Next Generation Optical Access Seamless Evolution

Concluding results by the European FP7 OASE project

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Abstract— **Increasing bandwidth demand drives the need for next-generation optical access (NGOA) networks that can meet future end-user service requirements. This paper gives an overview of NGOA solutions, the enabling optical access network technologies, architecture principles, and related economics and business models. NGOA requirements (including peak and sustainable data rate, reach, cost, node consolidation, and open access) are proposed, and the different solutions are compared against such requirements in different scenarios (in terms of population density and system migration). Unsurprisingly, it is found that different solutions are best suited for different scenarios. The conclusions drawn from such findings allow us to formulate recommendations in terms of technology, strategy, and policy. The paper is based on the main results of the European FP7 OASE Integrated Project that ran between January 1, 2010 and February 28, 2013.**

Keywords-component: broadband optical access, NGOA, FTTH, Fibre optic networks

1. Introduction and Motivation

End-user demand for bandwidth is continuously increasing [1]. As access networks currently constitute a bottleneck in the delivery chain, there is a common understanding that Fibre-to-the-Home (FTTH) will overcome the bandwidth limitations of today's copper-based and hybrid fibre access solutions, like, e.g., Fibre-to-the-Cabinet (FTTCab). FTTH can be seen as the ultimate and most future-proof access deployment and the basis for next-generation fixed access.

Considering the high costs associated with operation of access networks, there is a desire that next-generation optical access (NGOA) solutions not only cater for the increasing bandwidth requirements, but also enable site consolidation as an avenue for minimizing total cost of ownership (TCO). In addition to new technical solutions, the deployment of new access networks will require large investments, and potentially new business models, including new players like utilities, construction companies and public administration, as key infrastructure investors and drivers, especially in rural areas.

The goal of the OASE (Optical Access Seamless Evolution) project was to identify NGOA solutions that meet the future requirements in terms of e.g. bandwidth, availability, scalability, at minimum TCO. This paper summarises the results of the European FP7 OASE Integrated Project (1 January 2010 and 28 February 2013). Different NGOA solutions are proposed and benchmarked against commercially available fibre access solutions, such as Gigabit Passive Optical Networks (G-PON), or Active Optical Networks (AON).

2. The OASE NGOA Definition and Requirements

Within the scope of this project, and throughout this paper, we use the word "system" to refer to physical layer issues, and "architecture" to networking layer issues. The NGOA coverage as defined in OASE is illustrated in Figure 2-1, which shows NGOA coverage at system, architectural and service level. Within the scope of OASE, the NGOA system coverage is the domain for investigation of novel optical technologies and solutions. The NGOA system coverage comprises the segment from the optical termination (referred to NT1) at the optical network unit (ONU) up to the optical line terminal (OLT), placed at the local exchange or Central Access Node (CAN) depending on the degree of node consolidation. On the architectural level, which also is the basis for the techno-economic comparison, the NGOA coverage stretches from the end user data termination (referred to as NT2) at the customer side to the Edge node (hence including the aggregation section of the network).

2.1 NGOA requirements

Identifying the optimal degree of node-consolidation, shifting OLTs closer to the core, presents a trade-off between cost

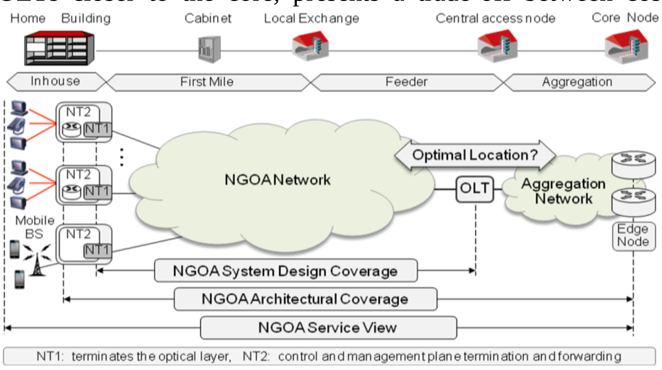

Figure 2-1: Overview of the NGOA coverage area as defined within OASE.

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reduction associated with node-consolidation and increased NGOA system. Support for larger service areas implies longer access reach and significantly higher customer concentrations per single fibre and single optical interface than in today's G-PON (maximum of 128 customers). It also requires effective redundancy and protection mechanisms. Migration to the NGOA network should not affect already deployed (legacy) systems and spectral usage. Leveraging sunk investments and using existing infrastructure needs to be considered for a cost-optimized design and migration strategies. Based on real network topologies and traffic forecasts up to 2030, requirements were identified as baseline for the design and assessment of the NGOA systems and architectures [2], [3]. The key requirements are presented in Table 2-1.

2.2 *Network Layers, Market Actors and Business Models*

Based on the technical and economic nature of the different parts of the network, responsibilities are typically split into three conceptual levels (Figure 2-2). On the lowest level, the physical infrastructure provider (PIP) is responsible for rights-of-way, ducts, fibres and passive equipment such as splitters and racks. The PIP leases this dark fibre infrastructure to the network provider (NP), who in turn installs the necessary active equipment to provide end-to-end connectivity. Finally, service providers (SP) are responsible for the actual delivery of services (which could be very diverse: single versus multi-play packages, streaming versus on-demand services, etc.). The passive infrastructure is typically characterized by high up-front investments with low economies of scale, and is often subject to regulation. The network layer is characterized by higher recurring costs and higher economies of scale. The service layer is dominated by marketing, customer relations and service innovation. Hence one can envision the PIP role to be taken up by infrastructure players, such as real estate companies, municipalities and utilities. NP players typically own and operate their network equipment. SP players are most successfully taken either by local companies with territory knowledge, or by large national and international service providers, with broad service offers and bundles and brand recognition.

Within OASE, the open access paradigm was studied in detail. We should note that we make a distinction between open access and unbundling. Unbundling refers to the case in which a single actor is exploiting both a particular layer and the layer on top of that, while still allowing the co-existence of other actors on top of its own passive infrastructure/network. Open access, on the other hand, refers to the situation in which the lower layer is provisioned in a non-discriminatory way to different actors on the layer above. The main difference with unbundling is that the actor responsible for the lower layer is not allowed to act in the layers above. While open-access and unbundling do not differ in terms of technical solutions, they tend to lead to different business cases. Figure 2-2 shows different open access and unbundling variants.

Business models for several existing open access and unbundled FTTH deployments have been studied in detail: Stockholm, Amsterdam, Hamburg, Bavaria and the rural municipal of Säffle (in Northern Sweden) [4]. The very high infrastructure costs (due to trenching) seem to discourage infrastructure-based competition at the fibre layer. In fact, we typically observe a single PIP per area, e.g. Stokab in Stockholm, M-net in Bavarian and Glasvezelnet Amsterdam in Amsterdam. On the other hand, the business case for NP-based competition seems more realistic (although the number

Table 2-1: NGOA requirements defined by OASE

Residential peak data rate (FTTH)	1 Gb/s
Business and backhaul peak date rate	10 Gb/s
Average sustainable downstream in peak hour per residential client	Moderate case 300 Mb/s Optimistic case 500 Mb/s
Maximum US/DS asymmetry	1:2 ratio between upstream and downstream
Split/Fan-out	256 up to 1024 ONUs per feeder fibre
	128 up to 500 Gb/s aggregate capacity per feeder fibre
Reach	20…40 km passive reach (working path)
	60…90 km extended reach (protection path), preferably passive
Migration, coexistence	Coexistence with existing ODN infrastructure (single fibre solution)
	Support of seamless migration (i.e., no user-wise manual switchovers)
	Deployed system and the existing spectrum must not be affected
Resilience	Redundancy and protection mechanism for a service availability of ≥99.98% for mass-market. A single failure impacts limited number of customers (e.g. 1000)
Open Access (OA)	Support of wavelength OA, either λ per NP/SP, or λ per user
	Support of fibre unbundling in the ODN (e.g., at ODF)
	Support of bit stream OA at L2 or higher

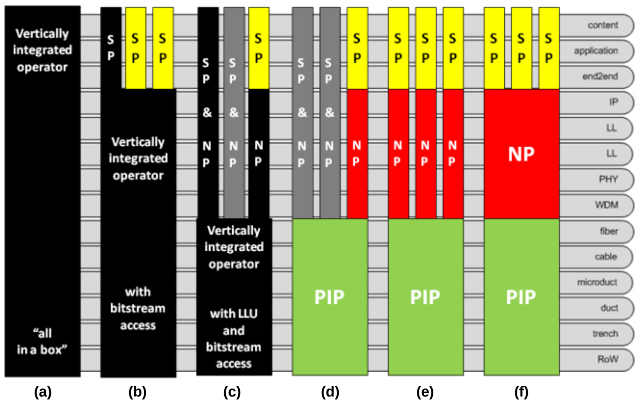


Figure 2-2: Conceptual business models for unbundling (a, b, c) and open access (d, e, f)

of NPs is typically limited to a few) and competition at the SP level is common in all examples (the number of SPs can be up to a dozen).

3. THE OASE NGOA SOLUTIONS

Different NGOA systems and architectures with the potential of fulfilling the NGOA requirements of Section 2, were identified [5] and categorized into four main groups of solutions:

- WDM-PON,
- Hybrid WDM/TDM-PON,
- WDM-PON backhaul,
- NG-AON.

These groups are described in this section. As reference solutions, we consider two widely deployed systems: G-PON and Ethernet point-to-point (which we will refer to as AON P2P, in the rest of the paper).

Figure 3-1 shows the different types of optical distribution networks (ODN) and corresponding NGOA systems in the generic NGOA architecture with consolidated CANs. Note that the same ODN may support multiple solutions and that one solution can be compatible with several ODN types. It should also be noted that despite the name, PON may in some cases contain active elements in the RN.

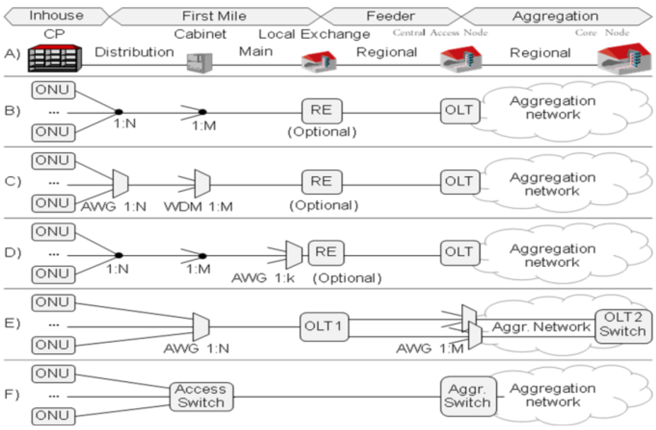


Figure 3-1: Typical locations and generic terminology of NGOA architecture (A) and NGOA systems solutions (B–F). B) WS-WDM-PON, UDWDM-PON and G-PON/XG-PON1. C) WR-WDM-PON with WDM-filtered ODN. D) Hybrid WDM/TDM-PON and (coherent) UDWDM-PON. E) WDM-PON backhaul, here with WR-WDM-PON in the first mile. F) NG-AON, with AON P2P from ONU to the access switch and P2P or WDM backhaul to the aggregation switch. RE = reach extender.

3.1 WDM-PON

Wavelength division multiplexed PON (WDM-PON) solutions span a set of solutions with dedicated wavelength-domain multiple access per client. These solutions can be categorized into Wavelength-Selected (WS-) WDM-PON with power-split ODN and Wavelength-Routed (WR-) WDM-PON with WDM-filtered ODN. All WDM-PONs can be considered as point-to-point links at the wavelength level and provide a high sustainable bandwidth per customer.

WS-WDM-PON (Figure 3-1B) is based on passive optical power splitters in the ODN (which limits the reach as compared to WR-WDM-PON). Each ONU is assigned one wavelength pair (downstream plus upstream), therefore the number of ONUs is given by the number of available wavelengths. All wavelengths are available at each of the ONUs. Therefore, tuneable receivers (e.g., tuneable filters) and a security layer are needed. In addition, tuneable lasers or seeded/reflective devices are required for colourless transmitters.

WR-WDM-PON, shown in Figure 3-1C, uses the same OLT as WS-WDM-PON, but uses one or several passive devices in the ODN that can multiplex/demultiplex wavelengths. These are typically arrayed waveguide gratings (AWGs) which route single wavelengths or wavelength pairs to each ONU. The ONUs can be designed either with tuneable lasers or seeded reflective transmitters, but do not require tuneable receivers.

Ultra-Dense (UD) WDM-PON is a variant of WS-WDM-PON where coherent receivers and ultra-dense channel spacing are used. Consequently, it can run via power-split or hybrid ODN, as shown in Figure 3-1B and D). It uses coherent detection, which enables dense wavelength spacing, increased reach, and high potential end-user numbers.

3.2 Hybrid WDM/TDM-PON

Hybrid WDM/TDM-PON is based on a combination of wavelength- and time-division multiplexing. It can be passive or semi-passive [4].

Passive hybrid WDM/TDM-PON (Figure 3-1D) aims to improve the fan-out of the WDM-PON architecture by using TDM for multiple-access. The ODN may be based on different combinations of power splitters and AWGs. A purely power-split ODN has the highest flexibility concerning resource allocation but suffers from large insertion loss. ODNs containing AWGs can achieve longer reach but with less flexibility. In both cases, ONUs require tuneable filters. The upcoming ITU-T Recommendation series G.989 on NG-PON2 describes a hybrid WDM/TDM-PON with four wavelengths with an option to overlay further (e.g., 8, this is not yet finally defined) WDM point-to-point channels.

In the considered semi-passive hybrid WDM/TDM-PON, the first passive splitting device is replaced by an active reconfigurable optical switch (e.g., wavelength selective switch, WSS). This active device can switch wavelengths to the different distribution fibres and assign resources in a reconfigurable, less static way while reducing the insertion loss compared to power splitters. For details on system implementations, see [6].

3.3 WDM-PON backhaul

This is a hybrid AON/PON architecture (see Figure 3-1E) consisting of two typically PON-based stages (backhaul and first mile) connected by an active element terminating and regenerating the optical signal. The backhaul stage is based on WR-WDM-PON, while the first-mile stage can be based on

G-PON, WDM-PON, or even AON P2P. Due to this mid-stage termination, high reach and client count can be achieved, at the cost of active equipment in the field.

3.4 NG-AON

The next-generation active optical network (NG-AON) architecture is based on active RNs which are placed somewhere in the ODN, for instance in the cellar in a multi-dwelling unit or in a cabinet (see Figure 3-1F). Each ONU connects to a layer-2 switch. Higher-layer (i.e., IP) and in principle also lower-layer (i.e., lambda layer) switching is also possible. The backhaul between RN and CAN can be based on different point-to-point technologies, e.g., WDM-PON.

NG-AON can be based on standard star topology (active star, or AS-AON), as shown in Figure 3-1F, but if desired, even meshed topologies (in which each node is connected to one, two or several other nodes) can be relatively easily implemented all the way to the first aggregation point (e.g. the cellar in a multi-dwelling unit or in a cabinet), assuming this is connected by multiple fibre connections, e.g. by connecting neighbouring buildings.

4. Assessment of the OASE Solutions

The assessment of the four NGOA solutions is presented in this Section, together with the reference solutions. First, a system-level assessment is performed, followed by an analysis on the architectural level. Finally, techno-economic and business-model assessments are performed.

4.1 System-level Assessment

All solutions are assessed with respect to performance and operational parameters with an impact on the TCO: client count per OLT port, floor space requirement (density), energy consumption, provisioning, maintenance, and open access compatibility. The assessment results are discussed in some detail in this section and summarised in Table 4.1.

All systems are configured to provide ≥1 Gb/s peak bit rate and 300 Mb/s or 500 Mb/s guaranteed bit rate per client, as defined by the requirements in Section 2. For hybrid WDM/TDM-PON and G-PON/XG-PON1, the ODN split ratio is adapted to these bit-rate requirements.

Assessment of reach and client count per OLT port is based on power-budget modelling, whilst floor space and energy consumption is based on modelling of the respective system configurations. A common power-budget model is used that comprises a total penalty of 5.5 dB for in-house patching, cabling, measurement couplers, etc. End-of-life fibre attenuation of 0.34 dB/km in the C/L-band and 0.44 dB/km at 1310 nm has been assumed. In addition, all systems were configured in order to comply with laser safety class 1M, i.e., a maximum accumulated power not exceeding 21 dBm.

In order to investigate floor space and power consumption, a common rack and shelf model is used. Each shelf includes mechanics, backplane, redundant power supply, management, and Layer-2 switching which is adapted to the guaranteed per-client data rate.

The calculations regarding cost, power consumption, form factor and reach are based on the performances of the key components or sub-systems of the respective system configurations. These parameters have been extensively discussed in industry fora like FSAN, conferences and workshops, other research projects, and bilaterally with various components vendors. More details on the system-level assessment can be found in [5], [7], [8] and [9].

The component figures for power budgets, power consumption, and cost are subject to uncertainty increasing in this order (i.e., power-budget / IL figures are stable, relative-cost figures have highest uncertainty). A sensitivity analysis shows that even changes of key-components cost by a factor of 2 do not change the overall result significantly.

4.1.1 Technical Performance Assessment – Calculations

Because of their inherent nature of a non-shared transmission medium, NG-AON solutions can achieve the longest reach (60 km from the access switch at the RN to the end user).

Moving to the more interesting analysis of PON-based solutions, WR-DWDM-PON can achieve a fibre reach of 60 km with a fully passive ODN for client counts of up to 80 per feeder fibre. A higher client count is possible, but when it is increased beyond 80, the fibre reach is reduced due to the insertion of additional WDM band splitters or interleavers.

Coherent UDWDM-PON can achieve ~60 km reach for a client count as high as 320. The client count can again be higher, but then the reach is decreased likewise.

For hybrid WDM/TDM-PON, the reach is limited to less than 30 km at a high client count (320 and above), even though booster and pre-amplifiers, forward error correction (FEC) and a very high achievable power budget (39 dB) between transmitter and receiver have all been considered.

With WDM-PON backhaul, both long reach (>40 km) and a large client count (several hundreds) can be achieved. These advantages come at the penalty of needing active RNs. This is addressed by the TCO calculations.

The reach of any of the WDM-based NGOA systems can be increased by active reach extenders, i.e., optical amplifiers. These require local electrical powering which again has to be considered for the resulting TCO.

The assessment further showed that power consumption is not a major differentiator. Power consumption at the ONU side is somewhat higher for UDWDM-PON and hybrid WDM/TDM-PON due to their complexity, compared to WR-WDM-PON. At the OLT side, power consumption per client is slightly lower for hybrid WDM/TDM-PON due to the sharing of wavelengths amongst multiple clients. Ethernet PtP has the lowest power consumption per access line. However, network-wide power consumption is increased by the higher number of active sites with aggregation switches.

4.1.2 Technical Performance Assessment – Experimental

We also investigated two relevant aspects of NGOA solutions experimentally. These aspects relate to the photonic layer of WDM-based PON. The results are applicable to WDM-PON as well as hybrid WDM/TDM-PON and similar hybrid PONs. The work targeted former weaknesses of WDM-PON: the limits of the achievable bit rate × reach product for seeded/reflective approaches, and lacking concepts for massive cost reduction in WDM-PON based on tuneable lasers.

Increased bit rate × reach with seeded/reflective transmitters was achieved for the specific variant of wavelength re-use with combined Inverse-Return-to-Zero (IRZ) / Return-to-Zero (RZ) modulation. Here, the modulated downstream laser wavelength is also used as a seed for a reflective ONU transmitter, which re-uses this wavelength for upstream re-modulation. In any time-slot, the ONU must receive seed light for upstream transmission. This can be achieved be modulating the downstream with IRZ On/Off-Keying (OOK) and then using bit-interleaved RZ OOK for the upstream. A block diagram of this system, which was specifically designed to cope with the problems of crosstalk and reflections arising from the use of the same wavelength for upstream and downstream [10], is given in Figure 4-1. The reach of the IRZ/RZ WDM-PON was increased to 20 km at 10 Gb/s per channel and 60 km at 2.5 Gb/s, respectively [6].

As an alternative to seeded/reflective transmitters, tuneable lasers can be used for colourless ONUs. In order to allow for low cost, the lasers must neither be fitted with their own dedicated wavelength lockers nor with coolers. Hence, they are subject to wavelength drift and require cost-effective wavelength control in the PON system context.

Several control mechanisms were developed and implemented for several different types of wide-band tuneable lasers (DS-DBR lasers, Y-Branch DBR lasers). This included closed-loop control and open-loop control according to a look-up table.

For closed-loop laser control, a distributed wavelength locker was implemented which can be shared between all WDM channels for cost efficiency. The set-up is shown in Figure 4-2. The upstream lasers in the ONUs were modulated with additional (AM or FM) pilot tones which were transparent for the payload. These pilot tones were detected in the OLT via a tap, followed by low-speed photo diodes and analogue-to-digital conversion. Laser drift could be detected and corrective action be signalled to the ONUs via an embedded control channel (ECC).

Closed-loop control allows wavelength stabilization of the uncooled lasers to within ±5 GHz over a broad temperature

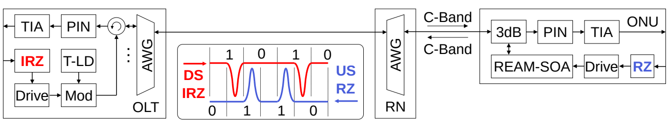


Figure 4-1: 10-Gb/s IRZ/RZ WDM-PON. MZM: Mach-Zehnder Modulator. T-LD: Tuneable Laser Diode. PIN TIA: p-i-n photo diode with transimpedance amplifier.

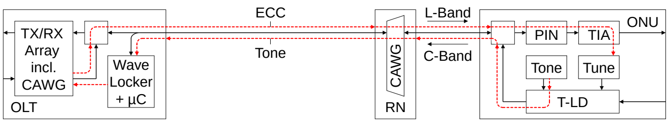


Figure 4-2: Closed wavelength control loop. CAWG: Cyclic AWG. Tone: pilot-tone generator. Tune: tuning micro controller (µC).

range, and ±2.2 GHz over ±0.5°C. This supports wavelength grids down to 25 GHz [11].

4.1.3 *Assessment of Operational Aspects*

The operational-aspects assessment revealed (see [6] for details) that all potential NGOA solutions support the basic Operations, Administration and Maintenance (OAM) tasks. These consist of Fault, Configuration, Account, Performance, and Security (FCAPS) management. In particular, automated service provisioning is possible with all solutions given that WDM-based ONUs are colourless and self-installing (which are operators' requirements). This can be achieved, e.g., with tunable lasers which are controlled by the OLT through related signalling channels. Certain advantages regarding fault isolation were identified for NG-AON and WR-WDM-PON due to their capabilities of unambiguously discriminating the individual distribution fibres. This is possibly only to a limited extent for broadcast (power-split) ODN.

Some differences were also identified with regard to the floor-space requirements. Here, hybrid WDM/TDM-PON shows best density, followed by WDM-PON with integrated multi-channel transceiver arrays. In third place is WDM-PON backhaul (due to the requirement for active RNs at the cabinet/local exchange), which is followed by the relatively complex UDWDM-PON. NG-AON has the highest floor-space demand, which can clearly be attributed to the high number of active sites.

Regarding Open Access (OA), no sever differences were found. For all solutions, OA focuses on Layer-2. For WDM-based PONs, OA on the wavelength level is seen possible, but requires significant additional effort when integrated multi-channel transceiver arrays are used.

4.1.4 *System-level Assessment Sum-up*

All assessments are based on the basic components-level properties. The systems-level performance assessment did not yet show a clearly winning solution. In general, maximum reach is traded-off by fan-out for all PON solutions, due to the increasing insertion loss. In this regard, AON solutions have an advantage. Regarding energy consumption, there is no clear picture, neither. On the positive side, this also means that all solutions do comply with, e.g., the EU Broadband Code of Conduct.

The system cost comparison shows somewhat higher cost for coherent UDWDM-PON, and large variations depending on specific system configurations. For most configurations, cost clearly depends on the guaranteed bit-rate. Hence, there are significant differences between the figures for 300 Mb/s and 500 Mb/s, respectively.

The operational assessment did not clarify the ranking. Most solutions perform fairly well with regard to basic operational as well as to open-access requirements. As an example, WR-WDM-PON performs slightly above average.

In order to single out a main system candidate for NGOA, it is necessary to understand which system aspects are cost-driving with regard to the *Total* Cost of Ownership (TCO). This analysis is presented in Section 4.3.

Table 4-1: Cost for the different NGOA solutions in relation to a G-PON ONU

System	ONT	Remote Node				OLT			
	Costs	Component		Capacity	Costs	Component	Component Capacity	Component Costs	Shelf Space / L2 switch capacity
Commons	0.6 CPE/mechanics					Shelf	18 tributary slots	100	
						L2 switch	n x 100 Gb/s	n x 10	
G-PON	0.4 (2.5G TDMA)	power splitter		1:4	1	port card	8 x G-PON	4.4	2 slots / 20 Gb/s
				1:8	1.8	G-PON MAC	1 x G-PON	1	on port card
		RE	chassis	8 ports	8	pluggable B+	1 x G-PON	2	on port card
			pluggable B+	1 port	3	pluggable C+	1 x G-PON	3	on port card
			outdoor cabinet	15 RE	150				
XG-PON 1	1.2 (PIN) (10G TDMA)	power splitter		1:16	3.4	port card	6 x XG-PON1	7.8	2 slots / 60 Gb/s
				1:32	6.6	XG-PON1 MAC	1 x XG-PON1	2	on port card
		RE	chassis	8 ports	20	pluggable Nom1	1 x XG-PON1	3.4	on port card
			pluggable Nom2b	1 port	8	pluggable Nom2b	1 x XG-PON1	5.2	on port card
			outdoor cabinet	15 RE	150	pluggable Ext2	1 x XG-PON1	6.8	on port card
Ethernet PtP	0.36 (1G)					port card	24 x compact SFP	12	3 slots / 48x300/500 Mb/s
						compact SFP	2 x GbE	0.72	on port card
DWDM-PON n=[1, 2, 4]	PIN: 1 APD: 1.6 (1G, tunable)	AWG		n x 80 λ	n x 24	port card	n x 80 λ	n x 8.8	n x 2 slots / n x 80 x 300/500 Mb/s
		diplexer			n=2: 1x0.3	TRX-array	80 λ	n x 64	on portcard
					n=4: 7x0.3	Diplexer	n x 80 λ	n=1: 1x0.3	on port card
		interleaver			n=4: 320x0.15			n=2/4: 3x0.3	
						Interleaver	4 x 80 λ	n=4: 320x0.15	2 slots
						pre-amp (optional) (EDFA/TDFA)	n x 80 λ	n=1: 15	n=1: 1 slot
								n=2/4: 33.8	n=2/4: 2 slots
Hybrid WDM/TDMA PON n=[4, 8]	2.5 (APD) (10G TDMA, tunable)	power splitter		1:16	3.4	port card	n x 10 x 10G-TDMA	n x 11.2	n x 2 slots / n x 100 Gb/s
				1:32	6.6	TDMA-MAC	1 x 10G-TDMA	2	on port card
		AWG		40 λ	12	TRX-array	n x 10 x 10G-TDMA	n x 26.26	on port card
				80 λ	24	diplexer	40 λ	8 x 0.3	2 slots
		RE	optical amplifier	40/80 λ	40		80 λ	12 x 0.3	4 slots
			outdoor cabinet	8 amplifier	150	Booster, pre-amp (EDFA)	40/80 λ	30	2 slots
Coherent UDWDM PON	2.32 + 0.15 (1G, tunable, coherent Rx, plus ASIC)	power splitter		1:32	6.6	port card	4 x 8 x 1G-ports (4 ITU λ)	6.4	2 slots / 4x8x300/500 Mb/s
		WDM filter		20 x 4 ITU λ	6	TRX-array	8 x 1 G-ports (1 ITU λ)	9.3	on port card
		RE	optical amplifier	20 x 4 ITU λ	40	ASIC	8 x 1 G-ports (1 ITU λ)	1.2	on port card
			outdoor cabinet	8 amplifier	150	Circulator	20 x 4 ITU λ	2	1 slot
						Booster (EDFA)	20 x 4 ITU λ	15	1 slot
						TFF	20 x 4 ITU λ	6	4 slots
Active Remote Node and WDM-PON backhaul	0.4 (GPON) 0.36 (Eth PtP)	power split	G-PON	1:4	1	port card	8 x XFP	8	2 slots / 80 Gb/s
				1:8	1.8	colored XFP	1 x 10GbE	8	on port card
		active RN shelf incl. L2 switch	G-PON	4 x G-PON, 1 x XFP	8.5	AWG (bidirectional)	40 λ	24	installed in separate passive shelf
			Eth PtP, 300 Mb/s	33 x 1 GbE, 1 x XFP	10.55				
			Eth PtP, 500 Mb/s	20 x 1 GbE, 1 x XFP	7.3				
		active RN pluggables	G-PON B+	1 x GPON	2				
			compact SFP	2 x GbE	0.72				
			colored XFP	1 x 10GbE	8				
		outdoor cabinet		12 x act. RN (Eth PtP) 24 x act. RN (G-PON)	150				
		AWG (bidirectional)		40 λ	24				

4.2 Architecture-level Assessment

Unlike system-level assessment, the evaluation presented in this section maps the selected NGOA options to some specific deployment scenarios and the results shows the impact of placing (or replacing) equipment in certain locations. In particular, we focus on the impact of node consolidation, providing open access on a wavelength basis, and migration towards the NGOA architectures. Beyond these aspects, evaluation results for power consumption, resiliency can be found in [12], [13], [14]. A summary of the overall assessment at the architecture level is provided at the end of this section.

4.2.1 Node Consolidation

With respect to node consolidation it is of crucial importance to understand the long-term effects of moving and concentrating equipment in certain locations for the considered technology options. The consolidation of COs implies that several traditional access networks are grouped together to form a new service area, which in turn has a wider coverage, i.e., with more users and longer distances. Two scenarios representing low and high degrees of node consolidation have been investigated. Starting from a today's scenario with 7,500 COs on a country-wide scale (assuming a country like Germany), we assumed a reduction towards 4,000 and 1,000 nodes, respectively. Here we summarize the results for the urban area, for two key operator-related performance metrics, i.e., footprint and failure rate, which are also analysed in the techno-economic study presented in Section 4.3. Similar findings were obtained for the other types of service areas (dense urban and rural). A complete assessment on architectural level with respect to node consolidation has been included in [15].

Figure 4-3 shows the footprint per line required at the various locations in the NGOA architectures, as well as in the reference architectures G-PON/XG-PON in combination with node consolidation scenarios for the urban service area. Footprint per line is defined as the floor space of all the network equipment that is taken on a per user basis. The methodology for the footprint calculation can be found in [16]. For all the variants of WDM-PON architectures, node consolidation does not bring an obvious impact on the total footprint per line. Hybrid WDM/TDM-PON requires the lowest amount of footprint in the outside plant among all the evaluated options, due to its relatively high sharing factor and fully passive ODN. In WDM-PON backhaul, the footprint of the active RN equipment at the cabinet/local exchange has also been taken into account. It can be seen that the total footprint for this architecture is slightly higher than for WR-WDM-PON. However, in the 1,000 CO scenario, equipment space is required at two different locations. It implies that a small portion of traditional CO/cabinets cannot be closed down even for the case with a higher degree of node consolidation. NG-AON requires the highest amount of footprint per line amongst all the architecture options. In contrast to the passive architectures, the footprint per line in

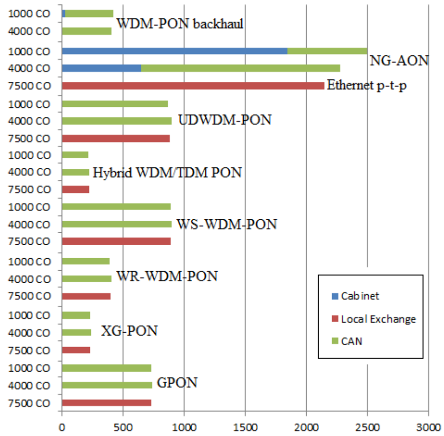


Figure 4-3: Footprint per line [mm^2].

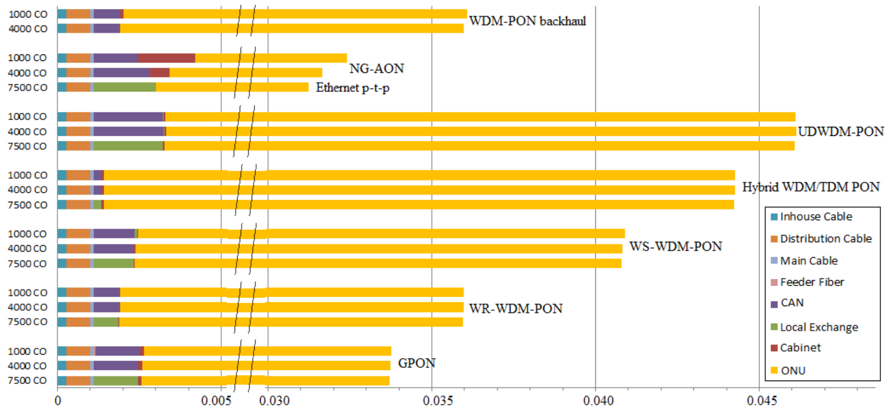


Figure 4-4: Number of failures per year normalized per line

NG-AON is obviously impacted by the degree of node consolidation, because of the active equipment needed at a RN (e.g., cabinet) in the field. It also means that the old COs or cabinets cannot be completely closed in the node consolidation scenarios.

Figure 4-4 shows the average number of failures per year normalized per line in different NGOA options and G-PON for various node-consolidation scenarios. It can be clearly seen that failures at ONUs dominate in all the evaluated options. In the case of an ONU failure it is assumed that a new device will be sent to, and installed by, the end user (plug-and-play). Other failures than at the ONE, however, are more costly, because they generally require a technician to be sent on field to perform repair (we can refer to these as critical failures). From Figure 4-4, we can see that NG-AON has the highest rate of critical failures (although it has the lowest total failure rate), followed by UDWDM-PON. Hybrid WDM/TDM-PON on the other hand has a high total failure rate but the lowest rate of critical failures.

4.2.2 Open Access Compliance

Based on the different system concepts and architectural investigations, in [17] all of the aforementioned NGOA solutions were analysed with respect to their potential to enable co-operation between different players as introduced in section 2, e.g., sharing part or all of the infrastructure and/or equipment. Three methods, namely fibre, wavelength and bit-stream open access for giving access to a network have been considered.

P2P fibre-level open access is only feasible with AON solutions with co-location possibility at the RN, or with P2P AON. Bit-stream open access can be adapted to any NGOA architecture option. Both these options are relatively straightforward to implement and widely used today. Here we chose to focus our analysis to wavelength open access.

The main impact of wavelength open access on the physical infrastructure provider (PIP) comes from the consequent need to manage optical devices (e.g., optical splitters, AWGs, and wavelength selective switches WSSs) and manage wavelengths. Wavelength open access can be implemented as:

- Wavelength open access at the feeder fibre
- Wavelength open access at the CAN

The latter option can be implemented by manual reconfiguration of the network each time the customer decides to change network provider (NP), or by automatic reconfiguration, either in the electronic or optical domain. Optical-domain reconfiguration can be done with:

- static spectrum distribution amongst NPs, using a waveband splitter as open access element, or
- dynamic spectrum distribution amongst NPs, using a power splitter or WSS as open access element.

Figures 4-5, 4-6 and 4-7 illustrate wavelength open access for a WR-WDM-PON. Similar schemes could be applied to the other PON approaches if the isolation issue caused by the power splitter in a power-split ODN could be solved properly, while it is not always possible for active architectures, i.e. WDM backhaul and NG-AON (see [12] for the details and complete assessment of all the OASE NGOA architectures). Figure 4-5 shows a typical example for the feeder fibre based WR-WDM-PON open access, where an M:N:AWG is used in the cabinet. Figure 4-6 shows an example of wavelength open access, using a static waveband splitter as open access element at the CAN. Figure 4-7 shows the general scheme for several variants with dynamic spectrum sharing between the NPs, either manually (using a patch panel, followed by an AWG to (de)multiplex all wavelengths towards the user) or automatically (using a power splitter or WSS).

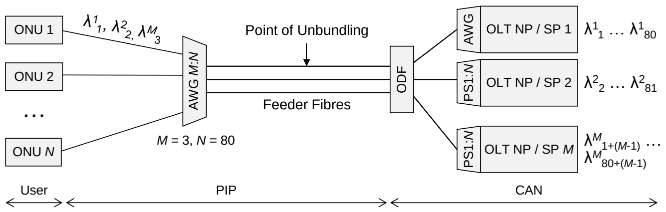


Figure 4-5: Feeder Fibre based wavelength open access in WR-WDM-PON

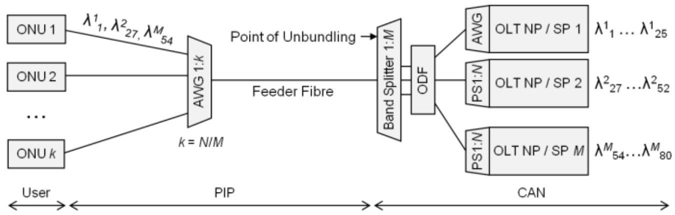


Figure 4-6: Wavelength open access at the CAN, using a static band splitter, in WR-WDM-PON

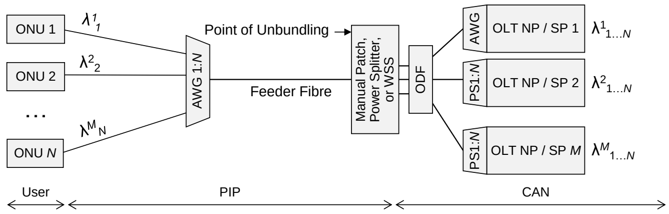


Figure 4-7: Wavelength open access at the CAN, with dynamic spectrum sharing, in WR-WDM-PON

It can be noted that additional fibres and/or equipment is needed to enable open access, which further increases the overall cost.

4.2.3 Migration

We define two starting points for assessment of migration towards the OASE NGOA architecture options: 1) from a TDM-PON based ODN (such as used in G-PON / XG-PON) and 2) from a P2P-based ODN (such as used in P2P AON). The assessment is based on the most important migration criteria, categorized according to 4 migration challenges (i.e. support of coexistence, reuse of legacy infrastructure, minimizing disruption time, and introducing node consolidation). It is clear that a P2P ODN as starting point offers the highest flexibility for migration; but in many cases such an ODN is not available. For a power-split ODN, the (passive) hybrid WDM/TDM-PON and WS-WDM-PON (and UDWDM-PON) are most suitable from a migration perspective. The other NGOA architectures are less suitable for migration, but offer other opportunities, such as better support for open access, protection, energy saving techniques, etc. as discussed in the OASE [12], [13], [14].

The main conclusions of the migration assessment are:

- Starting from an existing PON deployment, full coexistence is supported by hybrid WDM/TDM-PON, UDWDM-PON and WS-WDM-PON.
- Full coexistence is not supported by WR-WDM-PON, WDM-PON backhaul and NG-AON
- System performance (incl. number of ONUs per feeder fibre, passive and active reach) depends on the coexistence scenario (i.e. coexistence on the same ODN of NGOA and legacy technologies like G-PON, and/or XG-PON whether combined with RF video overlay or not).
- In principle, all NGOA architectures support node consolidation, with a migration of single users on demand.
- In principle, all NGOA technologies can be operated on an ODN with P2P architecture in the first mile; although in deployed multi-point TDM architectures there might be a shortage of available fibres from the cabinet to the local exchange level for P2P.

4.2.4 Summary of the Architecture-level Assessment

Table 4-2 summarizes the key findings of this architectural assessment. Several of the "passive" NGOA architectures, i.e., WS-WDM-PON, UDWDM/WDM-PON and hybrid WDM/TDM-PON turn out to consume more energy, but have better reliability performance, than their active counterparts, namely WDM-PON backhaul and NG-AON. From the operators' perspective, i.e., without considering the equipment located at the user side, thanks to its high splitting ratio, hybrid WDM/TDM-PON generally performs well considering operational aspects, such as footprint, failure rate, and operator related energy consumption. However, for hybrid WDM/TDM-PON there is an issue with resource allocation for scheduling upstream bandwidth. An efficient algorithm for hybrid PON is needed to mitigate the performance degradation caused by reach extension. Open access on wavelength level is technically easy to be realized in WR-WDM-PON, e.g., using M:N AWG to replace 1:N AWG (in case multiple feeder fibres are available). However, for all the other types of PONs the required power splitter in the ODN causes isolation issues for wavelength open access, while it is even not possible for some variants of WDM-PON backhaul and NG-AON. Furthermore, considering migration requirements on coexistence, a fully passive ODN of the type used for WS-WDM-PON, UDWDM-PON and passive hybrid WDM/TDM-PON is preferable.

A detailed assessment of the OASE architecture options comparing the considered architectural aspects can be found in [12], [15], [17].

Table 4-2: Summary for architecture assessment (legend: ++ very good; + good; O medium; - poor; -- very poor)

Architectural aspects		WDM-PON			Hybrid WDM/TDM-PON		WDM-PON Backhaul (AON P2P 1st mile)	NG-AON
		WS	WR	UD	Passive	Semi-passive		
Energy consumption		-	+	--	O		O	+
Resiliency		+	+	+	+	O	O	O
Operational complexity	Operator related energy consumption	-	+	-	++		+	-
	Footprint	O	+	O	++		O	--
	Failure rate	O	+	-	++		O	-
Complexity of resource allocation		++			-		O	O
Open access (wavelength level)		O	+	O	O		-	--
Migration (from G-PON)		++	+	++	++	O	-	--

4.3 Techno-economic Assessment

The NGOA techno-economic assessment targets the evaluation of the capital and operational expenditures (CAPEX and OPEX, respectively) of different NGOA architectures on different areas and node consolidation scenarios. For that purpose, a frame tool based on TONIC [18] has been developed as shown in Figure 4-8. The techno-economic frame tool is based on the dimensioning of the selected NGOA architecture for a given scenario. The dimensioning considers a geometric model of the user distribution [19] and based on the given penetration curve, area, and node consolidation scenario, it provides a yearly 'shopping list' of the equipment and infrastructure required.

Based on the yearly shopping list, and any required information on any network component and possible migration scenario, the cost assessment is performed and delivers yearly distribution of both CAPEX and OPEX. In order to use the cost assessment results in the business model studies, the PIP and NP costs have been differentiated. Any cost of equipment or infrastructure is given as CAPEX, which also includes any associated installation costs. Fault management (FM), energy consumption, service provisioning (SP) and floor space are all considered as OPEX. Due to the complexity of FM (complete failure reparation process) and SP (adding, changing and cancelling customer services) processes, they have been modelled in detailed using Business Process Model and Notation (BPMN) and integrated within the extended TONIC tool.

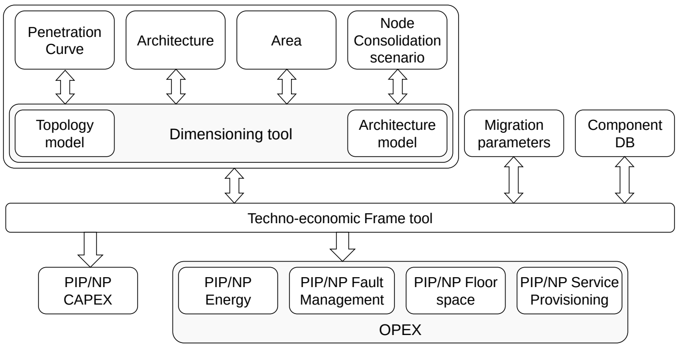


Figure 4-8: Techno-economic frame tool

4.3.1 *Migration Scenarios*

Among the several studies performed within the OASE project; this paper presents the cost evaluation of the migration from an existing traditional optical access network such as G-PON or AON. This is the case for many operators. In this migration scenario, the investments in terms of infrastructure and equipment are considered assuming an existing ODN, which can be used for migration towards the NGOA. The considered migration scenarios have been summarized in Table 4-3. The technology migration from G-PON 1:32 or AON P2P to WR-WDM-PON is not studied in the no-node consolidation (NNC) scenario, because in this case the new architecture requires considerable ODN upgrade, which is generally not economically feasible.

4.3.2 *Migration Cost Assessment without Node Consolidation*

The cost evaluation is presented in terms of Cost Units (CU), whereby 1 CU equals the cost of one G-PON ONU. Only non-discounted TCO values are presented. In this way, the real cost is shown as experienced in the given years.

The first cost comparison shows the average from 2020 (migration year) to 2030 of the non-discounted TCO per user, taking into account the users connected in each year (based on the assumed penetration curve). Figure 4-9 distinguishes the CAPEX contribution (in blue) from the OPEX contribution (in red) for dense urban (top) and rural (bottom) areas without node consolidation. In the scenario – realistic for one geographical area – the traditional optical access network is running from 2010 to 2019, with a migration starting in 2020 and lasting 1 year, so that at the end of 2020 all users are connected to the NGOA, and the traditional access network can be switched off. It can be observed that the relative cost among the architectures is the same, independently of the area type. Of course, when possible, upgrading existing technological solutions has the lowest cost as most of the existing ODN (though a lower split ratio may impose an ODN upgrade as well) and equipment (e.g., ONU) can be reused. As also foreseen by the component and system cost overview, UDWDM-PON appears as the most expensive solution, driven by the high OLT cost and less reliable components.

Table 4-3: Migration/upgrade scenarios considered in the cost assessment and corresponding node consolidation degrees (no-node consolidation [NNC] vs. aggressive node consolidation [ANC]). The minimum bit rate is 300Mb/s, although some solutions like XG-PON 1:16 and hybrid WDM/TDM-PON (HPON) 80λ 1:16 are able to support higher bit rates (500Mb/s).

Migration/upgrade scenarios		NNC	ANC
From	To		
G-PON 1:32	G-PON 1:8 (>300Mb/s)	Yes	Yes
G-PON1:32	HPON 40λ 1:32 (>300Mb/s)	Yes	Yes
G-PON1:32	HPON 80λ 1:16 (>500Mb/s)	Yes	Yes
G-PON1:32	WS-WDM-PON 64λ (>300Mb/s)	Yes	Yes
G-PON1:32	WS-WDM-PON 128λ (>300Mb/s)	Yes	Yes
G-PON 1:32	WR-WDM-PON 80λ (>300Mb/s)	N/A	Yes
G-PON 1:32	UDWDM-PON (>300Mb/s)	Yes	Yes
XG-PON1:32	XG-PON 1:16 (>500Mb/s)	Yes	Yes
AON P2P	WR-WDM-PON 80λ (>300Mb/s)	N/A	Yes
AON P2P	AON P2P (>300Mb/s)	Yes	N/A
AON ActiveStar (AS)	WDM Backhaul with AON P2P (>300Mb/s)	Yes	Yes

4.3.3 *Migration Cost Assessment with Node Consolidation*

Operators are considering node consolidation as an avenue to reduce costs associated with the number of central offices to be maintained. For the case of node consolidation, the average TCO per connected user has been evaluated for dense urban and rural areas as shown in Figure 4-10. It can be observed that, in contrast to the first migration study in a non-consolidation scenario, the relative costs among the architectures depend on the considered area. For Dense Urban areas, depending on the existing deployment, either upgrade of XG-PON or migration from AS-AON to AS-AON with WDM Backhaul shows the lowest cost due to the reuse of legacy network and infrastructure resources. Starting from G-PON, the less costly migration is towards hybrid WDM/TDM-PON.

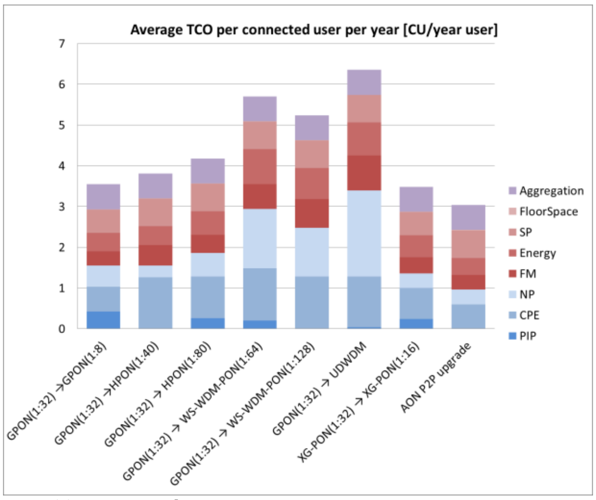
In rural areas, starting from G-PON, migration towards hybrid WDM/TDM-PON has similar cost as an (X)G-PON upgrade. Starting from AS-AON, migration towards WDM Backhaul with AON P2P remains a low cost solution.

Furthermore, it can be observed that rural service areas have higher infrastructure costs than dense urban areas, but lower operational costs such as maintenance and power due to fewer users per service area. The case of upgrading from AON P2P in a no-node-consolidation scenario to a node-consolidation scenario is not studied, because of excessive costs: in an aggressive node-consolidated area there is a higher number of users and longer ODN distances, which will lead to large fibre infrastructure costs to provide P2P connections between all users and their respective CO.

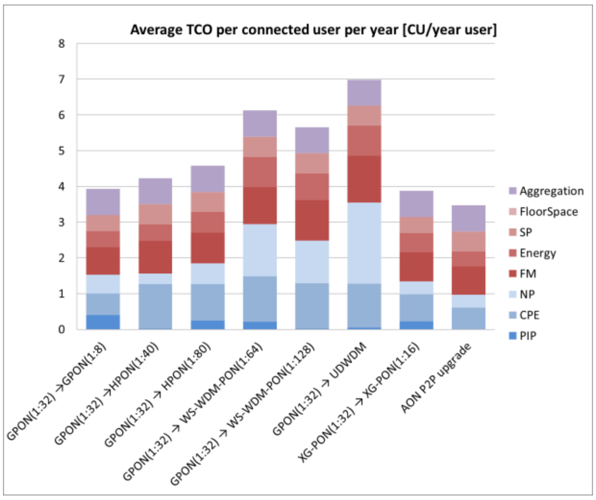
In order to better compare the techno-economic performance of no-node-consolidated architectures and node-consolidated architectures, further studies included the aggregation network cost in the TCO calculation (an aggregation cost model and values have been provided in the project [20]). It has been observed that the savings on node consolidation depend on the architecture as well as on the area. Node consolidation is strongly encouraged in rural areas, where the aggregation savings are significant. Note that additional savings associated with node-consolidation, beyond what is presented here, are expected (e.g. property value of evacuated central offices).

4.3.4 Sensitivity Analysis

A sensitivity analysis was performed to render a more detailed view on the sensitivity of the results to assumptions on the main influencing aspects in the context of the network. It was found out that a higher fan-out will, for all architectures, lead to a lower cost per home passed and to a lower overall cost. Cost reductions up to 30% and more are achievable by increasing the fan-out substantially (e.g. by a factor of 8). It should be noted that the higher fan-out cases might conflict with the consolidation possibilities – as a higher fan-out will reduce the reach – and maximum dedicated bandwidth – as with a higher fan-out, more customers are sharing the same OLT port. Relaxing the OASE requirements – for instance only in an initial phase – could as such reduce the upfront costs substantially. Regional differences could lead to a very

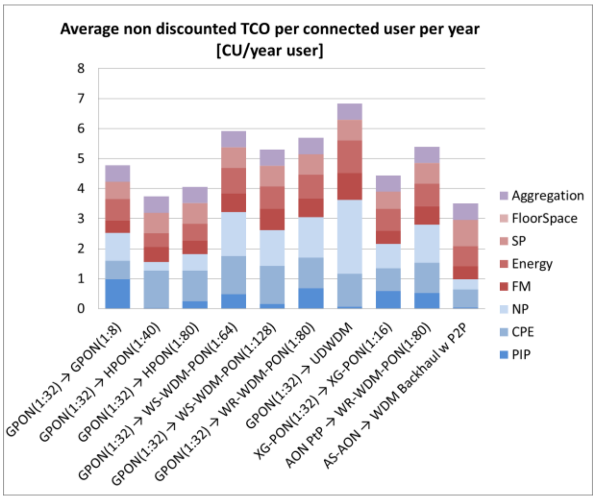


(a) Dense urban area

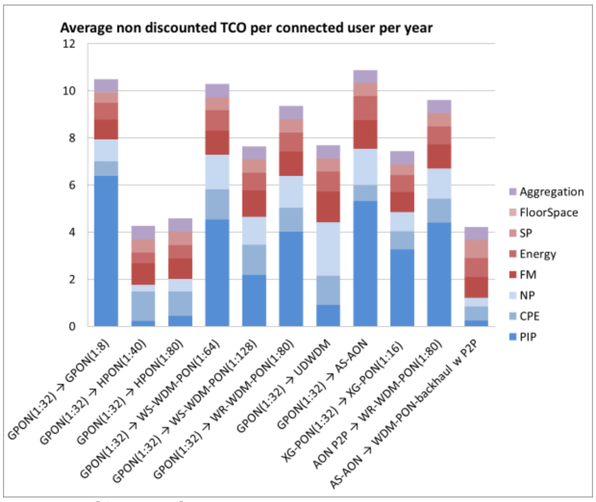


(b) Rural area

Figure 4-9: Average non-discounted TCO per connected user per year in today's deployment e.g. 7500 nodes (no node consolidation [NNC] assumed); above: dense urban rural; below: rural



(a) Dense urban area



(b) Rural area

Figure 4-10: Average non discounted TCO per connected user per year in the aggressive node consolidation (ANC) scenario (1000 nodes) different cost of deployment. Especially in those European countries with lower average salaries, the costs could be much lower. Next to the salary, the adoption is the most important impacting factor and a higher adoption will lead to a lower cost per customer in the end.

Adoption has probably the highest impact of all factors, and has been split into the initial adoption effect (e.g., by means of pre-subscriptions) and the steepness of the adoption curve. Increases in the initial adoption lead to the most substantial decrease in the cost per subscription year. The effect of having a faster adoption continues to be very important.

4.3.5 Concluding Remarks

The main findings regarding migration are summarized in Figure 4-11 (assuming required sustainable bandwidth is less than 500Mb/s/user). For further results from the techno-economic analysis, please refer to [20], [21], [22], [23].

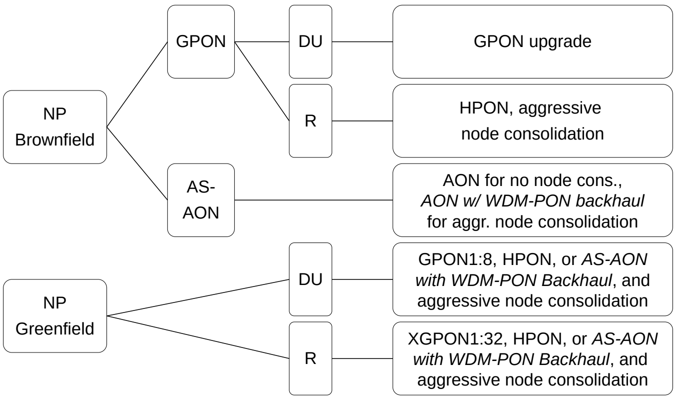


Figure 4-11: Main NGOA migration paths

4.4 Business Case Assessment of the OASE Solutions

As outlined in Section 2.2, NGOA business roles are typically split into three conceptual levels: PIP, NP, and SP, due to the technical and economic nature of the different parts of the network. In the following, the assessment of the business case for each role is presented summarily, with reference to specific studies for further detail.

4.4.1 Feasibility of the PIP Case

Based on an analysis of costs (model from Section 4.3) versus benefits (average monthly revenue of €10 per residential PIP connection, based on several realistic cases [22]–[28]), the business case for the PIP only proves viable in a dense urban area with aggressive adoption. The case can however be improved by a number of factors, which may help explain the fact that several deployments have been made in an economically sustainable way [19], [4]: (i) demand aggregation [29], i.e., pre-subscription of interested customers to the FTTH offer, leading to an assured substantial revenue stream for the PIP from the start of the project, therefore heavily reducing the investment risk, (ii) duct reuse, drastically reducing costs (iii) fibre lease outside the broadband access e.g., mobile backhauling, point-to-point connections for large businesses, banks and public institutions, transport for operators, leading to additional revenues (which can be significant, as Stokab reported they can add up to 50% of their total revenue [30]) and (iv) longer payback term [31], as also considered for other network infrastructures such as electricity or water, roads or railways. E.g. in e.g. [32], it is calculated that for the considered reference scenario, the business case of the PIP in an urban area only becomes feasible if the payback term is increased from 20 years to 40 years.

For some areas, even with the measures suggested above, green-field fibre deployment may remain economically infeasible. In those cases, government funding might be the way out. Such intervention would be justified by positive externalities (indirect or cross-sectorial effects accruing outside the broadband access value chain, but which are of significance for the economy and society as a large [33], [34]), which can be expected from a fibre deployment.

4.4.2 Providing an Open Infrastructure

Based on a qualitative analysis of the interactions between the different players in the value network (incumbent and alternative operators, municipalities, utilities, vendors, etc. [35]), fibre infrastructure deployed by a municipal infrastructure provider was shown to be the most promising. This can be explained both by the possible cost reduction (joint roll-out with other utilities, efficient coordination) and the relevant indirect effects (e.g. benefits for society that are typically directly valued by a municipality, such as increased attractiveness of the region).

A game theoretic analysis [36] allowed us to compare open and closed municipal infrastructures, from the viewpoint of all actors involved (municipal PIP, telcos and other NPs) [37]. Under competition, it was shown that it is always more interesting to deploy the open access network and that existing players will choose to migrate to the network. The extra revenues due to the increased uptake on the fibre network clearly offset the upfront and provisioning cost for the open network.

4.4.3 Feasibility of the NP Case

Our analysis showed that NPs can work cost-efficiently on top of an open infrastructure [4]. However, in-building deployment and CPE are significant cost factors that need to be addressed (entirely accounted for by the NP, as we assume the PIP terminates in the building basement). If this dominant in-building cost could be shifted to another player (house owner or partially tenant[1]), the business is positive for all scenarios (areas and adoption curves). Observing the case studies, we see that there is a limited set of NPs offering network connectivity in a certain area. Depending on the situation, either one NP wins the tender and offers exclusive

[1] Some examples exist of business cases in which property owners and tenants agree to a rent increase when in-building networks are installed (e.g., the infrastructure is viewed as an upgrade of the building, in the same way as a new elevator or a facade renovation would be **Error! Reference source not found.**)

connectivity for a predetermined period of time; or there's a free choice between different NPs offering connectivity to everyone. In any case, each end-user would be connected to only one NP at any one point in time.

4.4.4 Open Access from a Business Perspective

As indicated above, open access leads to important advantages: (i) infrastructure sharing which is the basis of open access solutions, considerably reduces investment costs; (ii) open access enables competition between service providers, which is expected to lead to lower prices and more choice for end users.

However, the presence of different actors at different layers also induces some additional costs. We have modelled the open access interfaces and calculated the costs in terms of extra equipment, as well as management, process and business interfaces. The combination of these equipment related costs, together with the management and process related costs form the production costs for the open offer, the business related costs are the so-called transaction costs [38]. Overall, additional costs induced by the cooperation between actors in an open access scenario can amount to up to 20% of the yearly PIP revenues, and will as such affect the profitability of this player [4].

From the perspective of transaction-cost reduction, there is a clear potential gain in promoting standardization, both at technical and business levels. There should be a coordinating rule set in place. This agreement should include all relevant technical (incl. e.g., resource allocation) processes, as well as business aspects / interfaces required for providing services to the customers. The rule set should be monitored and coordinated by an independent party; it should definitely not lie with one of several NPs offering service in the same area. The coordinating party can be the PIP or another independent (public) entity.

4.4.5 Summary of Business Insights

Based on the three conceptual levels identified (PIP, NP, SP), we have evaluated the business cases of the PIP and the NP. In several real deployments, the business case for the PIP is viable, because of demand aggregation, duct reuse, the availability of additional revenues and by considering longer payback terms. The business case for the NP is positive if the dominant in-building cost can be shifted away. An open infrastructure will be an enabler for competition; however, the additional costs related to this opening are to be considered carefully. For further details, please refer to [39].

5. CONCLUSIONS AND RECOMMENDATIONS

Based on the technical, architectural and techno-economic studies, as well as the assessment under business related aspects, the following conclusions with respect to the considered NGOA system concepts can now be drawn.

5.1 NGOA System Recommendation

Due to a pure technical or even architectural assessment of the different proposed NGOA concepts, it is not possible to single out a main system contender for NGOA. Even introducing operational aspects like power consumption, floor space or analysing the technical impact of system failures doesn't result in a clear favourite. The technology and architectural driven analysis has clearly shown that almost every initial requirement can be fulfilled, if additional components like reach extenders, more fibres, or improved technical functionalities such as superior receiver sensitivities, or additional wavelength bands can be embraced in the technical system evolutions. Also the studies of open access at the wavelength level reveal that this can be achieved with almost every WDM concept considered, if additional components or fibres are introduced. However, all of these technological enhancements are associated with an additional system cost, as will be shown in this summary.

From a pure technology perspective, the maturity level of the different technologies and associated system concepts was also addressed to establish a technology roadmap from we which we come to a conclusion which is somewhat in line with the current focus of the FSAN (Full Service Access Network): a so called TWDM approach which is a hybrid WDM/TDM-PON approach with a limited number of wavelengths of between four to ten channels.

Specifically, based on the final techno-economic analysis of the different NGOA concepts with the key assumption of a high guaranteed bandwidth during the busy hour of 300 Mb/s we conclude the following.

For a **brownfield** starting from a G-PON or AON P2P deployment, in a no-node consolidation scenario still G-PON/XG-PON or AON P2P is the preferred low-cost solution, depending on the start scenario for the infrastructure:

- if one starts with a P2MP infrastructure then G-PON or XG-PON will be the cost optimum
- if one starts with a P2P infrastructure then AON P2P gives the lowest costs, however, there is an additional initial investment for a AON P2P infrastructure in contrast to a P2MP.
- This holds independent of the area type, e.g. dense urban, urban or rural.
- UDWDM is always the most cost intense variant to migrate to, due to the high ONU cost.
- Hybrid WDM/TDM-PON is the lowest cost NGOA option, using WDM-only as another scalability layer
- WR- and WS-WDM-PON are in-between with respect to overall cost.

For a **brownfield** scenario starting from a G-PON or AON P2P deployment, with a node consolidation scenario goal, we can observe that:

- AON-P2P has high cost in node consolidation, and needs to be migrated to an AON-AS solution, where a first aggregation switch is at the cabinet level or in one of today's local exchanges.
- Migration towards WDM concepts using WDM as the access technology shows the highest cost in all considered areas.
- XG-PON shows lowest cost in dense urban areas followed by a hybrid WDM/TDM-PON for migration

from G-PON due to reduced splitting for a high guaranteed data-rate.

- In rural areas, due to the longer reach the active RN concepts (WDM backhaul) also enable a low cost AON-AS concept at similar cost like the migration of G-PON towards a hybrid WDM/TDM-PON; XG-PON is not the preferred choice in long reach (rural areas) due to increased infrastructure costs due to low sharing compared to hybrid WDM/TDM-PON and WDM-backhaul concepts.
- Overall cost savings for hybrid WDM/TDM-PON and WDM backhaul are mainly due to cost savings in the aggregation network due to improved utilization of resources and lower cost per bit due to faster utilization of higher bit rate interfaces offering lower cost per bit.

For a **greenfield** with G-PON or AON-P2P deployment, in a node consolidation scenario

- AON P2P has very high initial infrastructure cost, therefore a P2MP infrastructure is the preferred choice
- For moderate data-rates (< 300 Mb/s) pure G-PON or XG-PON with reduced splitting is the preferred choice
- Hybrid WDM/TDM-PON concepts show the lowest infrastructure costs for a high guaranteed data rate

From this cost study it can be seen that, for sustained bit rates up to 500 Mb/s, the NGOA concepts based on dedicated-wavelength customer access (e.g. UDWDM, WR- or WS-WDM) are outperformed by the shared-wavelength approaches (such as G-PON, XG-PON or AON AS), with WDM backhaul allowing for higher aggregation. For G-PON and XG-PON the sharing takes place in the access infrastructure itself due to the TDM mechanism; in AON-AS the sharing takes place in the switch located in the field. Therefore, in the context of the residential mass market, WDM from an economic point of view makes only sense as an additional overlay layer such as in the hybrid WDM/TDM-PON concepts, or WDM-backhaul concepts where WDM is purely used for increasing the scalability but not for addressing the residential customer. This conclusion is in good agreement with the focus of FSAN on hybrid WDM/TDM-PON concepts, specifically TWDM. In general it has been shown that node consolidation enables cost savings that mainly occur in the aggregation network due to better equipment utilisation.

From the investigated business concepts, on the other hand, increased operational complexity and additional requirements for coordination are unfavourable. Especially, from an open access perspective, WDM approaches with unbundling on wavelength level are more difficult in terms of business implementation, than as compared with open access at the fibre level or bit stream access.

5.2 Strategic and Policy Related Recommendations

Based on our findings concerning the economic viability for the different actors involved in an NGOA deployment, we have formulated some recommendations for policy makers.

- From an open access point of view the preferred way of opening up a fibre-based access network remains either at the passive layer (fibre lease), or bit-stream open access, as basically used today. Infrastructure-based competition (i.e. parallel fibre networks, one for each competitor) is very cost inefficient, and is difficult to implement in a smooth and effective way at the end user’s premises. Although in principle very interesting, open access at the wavelength layer (WDM) as an access technology for residential customers (e.g. a single wavelength per customer) results in significant additional system costs, further burdening the business case for any Network Provider. More importantly, it is not obvious who would take care of the WDM splitters and the wavelength management: currently PIPs are reluctant to deal with that, while coordination between competing NPs introduces increased complexity and cost.
- The business case for the PIP remains challenging, even when using measures such as demand aggregation and duct reuse. However, significant extra revenue can be generated by offering wholesale dark fibre lease to non-telecom actors. We observed in some cases studied that this can be up to 50% of total revenue, hence turning the business case from negative to viable. Moreover, a lot of indirect or cross-sectorial effects can be expected from a fibre deployment. This could be an additional stimulus for national, regional or municipal governments to support investment. In this way public support (in the form of state-aid or other) may be desirable.
- In order for the above point to hold, the construction of passive infrastructure must be shared on an equal and non-discriminatory basis. If the PIP is required to share the passive infrastructure, or the PIP is the only part of the value chain taken over by a single player, the deployed infrastructure should be technology agnostic; meaning that fibre consolidation should take place at flexibility points where fibres can be connected, and in which both active and passive equipment can be placed. This is important to maximise the potential wholesale customer base for a PIP (some NPs may run a PON, some an AON, some hybrids thereof, and the passive infrastructure should be built so that all solutions are supported.) In consequence, higher costs have to be recouped as well, e.g. in the case of the cabinet flexibility point, calculations have shown that significant additional costs are incurred and all involved parties need to share these in a fair manner.
- Public financial support should be focused on the PIP layer. Deployment of the physical infrastructure is mainly CAPEX driven, in which case support may be granted in terms of long-term loans, or over long depreciation periods, in order to increase the investment horizon.
- For the NP, in-house deployment and CPE are significant cost factors. Business models that allow the allocation of these costs to house- or home-owners should receive

greater attention. However, public financial support to the NP is unadvisable in the long term.

In summary, this document gives an overview of the potential NGOA solutions examined in the OASE project, enabling optical access network technologies, architecture principles and related economics, while taking CAPEX and OPEX into account. Key principles of the studies within OASE have included future network evolution towards node consolidation in the access network and understanding the impact of new business models on network architectures.

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