON	5.5W	0.027 W/client	1.39 W (1:32 / 1:10 AWG / 1:4 WSS) 1.40 W (1:32 / 1:5 AWG / 1:4 WSS)	1.98 kW (1:32 / 1:10 AWG / 1:4 WSS) 1.79 kW (1:32 / 1:5 AWG / 1:4 WSS)	7.92 kW (1:32 / 1:10 AWG / 1:4 WSS) 7.17 kW (1:32 / 1:5 AWG / 1:4 WSS)
UDWDM-PON	5.6 W	0.2 W (1:32 / 20 λ with Reach Extender)	2.4 W (1:8 / 40 λ; 300 Mbit/s) 2.8 W (1:8 / 40 λ; 500 Mbit/s) 2.3 W (1:8 / 80 λ; 300 Mbit/s) 2.7 W (1:8 / 80 λ; 500 Mbit/s) 2.3 W (1:32 / 20 λ; 300 Mbit/s) 2.7 W (1:32 / 20 λ; 500 Mbit/s)	0.58 kW (1:8 / 40 λ; 300 Mbit/s) 0.67 kW (1:8 / 40 λ; 500 Mbit/s) 0.59 kW (1:8 / 80 λ; 300 Mbit/s) 0.69 kW (1:8 / 80 λ; 500 Mbit/s) 0.59 kW (1:32 /20 λ; 300 Mbit/s) 0.69 kW (1:32 /20 λ; 500 Mbit/s)	2.3 kW (1:8 / 40 λ; 300 Mbit/s) 2.69 kW (1:8 / 40 λ; 500 Mbit/s) 2.35 kW (1:8 / 80 λ; 300 Mbit/s) 2.76 kW (1:8 / 80 λ; 500 Mbit/s) 2.35 kW (1:32 / 20 λ; 300 Mbit/s) 2.76 kW (1:32 / 20 λ; 500 Mbit/s)
Active Remote Node and WDM-PON backhaul (40 λ@10 Gbit/s; dual fibre)	4 W (G-PON) 5 W (XG-PON1) 3.5 W (Eth. p-t-p) 4.2 W (DWDM-PON)	2 W (G-PON 1:4) 1 W (G-PON 1:8) 0.9 W (XG-PON1 1:16) 0.5 W (XG-PON1 1:32) 2.2 W (Eth. p-t-p, 300 Mbit/s) 2.6 W (Eth. p-t-p, 500 Mbit/s) 1.9 W (DWDM-PON, 250 Mbit/s) 2.0 W (DWDM-PON, 500 Mbit/s)	1 W (G-PON 1:4) (XG-PON1 1:16) 0.5 W (G-PON 1:8) (XG-PON1 1:32) 0.5 W (Eth. p-t-p, 300 Mbit/s) 0.8 W (Eth. p-t-p, 500 Mbit/s) 0.4 W (DWDM-PON, 250 Mbit/s) 0.8 W (DWDM-PON, 500 Mbit/s)	1.2 kW (G-PON 1:4) (XG-PON1 1:16) 1.2 kW (G-PON 1:8) (XG-PON1 1:32) 1.2 kW (Eth. p-t-p, 300 Mbit/s) 1.2 kW (Eth. p-t-p, 500 Mbit/s) 1.2 kW (DWDM-PON, 250 Mbit/s) 1.2 kW (DWDM-PON, 500 Mbit/s)	3.6 kW (G-PON 1:4) (XG-PON1 1:16) 3.6 kW (G-PON 1:8) (XG-PON1 1:32) 3.6 kW (Eth. p-t-p, 300 Mbit/s) 3.6 kW (Eth. p-t-p, 500 Mbit/s) 3.6 kW (DWDM-PON, 250 Mbit/s) 3.6 kW (DWDM-PON, 500 Mbit/s)

Table 7-3: Footprint parameters of selected NGOA system concepts

System concept	Number of connected customers per 11U shelf (100% system utilization)	Number of connected customers per 44U rack (100% system utilization)	Active remote node: Number of connected customers per outdoor cabinet
G-PON	288 (1:4) 576 (1:8) 2,304 (1:32)	1,152 (1:4) 2,304 (1:8) 9,216 (1:32)	480 (1:4) (Reach Extender) 960 (1:8) (Reach Extender) 3,840 (1:32) (Reach Extender)

XG-PON 1	864 (1:16) 1,728 (1:32)	3,456 (1:16) 6,912 (1:32)	1,920 (1:16) (Reach Extender) 3,840 (1:32) (Reach Extender)
Ethernet p-t-p	288	1,152	
DWDM-PON (tuneable lasers)	480 (with pre-amp@OLT) 720 (without pre-amp@OLT)	1,920 (with pre-amp@OLT) 2,880 (without pre-amp@OLT)	
DWDM-PON (seeded reflective transmitters; multi-frequency-laser@OLT)	360	1,440	
DWDM-PON (seeded reflective transmitters; wavelength-reuse@OLT)	480 (80 λ) 576 (160 λ) 640 (320 λ)	1,920 (80 λ) 2,304 (160 λ) 2,560 (320 λ)	
DWDM-PON (seeded reflective transmitters; wavelength-reuse@OLT; 100 GHz spacing)	576	2,304	
Passive hybrid WDM/TDM-PON	960 (1:16 / 40 λ) 1,024 (1:16 / 80 λ) 1,920 (1:32 / 40 λ) 2,048 (1:32 / 80 λ)	3,840 (1:16 / 40 λ) 4,096 (1:16 / 80 λ) 7,680 (1:32 / 40 λ) 8,192 (1:32 / 80 λ)	10,240 (1:16 / 80 λ) (Reach Extender) 20,480 (1:32 / 80 λ) (Reach Extender)
Fully flexible passive hybrid WDM/TDM-PON	457 (1:16 / 1:10 AWG / 1:4 WSS) 426 (1:16 / 1:10 AWG / 1:8 WSS)	1,829 (1:16 / 1:10 AWG / 1:4 WSS) 1,704 (1:16 / 1:10 AWG / 1:8 WSS)	
Semi-passive hybrid WDM/TDM-PON	1,422 (1:32 / 1:10 AWG / 1:4 WSS) 1,280 (1:32 / 1:5 AWG / 1:4 WSS)	5,688 (1:32 / 1:10 AWG / 1:4 WSS) 5,120 (1:32 / 1:5 AWG / 1:4 WSS)	
UDWDM-PON	240 (1:8 / 40 λ) 256 (1:8 / 80 λ) 256 (1:32 / 20 λ)	960 (1:8 / 40 λ) 1,024 (1:8 / 80 λ) 1,024 (1:32 / 20 λ)	5,120 (1:32 / 20 λ) (Reach Extender)
Active Remote Node and WDM-PON backhaul (40 λ@10 Gbit/s; dual fibre)	1,152 (G-PON 1:4) (XG-PON1 1:16) 2,304 (G-PON 1:8) (XG-PON1 1:32) 2,376 (Eth. p-t-p, 300 Mbit/s) 1,440 (Eth. p-t-p, 500 Mbit/s) 2,880 (DWDM-PON, 250 Mbit/s)	3,456 (G-PON 1:4) (XG-PON1 1:16) 6,912 (G-PON 1:8) (XG-PON1 1:32) 7,128 (Eth. p-t-p, 300 Mbit/s) 4,320 (Eth. p-t-p, 500 Mbit/s) 8,640 (DWDM-PON, 250 Mbit/s)	384 (G-PON 1:4) 768 (G-PON 1:8) 1,536 (XG-PON1 1:16) 3,072 (XG-PON1 1:32) 396 (Eth. p-t-p, 300 Mbit/s) 240 (Eth. p-t-p, 500 Mbit/s) 640 (DWDM-PON)

When looking at the raw results summarized here, we can see that the pure WR-DWDM-PON variants can achieve a fibre reach of 60 km with a fully passive ODN for client counts of up to 80 per OLT port. As the number of clients is increased beyond 80, the fibre reach is reduced due to the insertion of additional band splitters or interleavers. For coherent UDWDM-PON, it is assumed that wavelength filtering at 200 GHz is performed first, followed by a variable power split. Accumulated insertion loss then scales via this power split. Alternatively, AWGs with variable port count (and insertion loss) may be used, followed by 1:8 power splitters. This approach has better accumulated insertion loss, but less flexibility with regard to the power-split ratio. The coherent UDWDM-PON can achieve a reach close to 60 km even for client count as high as 320. For the passive hybrid WDM/TDM-PON variants, the reach is limited to less than 27 km at high client count without REs, but this can be increased to 60 km with REs comprising booster and pre-amplifiers, FEC and very high transceiver power budget have been considered. Semi-passive hybrid WDM/TDM-PON, on the other hand, can combine a long reach of 80 to 90 km (the longest of all considered system concepts) with a high client count. As this system concept, using an active remote node in PCP5, is still in proposal phase, it will be further investigated during the course of the OASE project (as part of Task T4.4, which will be reported in deliverable D4.4). Finally, if active hybrid concepts based on WDM-PON backhaul are treated as integrated systems, both long reach (40 km) and large client count can be achieved. However, these performance advantages come with the compromise of having to adopt active remote sites. This trade-off needs to be addressed by complete TCO calculations, to be performed towards the conclusion of the OASE project.

Among the considered configurations, differences can be identified for the reach-vs.-client-count performance, and also with respect to the capability to concentrate the termination of a large number of clients in a single rack in the CAN.

Increased reach can be achieved by active reach extenders. Since all WDM-PON variants discussed herein are based on dense or ultra-dense spacing, optical amplifiers are the most (cost-) effective approach. For the coherent UDWDM-PON, C-band erbium-doped fibre amplifiers (EDFAs) can be used together with separation of the two directions of transmission. For the directly-detected DWDM-PON variants, C-band plus L-band EDFA combinations can be used. If the S-band is used for client-count increase, thulium-doped fibre amplifiers (TDFAs), Raman amplifiers or semiconductor optical amplifiers (SOAs) can be used additionally. The optical amplifiers require local electrical powering, but management and supervision can be performed via the feeder fibre.

The analysis of the different NGOA systems in

Table 7-2 shows that power consumption is not a major differentiator. Power consumption at the ONT side is higher for UDWDM-PON and hybrid WDM/TDM-PON due to the coherent TRX and 10 Gbit/s burst-mode TRX, respectively. At the OLT side, power consumption per client is slightly lower for hybrid WDM/TDM-PON due to wavelengths-sharing among multiple clients. Pure Ethernet PtP has lowest per-line power consumption, but as discussed in the previous chapter, without a suitable backhaul infrastructure it cannot achieve the reach requirements. Hence, network-wide power consumption will tend to increase over the other solutions due to the higher number of active sites with aggregation switches required.

The following graphs, Figure 7-1 and Figure 7-2, show the relative cost-per-line for the various system concepts presented here, for 300 Mbit/s and 500 Mbit/s minimum guaranteed data-rates per customer. We note that the classes of system concept labelled “Hybrid TDMA/WDM PON” in the following figures are equivalent to the passive hybrid WDM/TDM-PON class of system discussed in this deliverable.

Although, as might be expected the Ethernet PtP solution shows the greatest increase in cost as a function of feeder length (km), when it is coupled with an appropriate WDM-PON backhaul infrastructure, the resulting hybrid active Ethernet solution offers a significantly lower relative cost per line. This is true for both 300 and 500 Mbit/s cases. However, the hybrid active WDM-PON backhaul systems appear to offer the lowest relative costs per line for 300 Mbit/s as feeder fibre lengths increase from 5 km to somewhat less than 40 km. That said, such findings (which are critical for node consolidation strategies) need to be confirmed by the comprehensive techno-economic analysis being performed in WP5.

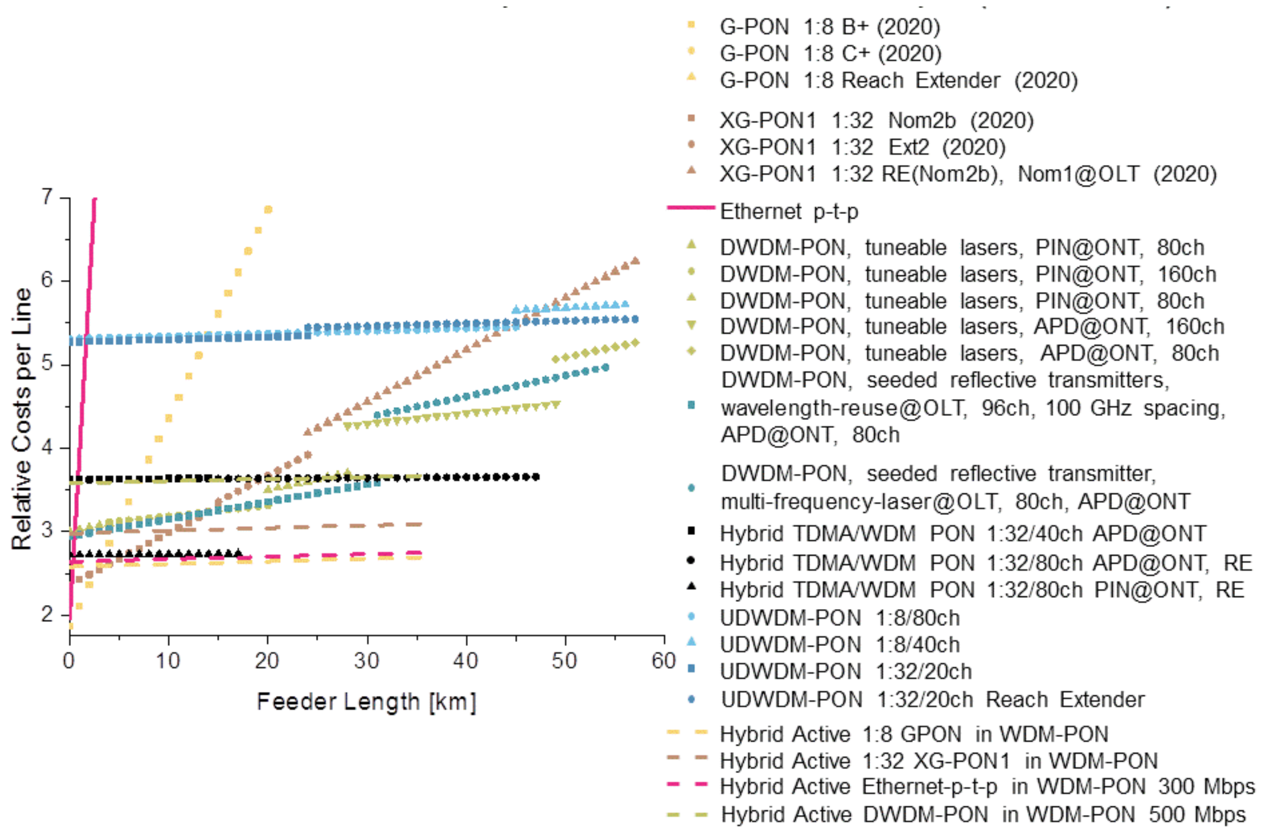


Figure 7-1: Cost per line analysis with 300 Mbit/s minimum guaranteed data rate per customer

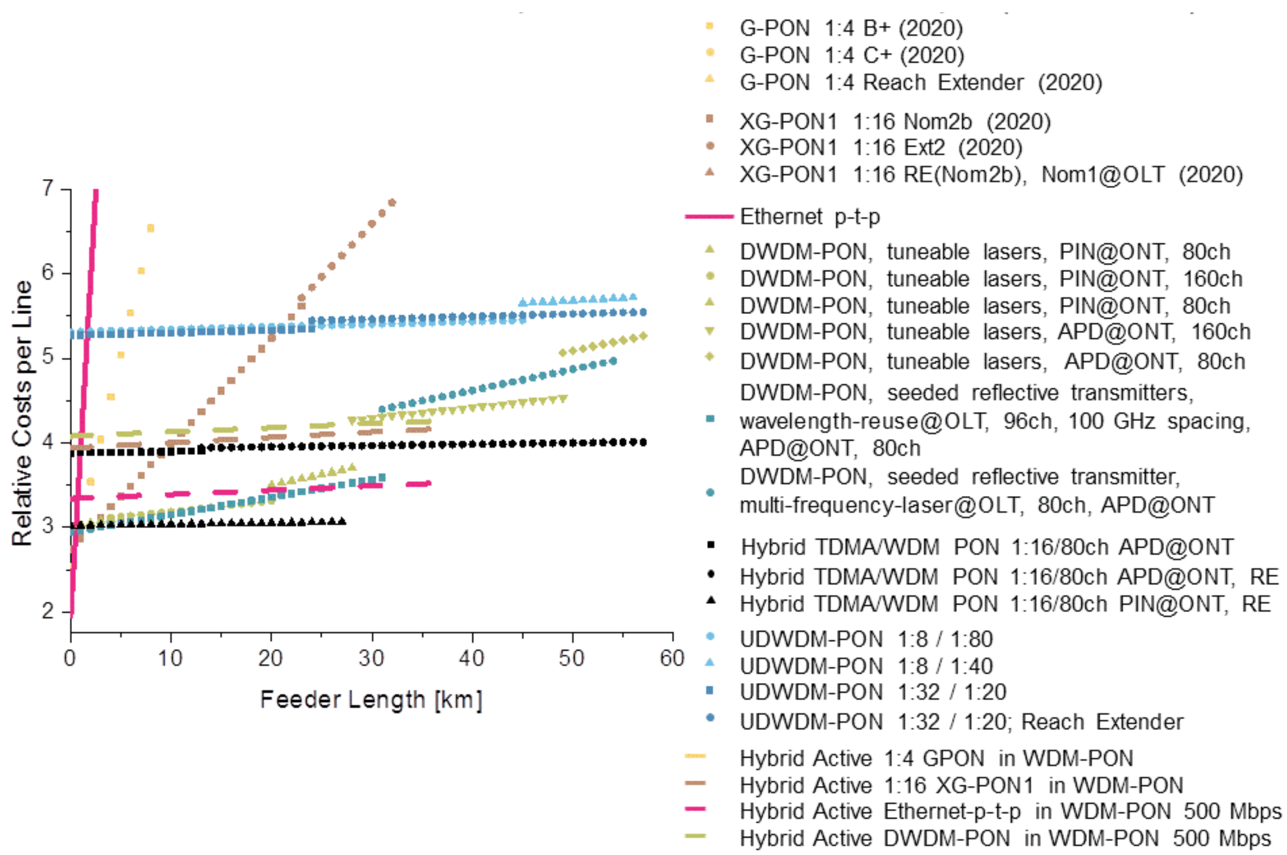


Figure 7-2: Cost per line analysis with 500 Mbit/s minimum guaranteed data rate per customer

In terms of the power consumption figures (see Figure 7-3 and Figure 7-4), as previously noted, there is not much to differentiate between the various architecture classes and their variants, with the total power per line varying between 5 W and 8 W per line at 300 Mbit/s, increasing to between about 6 W and 9 W per line at 500 Mbit/s. However, it is worthwhile to point out that the Ethernet PtP solution consistently offers close to the lowest power consumption in both cases.

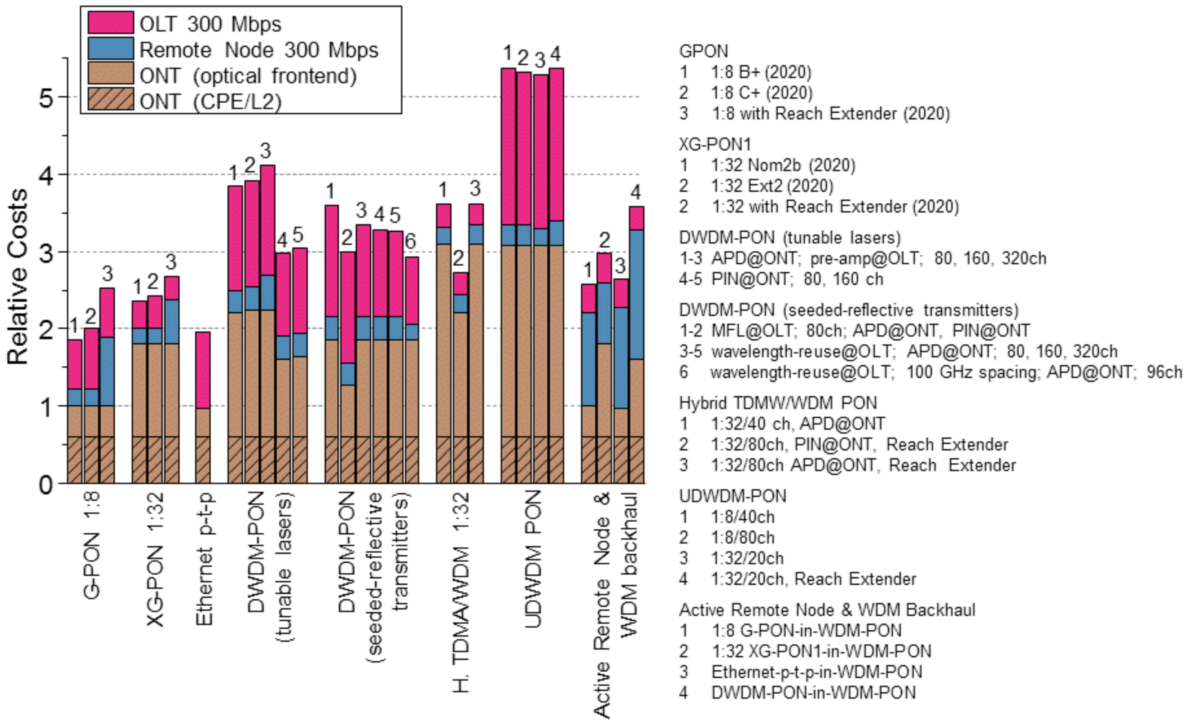


Figure 7-3: Power per line analysis with 300 Mbit/s minimum guaranteed data rate per customer

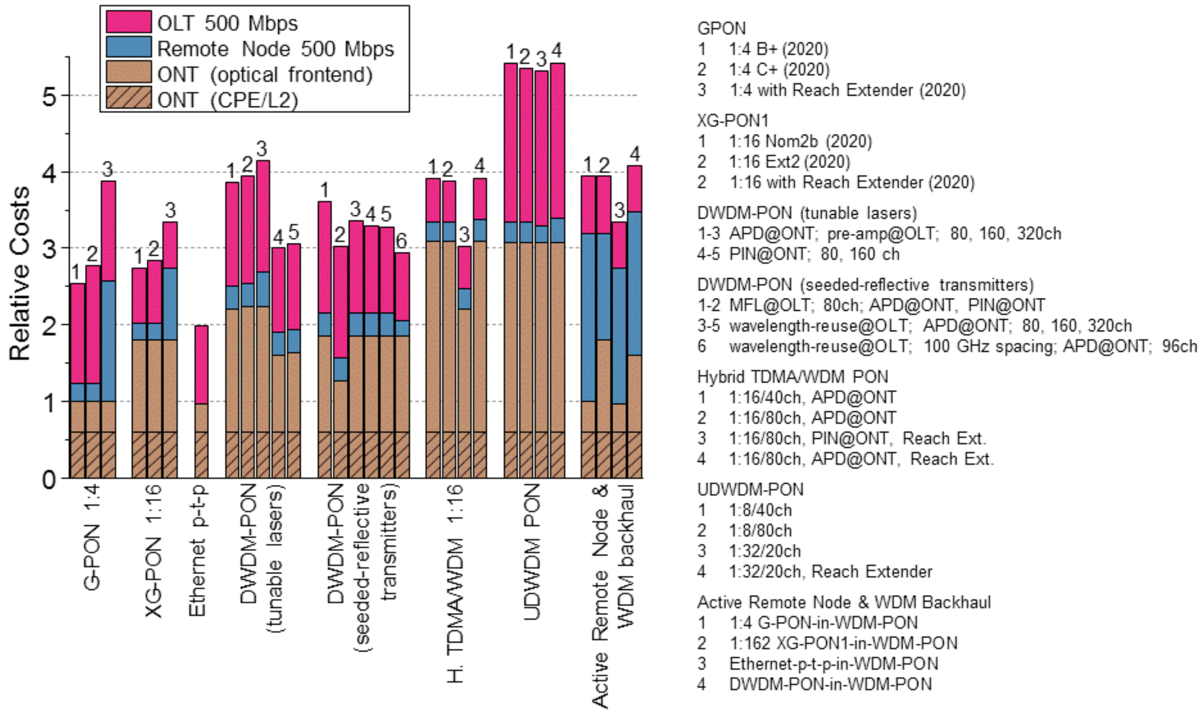


Figure 7-4: Power per line analysis with 500 Mbit/s minimum guaranteed data rate per customer

In this deliverable we have studied a range of different architecture and systems solutions, including Ethernet PtP, various PON flavours, and hybrid active approaches, all with respect to their suitability to fulfil the technical requirements and costs that we have identified in the NGOA context. Particular focus has been placed on providing the capability for supporting node consolidation, i.e., increased feeder section lengths and splitting ratios. Our studies appear to indicate that a hybrid active WDM-PON backhaul system can provide lowest system cost per line, but will require active equipment at the location of the local exchange (LEx) at PCP5.

Figure 7-5 and Figure 7-6 show the analyses for the various architectures and their system variants for their OLT rack space, for both 300 Mbit/s and 500 Mbit/s minimum guaranteed data-rate respectively. In this case, the Ethernet PtP architecture and UDWDM-PON architecture consistently exhibit the lowest rack space requirements for the two data-rates studied, while the hybrid active solutions tend to require the greatest footprints. As indicated in the figures, the floor space of any active and passive remote nodes have not been included in this analysis.

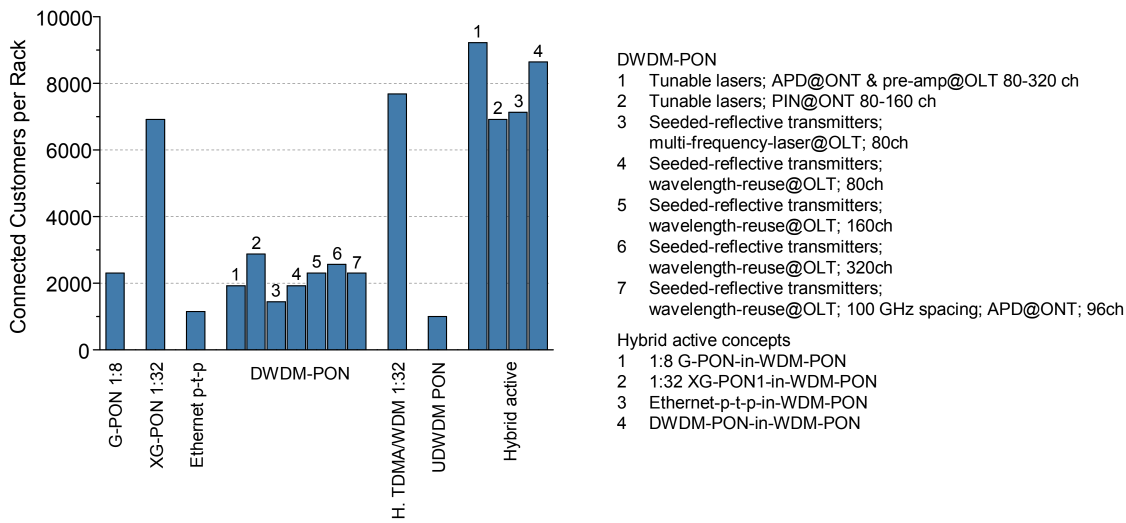


Figure 7-5: OLT rack space analysis with 300 Mbit/s minimum guaranteed data rate per customer

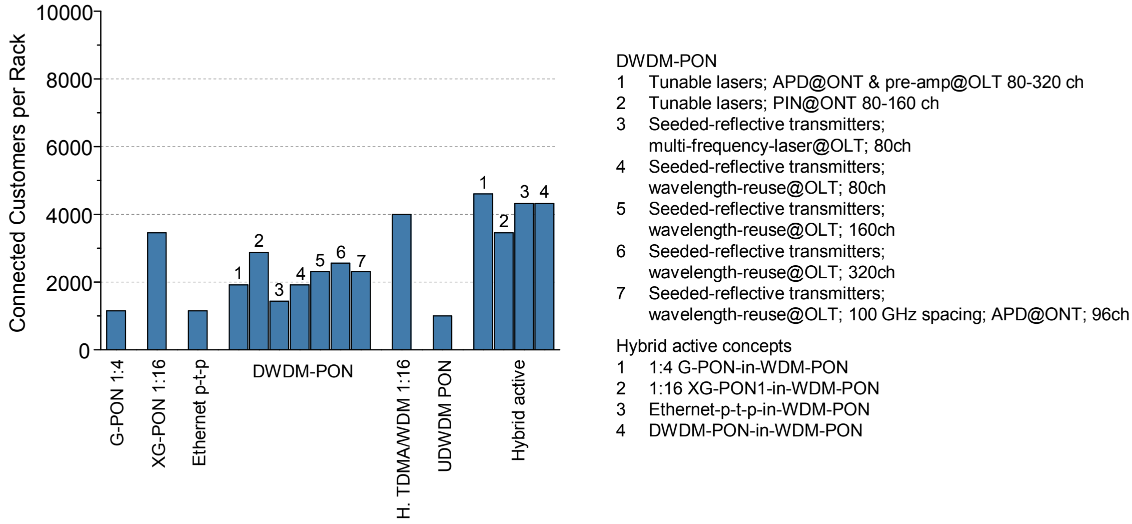


Figure 7-6: OLT rack space analysis with 500 Mbit/s minimum guaranteed data rate per customer

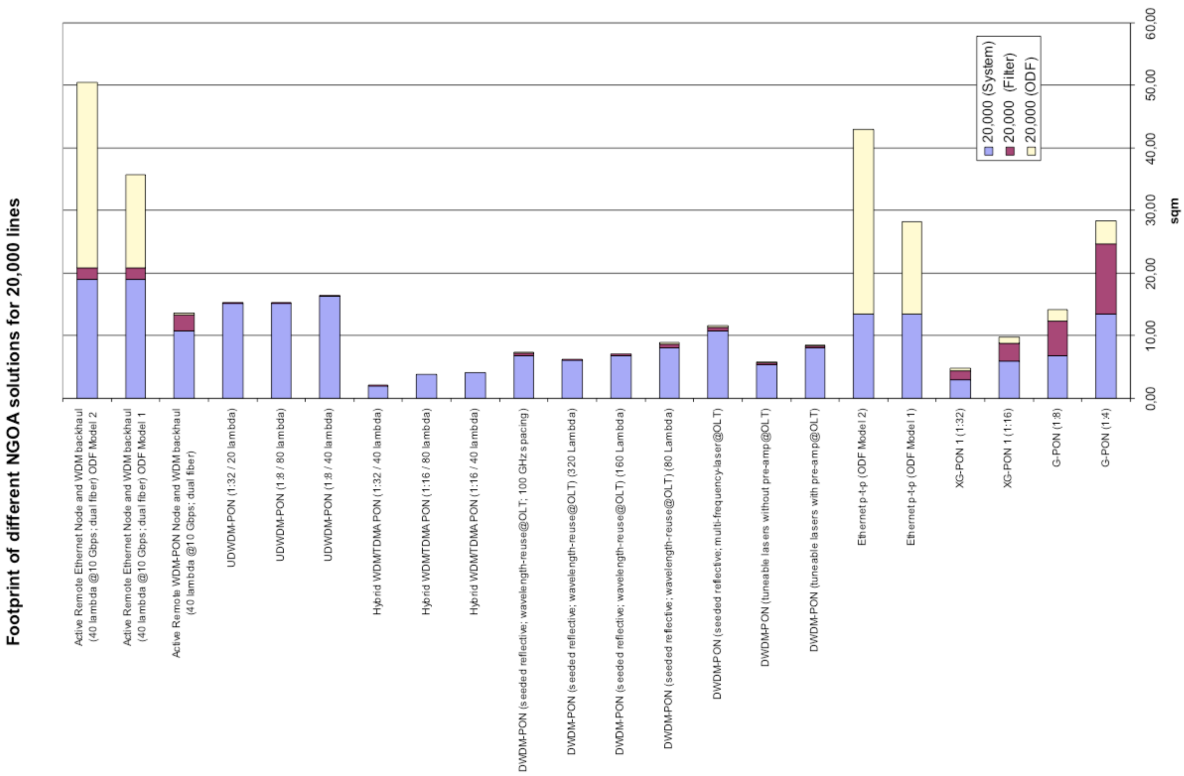


Figure 7-7: Total footprint analysis of 20,000 lines, with 500 Mbit/s minimum guaranteed data rate per customer

The total floor space footprint requirements of a fully scaled-up system serving 20,000 customers with a guaranteed data-rate of 500 Mbit/s is shown in Figure 7-7. Here, the hybrid WDM/TDMA PON systems exhibit the smallest footprint, whereas the Ethernet PtP and hybrid active concepts possess largest footprints.

Several of the relevant technical requirements identified in the deliverable D2.1 (e.g. reach, customers per feeder fibre) are specified as permissible ranges allowing for flexibility in the system design in order to ensure that the overarching OASE objective of minimum total-cost of ownership (TCO) is met. In this deliverable D4.2.2, a large number of system variants are found to satisfy at least the lower end of these ranges. It is not possible to further select or reduce the number of candidate systems based on technical requirements solely. As seen in the results of this deliverable, systems satisfying the high end requirements in general also are more costly. Hence to further select promising candidates requires an understanding of the detailed trade-off between the system cost and the impact of system performance on OpEx. Even though design parameters that drive CapEx are well understood from the analysis in this deliverable, to further select suitable NGOA design variants, design parameters that drive OpEx must also be quantified. This will be part of the comprehensive techno-economic analysis in WP5.

In this final deliverable D4.2.2 we have provided an updated quantitative assessment of the costs, power consumptions, reach, client-count and footprint requirements of a set of variants of the system architectures being studied within the OASE project. We have also provided additional qualitative discussions of the resilience, security, upgradeability and mobile backhaul requirements that each system variant needs to satisfy. The quantitative results will be provided to the parallel workpackage WP5 which will use the raw data to conduct a comprehensive techno-economic (total cost of ownership, TCO) calculation for the various system variants. Alongside the results emerging from WP6 which considers additional regulatory and competition (open access) impacts, as well as the migration studies arising from WP3, the results presented here provide additional important insights into the most-likely evolution paths of next-generation optical access networking.

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