D2.2.2 Consolidated requirements for European next-generation optical access networks

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Short Abstract:
This document is part of the ICT – 2009.1.1 [The Network of the Future] program‘s OASE (Optical Access Seamless Evolution) project, as deliverable D2.2.2 (Consolidated requirements for European next-generation optical access networks). It is intended to describe the final review results of the requirements towards a European Next Generation Optical Access Network (NG-OA) as described in D2.1 Requirements for European next-generation optical access networks and the interims Deliverable D.2.2.1, based on the inputs and discussions derived from the collaborative work of the partners.

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Executive summary

This document provides an overview of the consolidated requirements for Next Generation Optical Access (NGOA) networks derived from the review process and based on the results obtained in project. A comparison of the consolidated requirements with the architecture capabilities and an overview of major cost driving requirements are provided as well.

Other related sources have been used to review the requirements to ensure wide acceptance. These sources include the results of the Industry board meetings of OASE, related FP7 projects, and the Full Service Access Network Initiative (FSAN) which defines NG-PON2.

According to the quantitative OASE results most of the consolidated requirements can be achieved, but a few of the requirements will not be met by some of the concepts. There are issues with the following requirements for some concepts: network availability revised from ~~99.99%~~ to 99.98% for mass-market, delay in mobile backhaul in case of dynamic resource allocation and network migration coexistence with ODN and spectrum. However, there are no knock-out criteria that exclude any concept from the technical point of view because all technical constraints could be overcome with additional measures and money. Results from the economic evaluation and from the business analyses are therefore of major importance for the refinement of the requirements.

From the business perspective, multiple network providers in an area must be supported, taking into account open-access-enabling interoperability via standardized interfaces, isolation functions and dynamic allocation of resources depending on Market share. There should also be a coordinating rule set in place.

From the economical perspective some key results are summarised as following:

- 500 Mb/s per user has significant impact on aggregation network and OLT switch cost and in the TDM PON variants also on feeder and ODN dimensioning cost
- The higher the fan-out, the lower the TCO is valid within same architecture. The range 256–1024 users on a single feeder fibre can be confirmed for the NGOA architectures.
- Passive long reach 20-40 km (working path) will be fulfilled by all architectures, except of AON. The 60-90 km extended reach option can in most cases not be realised purely passive and additional cost for reach extenders arise.
- WR-WDM PON and NG AON could not reuse a power splitter based ODN (also a seamless migration on a PtP based ODN, i.e. no user-wise switchover, is not possible).
- An availability of ≥99.98% for mass-market can be achieved without additional costly protection in the ODN, in contrast to the original requirement of ≥99.99%.
- Zero touch provisioning requires high upfront cost for full network deployment.
- Most failures are caused by faulty ONTs. To avoid costly personnel effort at customer premises, an IT-supported remote diagnosis and measurement solution is required.

The NGOA requirements specified in OASE are essentially in-line with the key requirements for the NG-PON2 concepts defined in FSAN and with feedback received form the Industry board meetings. The related FP7 projects have different targets, but in general, they are also quite well aligned with the OASE requirements. The technical focus of these projects is, in most cases, complementary to OASE, and can deliver interesting input on OFDMA-PON (ACCORDANCE), higher network layers (SPARC), core network aspects (STRONGEST), as well as on low-cost system design (GigaWaM). The ALPHA and SARDANA projects are most in line with the OASE project, and in general their requirements are very similar.

Referred documents

[1] OASE Deliverable D2.1, "Requirements for European next-generation optical access networks", September 2010
[2] OASE Deliverable D2.2.1, "Review of requirements for European next-generation optical access networks", January 2012
[3] OASE Deliverable D4.2.2, "Technical Assessment and Comparison of Next-Generation Optical Access System Concepts", March 2010
[4] OASE Deliverable D4.3.2, "Operational impact on system concepts", March 2012
[5] OASE Deliverable D4.4.1, "Implementation and integration into new system concepts", September 2012
[6] OASE Deliverable D3.2.2, "Description and Assessment of architecture options", October 2012
[7] OASE Deliverable D3.3, "Co-operation models", November 2012
[8] OASE Deliverable D3.4, "Migration paths", December 2012
[9] OASE Deliverable D6.2, "Market demands and revenues", October 2011
[10] OASE Deliverable D6.3, "Value network evaluation ", December 2012
[11] ALPHA Deliverable D1.3p, "White Paper: Roadmap for access and in-building network solutions", May 2011
[12] Josep Prat, "Final practical results of the SARDANA project", presentation at OASE open event "Next generation optical access technologies, from an FP7 research perspective", FTTH Conference 2011, Milano, Italy, February 2011
[13] ACCORDANCE Deliverable D2.2, "Final report on network architecture and elements' requirements", April 2011
[14] Christian Mikkelsen, "GigaWaM – a Cost-Effective WDM-PON System", presentation at OASE open event "Next generation optical access technologies, from an FP7 research perspective", FTTH Conference 2011, Milano, Italy, February 2011
[15] STRONGEST Deliverable D2.1, "Efficient and optimized network architecture: Requirements and reference scenarios", September 2010
[16] SPARC Deliverable D2.1, "Initial definition of use cases and carrier requirements", November 2010
[17] IEEE Network, Philippe Chanclou, Anna Cui, Frank Geilhardt, Hirotaka Nakamura and Derek Nesset, "Network Operator Requirements for the Next Generation of Optical Access Networks", March/April 2012

List of tables and figures

Abbreviations

AAA	Authentication, Authorization and Accounting
ARQ	Automatic Repeat Request
BBU	Baseband Unit
BER	Bit Error Rate
BS	Base Station
BSA	Bit-stream Access
CAN	Consolidated Access Node
CDN	Content Delivery Network
CoMP	Coordinated Multi-Point
CP	Central Processor
CPE	Customer Premises Equipment
C-Plane	Control Plane
CPRI	Common Public Radio Interface
DL	Downlink
eNB	enhanced NodeB (LTE Radio Base Station)
E-UTRA	Enhanced UMTS Radio Access (=LTE RAN)
FEC	Forward Error Correction
FF	Feeder Fibre
FTTA	Fibre to the Antenna
FTTC	Fibre to the Cabinet
FTTH	Fibre to the Home
FTTx	Fibre to the x
GBR	Guaranteed Bit Rate
HARQ	Hybrid Automatic Repeat Request
ICI	Inter-Cell Interference
IMT	International Mobile Telecommunications
IMT-A	IMT Advanced
IQ	In-Phase and Quadrature
KPI	Key Performance Indicator
LLU	Local Loop Unbundling
LTE	Long-Term Evolution
LTE-A	LTE Advanced
M2M	Machine-to-Machine
MDU	Multi-Dwelling Unit
M-Plane	Management Plane
NGOA	Next Generation Open Access
NP	Network Provider
NT	Network Termination
OAM	Operation, Administration, Maintenance
OAN	Optical Access Network
ODN	Optical Distribution Network
OFDM	Orthogonal Frequency Division Multiplexing
OLT	Optical Line Termination
ORI	Open Radio equipment Interface
PIP	Physical Infrastructure Provider
PLR	Packet Loss Ratio

PPM	Part Per Million
PS-PON	Power Splitting PON
PTP	Precision Time Protocol
QCI	Quality Class Identifiers
QoS	Quality of Service
RAN	Radio Access Network
RE	Radio Equipment
REC	Radio Equipment Control
RF	Radio Frequency
RoF	Radio over Fibre
RRU	Remote Radio Unit
RTT	Round Trip Time
S1	Interface between radio base stations and core network in LTE
SAE	System Architecture Evolution (LTE)
SFU	Single Family Unit
SMP	Significant Market Power
SP	Service Provider
SW	Software
TCO	Total Cost of Ownership
TMA	Tower Mounted Amplifiers
TTI	Transmission Time Interval
UE	User Equipment
UL	Uplink
U-Plane	User Plane
VoD	Video on Demand
WP	Work package
X2	Interface between LTE radio base stations

1. Introduction

Based on the requirements and their backgrounds which were provided in OASE Deliverable D2.1 [1] and the requirements review provided in the intermediate Deliverable D2.2.1 [2], the information presented in ***Table 1*** below summarizes the key requirements consolidated during the course of third OASE project year in 2012 and which need to be taken into account for system and architecture design.

The review addresses the categories “service and network requirements” as well as “business and operation” requirements. They cover, for example, network architecture and system design, network topology, geographical distribution and coverage of customers, future traffic growth, service penetration evolution, and open access solutions amongst others.

In addition, an economic evaluation of the NGOA requirements has been performed and the impact of the major cost driving requirements were analysed and considered for the refinement of the requirements.

Furthermore, related sources have been used to review the requirements in order to ensure a wide acceptance to enable a cost efficient design. These sources are: the results of the Industry board meetings of OASE, related FP7 projects and the Full Service Access Network Initiative (FSAN) which defines the NG-PON2 standard.

The summary chapter compares the consolidated requirements for European next-generation optical access networks with the capabilities of the investigated architectures, given in a fulfilment matrix, and puts the OASE requirements in the context of FSAN, FP7 related projects as well as feedback received form the Industry board meetings.

Table 1 Consolidated OASE requirements on a NGOA network

Category	**Summary of requirements on the NGOA network**
	Service
End-user	• FTTH Residential: – Full service access – High quality, accessibility and retain-ability – Low up- and download times – Plug & Play installation and configuration – Data security and data integrity – Portability of identification data (Nomadism services) – Single-sign-on • Business: – Similar to Residential but often with higher requirements on: • Data security and data integrity • Availability (resilience) • Data correctness – Special troubleshooting requirements (e.g. 4 hour service for fault recovery)
Backhaul	• Fixed backhaul: – Like residential, services with highest requirements define backhaul link parameter

	• Mobile backhaul/RAN transport: – Very Low delay and Jitter (see Quality), Synchronization – High availability
Quality	• At least 4 QoS classes, as highest requirements the following parameter have to be meet: – Availability mass-market: revised to ≥99.98% one-way (equates to 99.96% E2E resp. round-trip) – Availability special business users or backhaul: ≥99.99% one-way (equates to 99.98% E2E resp. round-trip) – Delay: <1ms, Jitter: <<1ms, mainly imposed by special mobile use cases → separate handling of mobile quality in the network – BER: < 1,00E-07; Packet loss rate: < 1,00E-05
Bandwidth	• FTTH residential peak data rates ≥1 Gbit/s • Business, backhaul (fixed, mobile) peak rate: ≥10 Gbit/s
Network	
Architecture	• Legacy ODN compatibility: – Passive, not wavelength selective, single fibre • High system- and infrastructure-sharing: 256 – 1024 users on a single feeder fibre • Migration coexistence with existing ODN infrastructure and spectrum (seamless and without affecting the deployed system) • Support of 10G interfaces for business and mobile backhaul demands • Support of E2E protection for special business users as well as feeder fibre and OLT protection for mass-market for service availability • Multi-stage splitter architectures in PON architectures • Common access and aggregation for residential, business, fixed and Mobile backhaul/RAN transport • Efficient content distribution (Multicast, optimised CDN structure …) • Support of IPv6 • Resource control and management • Security better than XG-PON1
Topology	• Long reach transmission: • Support of 20 to 40 km passive reach option for the working path, depending on degree of node consolidation • Support of 60 to 90 km extended reach option for the protection path, depending on degree of node consolidation • Extended reach should be realized passively (preferred solution)
Dimensioning	**Sustainable Bandwidth based on Traffic forecast model:** • Average sustainable downstream (based on service usage during peak hour) of 500 Mbit/s per Optical Network Units (ONU -s)/customers • Support for traffic symmetry, at least a ratio of 1:2 between upstream and downstream for mass-market and 1:1 symmetry of 10G

	connections e.g. for special business and mobile backhaul demands • Support for 128 – 500 Gbit/s aggregate capacity per feeder fibre
Business & Operations	
Network operations	**General requirements on operation** • Support functions and systems for operations, administrations and maintenance (OAM) • Process automation to minimize manual switching and increase process efficiency • Next generation Naming and Numbering addressing schemas • Standardized Systems • High availability • Low power consumption **Provisioning** • Technology neutral e-t-e provisioning of All-IP service portfolio (zero touch after initial roll-out) • Do-it-yourself installation capable NTs • Customer NT should be not customer specific (means e.g. "colourless") • Portability of customer identification data, e.g. for location moves (nomadic) or provider changes • Web-based customer self-provisioning and self-configuration **Maintenance** • Easy, fast and efficient maintainability and restorability • Remote management of all active network elements • Seamless SW upgrade without service interruption • End-to-End service/traffic performance monitoring per customer and service (supervision) • Remote auto-configuration and management of customer equipment by the operator **Fault management** • Low failure penetration ranges, ≤ 1000 User • Resiliency incl. automatic re-connections through redundant network concepts • IT-supported optical diagnosis and measurement solutions up to the home for fault prevention , detection and localization **Hardware and facilities** • Scalable and upgradable network elements capable of handling new service req. and demands • Support for modular hardware and pluggable optical modules (for NT

	only if economical viable) • Small size systems and optical components (esp. OLT, ODF), retaining operation ability • Reduced power consumption, "Green IT", and optimized climate concept (e.g. support of a "full power" mode and a "sleep" mode) • Different customer NT for residential, business and mobile/wire-line backhaul (Universal NT has to be analysed) • Support for the TL9000 Quality Management System
Co-operation / Open access	• Support of co-operation network interconnection and open-access-enabling interoperability across different carrier networks. • Functions to be supported and provided via a "Co-operation" interface: Connectivity & Forwarding, QoS, Multicast, Security, AAA & Auto-configuration, CPE control, Management & OAM • Multiple NPs can have access to any customers, limited to one NP to one customer at one point in time (limited set of NP in an area) • Inter NP isolation. It is desired to isolate misbehaving network equipment (e.g. rogue ONT) in case of failure. • There should be a coordinating rule set in place. This agreement should include all relevant technical (incl. e.g. resource allocation), process related as well as business aspects. The PIP should remain technology agnostic. • Dynamicity of Market share should be supported by technology, allowing dynamic allocation of resources, transparent to all providers.
Regulation	• Regulation decisions have to be fulfilled • Regulation is focused on the actors and their market position. Remedies can include: – price control, including cost orientation – limiting wholesale pricing to the cost of maintaining the access network – transparency – the basis of wholesale pricing must be made public – accounting separation – non-discrimination – wholesale prices must not be dependent on purchase volume – mandatory access to specific facilities – typically access to the central office – mandatory provision of specific facilities – e.g. power in the central office

2. Review of requirements based on the project results

2.1 System Design

Some of the NGOA requirements presented in OASE Deliverable D2.1 [1] are directly related to the system design. This includes various requirements belonging to categories such as Bandwidth, Architecture, Topology, Dimensioning, Network Operations, and Co-operation found in ***Table 1***. Among these, some of the more fundamental requirements for the system design concern bandwidth, reach and client count per feeder fibre.

An assessment of NGOA alternatives was performed in WP4 [3] [4], and it was found that the main constraint comes from the ODN requirements (legacy ODN compatibility, e.g. multi-stage splitter architectures). If these requirements are relaxed, all the technical requirements could be fulfilled by the system designs. The WR-WDM-PON, the hybrid WDM/TDM PON and the UDWDM PON concepts provide alternatives that comply with the high fan-out requirement (256 – 1024). Power splitter based ODN is supported by the hybrid WDM/TDM PON, the WS-WDM PON and the UDWDM PON. Several of the more attractive system design variants (measured by system cost) do not fulfil all the requirements simultaneously. It is therefore important to consider the origin and priority of each of the requirements when evaluating the system design. Some of the technical requirements, such bandwidth, were proposed based on modelling of future traffic demand and should be considered hard requirements. Other requirements, such as reach and client count per feeder fibre are rooted in the concept of node consolidation and the idea of associated cost reduction. For some of these latter requirements, which are guiding the project towards a low total cost of ownership (TCO) solution, a detailed techno-economical study has been performed in WP5 to identify the main cost driving requirements. For optimisation, the parameter ranges of the cost driving requirements were varied in a sensitivity study, where lowest TCO is the overarching requirement. With this in mind several of the system designs presented in WP4 [3] only partially fulfil the initial NGOA requirements presented in D2.1 [1].

The particular requirements related to fixed and mobile backhaul were addressed in D4.4.1 [5]. Note that several low cost system concepts are designed for the residential peak rate of >1 Gbit/s and fulfilment of business or backhaul (fixed, mobile) peak rate (≥10 Gbit/s) requires additional effort. Due to bandwidth and latency requirements, backhaul needs to be provided by dedicated PtP links or wavelengths in PON based architectures. In any NGOA architecture, backhaul could, with effort, be provided by means of dedicated 10Gb/s PtP links. However, this requires that the necessary fibre infrastructure be made available, as well as dedicated 10G backhaul interfaces and associated fibre patching, at the access node. Alternatively, different system concepts support (or could be made to support) the backhaul requirements. It was found that for the different system concepts a limited number of backhaul clients per system can be supported with limited effort. For larger number of clients limitations are due to either manual patching effort or bandwidth constraints. Hybrid WDM/TDM PON supports 10G natively, but can only support a limited number of backhaul clients. The WDM and NG-AON solutions require additional effort through manual patching of 10G overlay wavelengths or PtP links, or alternatively additional cost through use of multi-rate transceivers supporting 10G.

2.2 ARCHITECTURE DESIGN

In WP3, an evaluation of the OASE next-generation optical access (NGOA) architecture options was carried out in respect to several criteria (for example the impact of aggregation network, energy consumption, resilience, operational aspects, control and management, resource allocation, migration, and open access). The results of the assessment are presented in deliverable D3.2.2 [6]. For open access and migration, additional results will be included in the deliverables D3.3 [7] and D3.4 [8], respectively.

According to the results obtained within WP3, most of the requirements defined in the OASE Deliverable D2.1 [1] are feasible for OASE NGOA architectures. The exceptions are indicated below.

- Quality requirements:
  - Availability (one-way) revised from ~~> 99.99%~~ to 99.98% for mass-market

In the assessment performed in WP3, protection down to the node in today's CO (i.e. PCP5) has been considered, as it could efficiently reduce the risk that a large number of end users are affected by any single failure which occurs in the access network. However, with this type of protection, the connection availability for different NGOA architectures varies between 99.978% and 99.991% one-way (which equates to 99.98% E2E resp. round-trip). WDM PON can reach 4 nines connection availability only in a dense urban area, while it hardly satisfies this requirement for urban and rural cases. All other OASE NGOA architecture options (i.e. hybrid WDM/TDM PON, two-stage WDM PON and NG AON) cannot achieve 99.99% availability by applying protection to the node in today's CO in any deployment scenario. For residential users, the requirement of availability higher than 4 nines must be reconsidered and needs to be adjusted. However, for some business customers or mobile backhauling, protection down to the end user could improve connection availability to 4 nines and beyond.

  - For backhaul, delay < 1ms and jitter << 1ms

Delay and jitter performance for the different architectures was evaluated in WP3 by a simple node-link model assuming that latency consists of four components: propagation delay, processing delay, transmission delay and queuing delay. Disregarding any dynamic resource allocation and assuming backhaul traffic is prioritized, all architectures support a round trip delay of <1ms and jitter of <<1ms for reaches of up to 95 km in node consolidation or for backup paths. The use of dynamic resource allocation within a concept will, however, seriously constrict fulfilment of the backhaul delay and jitter requirements. Hence, for clients with the most stringent backhaul requirements, backhaul should be based on static resource allocation and preferably utilise dedicated PtP links or wavelengths.

- Architecture requirements: Migration (co-existence requirements)
  - NGOA system has to work on the existing ODN infrastructure (single fibre solution)
  - NGOA system does not affect the deployed system and the existing spectrum

The WP3 assessment on migration aspects has shown that three out of the NGOA architecture options (i.e. WR-WDM PON, NG AON, and two-stage WR-WDM PON) could not reuse a power splitter based ODN infrastructure and would also not allow a seamless migration (i.e. no user-wise switchover) on a PtP based ODN infrastructures. A migration towards these solutions starting, for example, from a GPON architecture would result in an extra cost to upgrade the infrastructure. For Greenfield scenarios this has no relevance.

2.3 TECHNO-ECONOMICS

The objective of WP5 is to validate the requirements defined in WP2 from the economic point of view. WP5 investigates the impact of cost-driving requirements on the total cost based on sensitivity studies, to give guidelines for overall TCO reduction. WP5 does not impose or revise requirements from a technical perspective. ***Table 2*** gives an overview of major cost-driving requirements and the influenced costs.

Table 2 Cost driving requirements on NGOA networks

Cost-driving requirement*	influenced Cost driver
Zero touch provision	• Upfront deployment of the whole ODN infrastructure • In-house network preparation
Extended Reach option 60-90 km Passive preferred (alternative: Reach extender)	• (e.g. for backup path) • Passive preferred • Alternative: Reach extender
Traffic per user (500 Mb sustainable)	• Aggregation dimensioning • OLT switch capacity • HPON: power split reduction to 1:20
10G support, 1:1 symmetry for some business users or mobile backhaul	• HPON: supports 10G natively • (x)WDM PONs: additional 10G upgrade (e.g. 10G overlay wavelengths or alternative use of multi-rate transceivers)
Migration support and ODN coexistence	• New provision of existing customers and replacement of "old" ONTs • Without ODN coexistence: Additional ODN infrastructure upgrade
High availability 99.98% one-way **Low failure penetration range (FPR)** ≤ 1000 Users affected per single failure	• Protection OLT, Feeder fibre and aggregation • E2E protection e.g. for some business users or mobile backhaul, considering the ODN part

* Note: The requirement "high fan-out" is not listed, because it is not cost-driving rather than cost-saving.

Network requirements validation

Traffic evolution:

A variation of the average sustainable bandwidth during peak hour of the WP2 traffic forecast model within the traffic corridor between **150 – 500 Mbit/s per customer** has less impact on the access and feeder dimensioning but high impact on dimensioning of the OLT switch capacity and aggregation network. Especially the TDM based PON reference architectures but also the HPON in case of 500 Mb per customer require an additional reduction of the power split ratio and thus an upgrade of the feeder cable infrastructure. The aggregate capacity between **128 – 500 Gbit/s per feeder fibre** will only be reached by architectures as the HPON with a high fan-out of about 1000 users per feeder fibre.

Fan-out:

The benefits of high system and infrastructure sharing between **256 – 1024 users on a single feeder fibre** have been investigated. The results confirm that the TCO will become lower with higher fan-out in general, within the same regarded architecture. However, especially the reference architectures GPON and XGPON1 have no higher TCO than the NGOA variants, despite of a much lower fan-out. The results of the HPON show a significant TCO reduction for a fan-out of about 1000 users, whereas a further increase of the fan-out shows no significant further cost savings and would lead to a higher failure penetration range. Also the WDM PON variants show no consistent picture. The main reason is that the requirement is related to the fan-out per feeder fibre, which does not necessarily comply with the required OLT interface demand and OLT slot space occupancy. The UDWDM PON, for example, has the highest fan-out per feeder fibre of all WDM variants but also the highest TCO, because of the aforementioned reason.

Reach:
The requirements on pure passive long reach transmission support of **20 to 40 km** for the working path will be fulfilled by all architectures, except of AON. However, some architectures have constrains, in reaching the upper bound of the range pure passive. The HPON reaches only about 27km in the 40 channel configuration and reduced power split of 1:16. The TDM based PON reference architectures reach the 40km only with long reach interfaces and highly reduced power split ratio of ≤1:8. The requirement on **60 to 90 km extended reach** option for the protection path (depending on degree of node consolidation) can only be achieved in all architectures through the use of active reach extender (i.e. not passive as originally required). There are two exceptions, for the WR-WDM PON, which may reach pure passive the lower bound 60km of the range in the 80 channel & preamp configuration with APD ONTs and for the UDWDM PON, which may reach 60km in the 40 ITU cannel configuration and 1:8 power split ratio.

Migration:
The requirement on general migration support on system and service level can be fulfilled by all architectures, whereas the requirement on ODN coexistence depends on the existing FTTH deployment. The main migration cost driver is the new-provisioning of the existing customers including the replacement of the “old” ONTs. An additional ODN infrastructure upgrade would be required, in cases of non-coexistence with the existing FTTH deployment. The WR-WDM PON and the AON are not coexistent with e.g. an existing GPON deployment. The results from the sensitivity study show that the migration cost mainly depend on the migration start penetration. That means the more customers are connected at the existing platform, the higher are the migration cost.

Resilience:
The requirements on high availability and low failure penetration range impose the necessity for network redundancy and protection mechanisms, especially in node consolidation with the expected higher system compactness and fan-out. To achieve an availability of ≥99.98% (one-way), a protection of feeder fibre and OLT is required in all architectures in addition to the aggregation protection. Some business customers and some mobile base stations may ask for an availability of ≥99.99%, which may require additional costly protection in the ODN infrastructure.

Operation requirements validation

Service provisioning:
The requirement on Zero touch provisioning can only be fulfilled by a full system and infrastructure deployment in the beginning, which causes high upfront cost for e.g. ODN

infrastructure and in-house network preparation. This has been considered for all PON architectures. A gradual system extension by demand has been considered in the AON case, resulting in higher provisioning costs (e.g. for manual fibre patching) but less system up-front investments.

Fault Management:

The requirement on resiliency mechanisms for low failure penetration ranges and high network availability influences the fault management costs in different ways. Network resiliency allows on the one side the bundling of several fault recovery orders, because the customer SLAs are further fulfilled in failure case, but results in on the other side a totally higher number of failed network elements which have to be recovered. Since the network availability and thus also the resiliency mechanisms is a hard requirement, a reduction of costs would have to be achieved by sufficient quality of the network elements (e.g. high MTBF) and by optimisation of the fault management process itself, which has not been studied. The results show also that most of the failures are caused by faulty ONTs, because of the high number. To avoid costly personnel demand at customer premises, an IT-supported remote optical diagnosis and measurement solution up to the home is required for fault prevention, detection and localization.

2.4 Business Analysis

WP6 has complemented the cost studies from WP5 by providing information about revenues [Del. 6.2]. Based on this a full cost-benefit analysis for the different system and architecture designs will be performed [Del. 6.3] The focus of this task lies in the evaluation of the TCO influences to/by different business scenarios and value chain networks, by interaction between WP5 and WP6. WP6 scenarios take into account the actual business model (number of actors in each layer (PIP, NP, SP), demand and uptake (low, average or high uptake or adoption), geographical areas (dense urban, urban or rural area), architectures/technological solutions and node consolidation scenarios.

This work, however, is not expected to effect the technical requirements directly. But requirements on cooperation, for example, will be fulfilled by the technical designs so that the scenarios evaluated in WP6 will be compliant with them. Many of these requirements originally arose from business requirements (such as open access support). The overall results will be reported in Del. 6.3 and 6.4 but some main conclusions can be extracted already and can be also translated into business requirements accordingly. Some of them allow clarification of the requirement on co-operation. In order for a co-operation model to work in practice, the following requirements are important for the network provider.

- *Multiple NP have access to any customers, limited to one NP to one customer at one point in time.* This means that there is a limited set of NPs offering network connectivity in a certain area and that an end-user can freely choose between them. However, they are only connected to a single NP at a certain point in time.
- *Inter NP isolation.* If multiple NPs share the same infrastructure there should be mechanisms in place to detect a rogue ONU (a misbehaving ONU – deliberate or not) and to react by switching it off. It is desirable that misbehaving network equipment should be isolated in cases of failure.
- *There should be a coordinating rule set in place.* This rule needs to be defined and agreed upon by all players within one dedicated area. In general this count for all possible open access scenarios incl. fiber unbundling but is even more relevant for wavelength

unbundling and BSA. This agreement should include all relevant technical (incl. e.g. resource allocation) processes as well as business aspects / interfaces required for providing services to customers. In the best case there is a basic framework already defined by a public authority (e.g. L2 BSA, NGA Forum, Germany). If a coordinating role is required this can be taken on by one player or one independent entity to be agreed on.

- *The PIP should be technology agnostic.* From the perspective of the PIP there is typically the intention to remain *technology agnostic*, which is perfectly in-line with the PIP character being an infrastructure provider. However, in some case this might conflict with some technical requirements.
- *Dynamicity of Market share should be properly supported by technology*. There should be an open operating mode for resource allocation. It should allow a dynamic allocation of resources based on market demands with a to all other providers transparent allocation of resources and control accordingly. For example taking varying market shares into account requires rearrangement of fibre released or band filter to other providers.

Finally, the co-operation requirement might conflict with the implicit requirement of lowest TCO. The Open access model (separated layer) implies higher total costs versus an integrated model, however faster penetration evolution is also to be expected within the open access model (based on different types of services providers and interest of public parties that benefit from indirect effects). The general positive effect on open access networks in the context of FTTH is also the share of risk between the involved parties especially considering the huge upfront investments, as opposed to competing infrastructures. Therefore, careful cost-benefit analysis of open access models is crucial.

2.5 Industry Board meetings

In order to facilitate collaboration with other European operators, mainly with respect to common requirements and needs, an OASE industry board has been established. Currently, the following European network operators are members of this board: British Telecom, Telecom Italia, France Telecom, and Telefónica.

The OASE Industry Board held several meetings in 2010 and one meeting in May 2011, co-located with the FSAN meeting in Berlin, Germany. The main topic of this OASE meeting was the discussion of the requirements reached so far and the impact on fibre access technologies and system concepts which are also currently still studied in FSAN. It was concluded that there is a good agreement between the OASE key requirements, such as 1G per residential customer, longer reach (20-40 km) and higher splitting. Perhaps the most important feedback was that, as is also stated by OASE, the main focus is on overall cost evolution, meaning that even short reach or lower splitting ratios are acceptable if it leads to lower overall cost.

2.6 Related Projects

There exist several projects which are, to some degree, related to OASE. A benchmark of the OASE requirements with these different project's results has been carried out. In this document, we mainly focused on other EC FP7 projects, as it is important to be in line with all these projects. Six important projects are listed in this section, together with their requirements and (targeted) results. Next to the FP7 projects, the OASE project also considered different national projects over Europe.

The requirements and (targeted) results of the following FP7 projects are monitored to benchmark the OASE requirements: ALPHA, SARDANA, ACCORDANCE, GigaWaM, STRONGEST and SPARC.

FP7 ICT-ALPHA

The ALPHA (Architectures for flexible Photonic Home and Access networks) IP project addressed the challenges of building the future access and all types of in-building networks for home and office environments. The project investigated innovative architectural and transmission solutions based on the manifold of optical fibres (single-, multi-mode and plastic) to support both wired and wireless services in a converged network infrastructure.

Requirements for bandwidth, delay, and error tolerance of different service categories were defined in the ALPHA project, and all services were mapped to the following three categories (each with varying bandwidths):

- Low delay but relaxed error tolerance: going from communication and current multimedia @10Mbps to future multimedia @1Gbps
- Low error tolerance but relaxed delay [going from today's Internet surfing @10Mbps to file exchange @1Gbps]
- Low delay and low error tolerance [going from robotics @10Mbps, e-Health @100Mbps, to teleworking @1Gbps].

The impact of evolving residential scenarios on the access networks is dominated by an application, like teleworking, which will become the most demanding as it simultaneously requires large bandwidth, low delay and low error rate.

A roadmap for the access network was defined, with the following trends [11]:

- Now (2011): a plurality of FTTH solutions are available: GPON, EPON, WDMPON, Fast Ethernet, Gigabit Ethernet and others, with physical bit rates not exceeding 1.25 Gb/s for the upstream part and 2.5 Gb/s for the downstream part.
- Short term (1-3 years): the next generation of access networks foreseen is focused on **higher bit rates for the subscriber**, resulting in 10G EPON and XG-PON for the PON systems and 1G/10G AON systems.
- Medium term (3-5 years): the next big step could then be the evolution towards WDM concepts to offer **higher flexibility**, a first level of convergence with an overlay approach like radio over fibre (RoF), and higher bit rates (targeting peak rates at 1 Gb/s).
- Long term (> 5 years): the key question during this timeframe is how to increase the capacity to **ultrahigh bit rates** at the user side (average 1 Gb/s per user) leading to physical bit rates at the TX/RX part > 10 Gb/s, **at low cost and power consumption**.
- Very long term (> 10 years): one target could be a **convergence scenario between the access and the metro** with one unique data protocol and a unified control and management plane to optimise resource allocation. This scenario is particularly interesting because of the possibility of fixed and mobile network convergence.

The ALPHA roadmap is well in line with the OASE requirements for 2020, targeting 1 Gb/s peak, 500 Mbps sustainable, 1000 customers/feeder and 100 km transmission. Especially of note, the bandwidth requirements are very similar. The number of customers and reach is not explicitly mentioned in ALPHA, but the convergence scenario between access and metro definitely corresponds to the node consolidation scenarios within OASE. Typically, the number of customer and reach will depend on the scenario, and it will probably be difficult to target hard requirements for these parameters.

FP7 ICT-SARDANA

The SARDANA (Scalable Advanced Ring-based passive Dense Access Network Architecture) STREP project targeted the performance enhancement of dense Fibre-to-the-Home networks or PONs. They constitute the fundamental segment with the required potential to match the huge capacity of transport networks with the new user communication demands, where deeper research is still to be performed. The key performance indices that this project aims to radically improve are scalability and robustness, since they constitute pillars of such a cost-sensitive segment.

The SARDANA WDM/TDM PON aims at achieving [12]:

- Higher performance than GPON (L, ONUs, BW, resilience)
- At a similar cost (passive PON, reflective ONU, etc.)
- Maximum compatibility with NG-PON

The most important network requirements for SARDANA are [12]:

- Passive external plant
- Single fibre access
- Scalability and upgradeability
- Compatibility with G/EPON MAC
- Robustness:
    - Protection
    - Monitoring and electronic compensation

In SARDANA, the compatibility with legacy systems is an important requirement, which is reflected in the requirements for a passive external plant and compatibility with G/EPON MAC. In OASE, we also keep the migration/coexistence in mind, but keeping the external plant completely passive is not a firm requirement. However, different migration scenarios will be evaluated from a technical and TCO point of view in the last year of the OASE project. Then, it will become clearer if keeping the external plant completely passive should be targeted.

FP7 ICT-ACCORDANCE

The ACCORDANCE (A Converged Copper-Optical-RaDio OFDMA-based Access Network with High Capacity and FlExibility) STREP project investigates a new paradigm for the access network: The introduction of OFDMA (Orthogonal Frequency Division Multiple Access) into a Passive Optical Network (PON) architecture concurrently offering optical backhauling for wireless and copper-based broadband networks.

OFDMA-PON is a new approach to realize the requirements of next generation FTTH networks (one of the candidates for NG-PON2) [13]:

- NG-PON2 should support Long Reach (up to 100 km), high capacity (up to 100 Gb/s shared system bit rate; over 300 Mb/s per user) and high split ratio (more than 1:128), while maintaining low hardware and operation costs to remain attractive and practical.
- Depending on the Tx/Rx implementation, OFDMA PON can realize up to 100 Gb/s and up to 100 km reach (in some cases without the need of using optical amplification

or/and WDM)

The ACCORDANCE project is expected to realize and demonstrate in 2012 the performance of OFDMA for next generation FTTH/FTTA networks used to offer connectivity to business/residential customers and to backhauling of LTE/WiMAX/VDSL originating traffic.

In OASE, the OFDMA-PON architecture is not kept as one of the OASE architectures. As such, it is very interesting to monitor the ACCORDANCE results to judge if the OASE requirements can be met by OFDMA-PON

FP7 ICT-GIGAWAM

The GigaWaM (Giga bit access passive optical network using wavelength division multiplexing) STREP project targets a system-cost-per-subscriber below today's implementation of GPON by developing innovative new low-cost components with high levels of integration in addition to new manufacturing processes. Today, even the cheapest WDM-PON solutions cost 2–3 times as much as GPON. Up to 95% of the cost of optical components is due to packaging. The project aims to develop a system with an integration scale that is around 100 times higher than State of the Art that can be implemented as an upgrade of xPON systems that are currently being installed, and will not require changes or re-routing of optical fibres.

The main target of GigaWaM can be summarized as the design of a cost-effective WDM-PON system. They have set some clear technical goals, but they also have a strong price target which is interesting to mention as a benchmark for the TCO modelling in WP5 of OASE. The goals for GigaWaM can be summarized as [14]:

- Technical goals:
  - 64 channels, 1.25 Gbps
  - 50 GHz channel spacing in C-band [upstream] (~48.7 GHz in L-band [downstream])
  - Reach 20 km over SMF
  - Improvement and integration of components
- Price target: 120 EUR per subscriber to a system integrator, in 2012, in volume [60 EUR home unit, 40 EUR central office, 20 EUR: remote node]

FP7 ICT-STRONGEST

The STRONGEST (Scalable, Tuneable and Resilient Optical Networks Guaranteeing Extremely-high Speed Transport) IP project is concentrating on the core optical transport network, in contrast to the OASE project that is focusing on the access and aspects of the aggregation networks. However, clearly, there will be an interface between these network domains, with suitable compatibility required to ensure smooth operation.

With regard to the specific STRONGEST aims and requirements that will have a bearing on the access/aggregation parts of the network, the following objectives have been stated by the STRONGEST project [15]:

- ×100 traffic increase by 2020 (assumption of 100 Tb/s throughput per transport node)
- ×100 reduction in power consumption (J/b) by 2020
- Control plane for end-to-end service delivery
  - Provisioning and restoration times to be less than current networks
  - 20% TCO for the unified control plane

With these specific aims and objectives, the STRONGEST project also has the following assumptions related to access bandwidth requirements, which are of particular relevance to OASE. The following intensive, bandwidth consuming applications have been identified in the STRONGEST project:

• Business services:	Optical VPN	1-100 Gb/s
	SAN	1 Gb/s
• Tele-surgery	Decoded HD video	1 Gb/s
• UHDTV		400 Mb/s
• Residential services:	2D high-def TV & videoconferencing	10-15 Mb/s per channel
	3D high-def TV & videoconferencing	100 Mb/s per channel

In addition, the STRONGEST project is basing its projections on the assumption of node consolidation, such that larger European countries (e.g. UK, D, I, F etc.) will have on average 1000 CANs, with about 20,000 customers per CAN, with a 10:1 contention ratio, such that the average network demand at the access node will be about 2 Tb/s. This means that bandwidth capacity at the CAN is expected to reach 1–10 Tb/s by 2020.

Although STRONGEST is dealing with the core network, it is very important to check if the targeted applications at the customer side fit with the OASE requirements. Moreover, the STRONGEST assumption of node consolidation is completely in line with OASE.

FP7 ICT-SPARC

The SPARC (Split architecture carrier grade networks) STREP project aims to investigate and implement a new split in the architecture of the Future Internet and its building blocks. The design of the new architecture will focus on the split of control, forwarding and data processing elements.

The access/aggregation network is one of the use cases considered in SPARC. The requirements identified for this use case are summarized in the figure below [16].

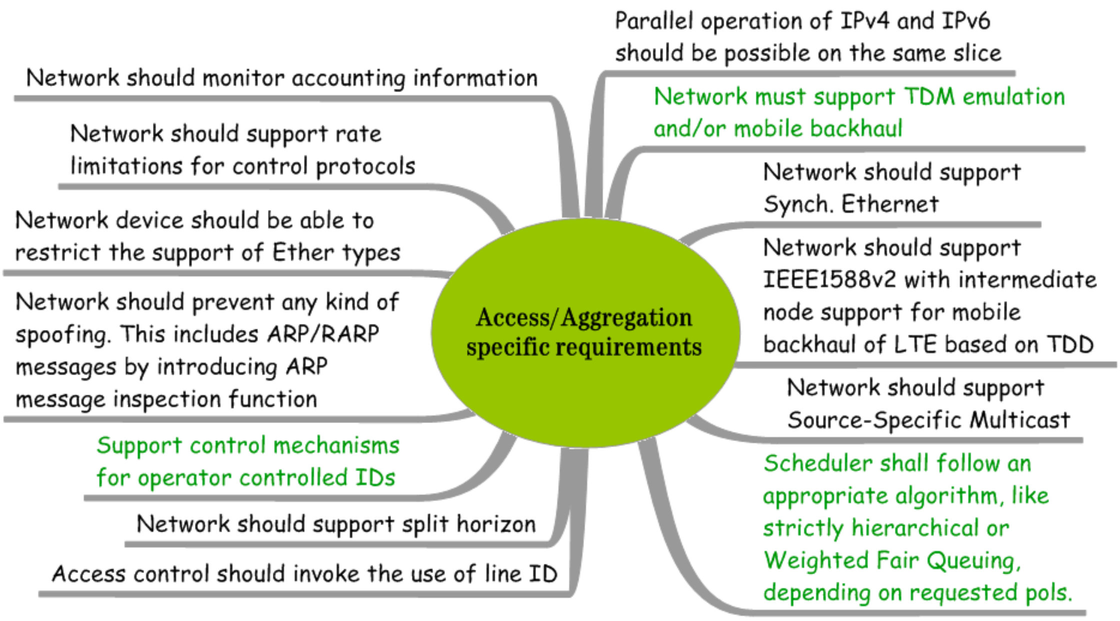

Figure 1: SPARC project – requirements overview

Although the access/aggregation use case in SPARC is situated in the same network domain, it is clear that SPARC is looking at different layers and problems than OASE. In this way, both projects are complementary, and SPARC can probably assist OASE to provide a seamless migration path to NGOA and to facilitate open access. However, this also implies that the SPARC results will have no impact on the key OASE requirements. Note that SPARC is technology agnostic and can support the different OASE architectures.

SUMMARY

The different FP7 projects in this section are targeting different requirements, but in general they are quite well aligned with the OASE requirements. A lot of projects are complementary to OASE, and can deliver interesting input on OFDMA-PON (ACCORDANCE), the higher layers (SPARC), the core network (STRONGEST) and low-cost system design (GigaWaM). ALPHA and SARDANA are most in line with the OASE project, and in general their requirements are very similar.

2.7 FSAN

After the standardization of 10-Gigabit-capable passive optical network (XG-PON) systems in 2010 FSAN started to define system requirements for fibre access beyond those PON systems standardized to date, i.e. NG-PON2 in FSAN terminology. In general, NG-PON2 aims to increase the overall capacity and addresses the market needs in the 2015 timeframe and beyond. The key FSAN requirements for NG-PON2 [17] are listed below:

Capacity

NG-PON2 must support at least 40 Gbit/s aggregate capacity per feeder fibre in the downstream direction and at least 10 Gbit/s aggregate capacity in the upstream direction.

All ONUs shall be capable of 1 Gbit/s up- and downstream but some ONU types can have a higher rate e.g. 10 Gbit/s for business or backhauling applications. The NG-PON2 system should allow provisioning of services with different sustained/peak rates and different DS/US ratios as required. NG-PON2 solutions that increase the overall level of data rate symmetry, e.g. between 2:1 and 1:1 (downstream: upstream), are desirable.

Reach (passive and non-passive)
The minimum requirement for NG-PON2 passive fibre reach is 40 km whereas the non-passive fibre reach is 60-100 km.

ONU per PON feeder (passive and non-passive)
The number of ONUs that NG-PON2 should passively support is at least 64-128 and the number of ONUs that NG-PON2 should actively support is at least 256-512 but this could be greater depending on the requirements.

Services and applications
NG-PON2 should be capable of delivering a mix of services on a common ODN. It should support Residential (MDU/SFU) and Business customers and applications as well as mobile backhaul and distributed eNodeB applications. In addition, NG-PON2 should support transport (e.g. CPRI, OBSAI) between BBU (Baseband Unit) and RRU (Remote Radio Unit).

Co-existence and support for legacy ODN
For maximum flexibility, NG-PON2 should support co-existence with both GPON and XG-PON1 on the same ODN. In addition, the co-existence of NG-PON2 with legacy RF overlay is desirable. This means that NG-PON2 should operate in the available spectrum not used by legacy PONs. NG-PON2 should be capable of reusing existing legacy PON optical power splitters, meaning it should be able to operate over a non-wavelength selective ODN. NG-PON2 should be able to accommodate flexibility in terms of splitting stages and number of splits in each stage no matter what splitting technology is used (whether power splitting, wavelength splitting, or a combination of both).

Migration
NG-PON2 should allow a technology migration on existing infrastructure without any prolonged service interruption. It must be capable of upgrading single customers on demand. NG-PON2 must support a migration from XG-PON1 to NG-PON2 and a migration directly from GPON to NG-PON2 leaving out the XG-PON technology. In addition, it should support a migration path that enables a co-existence of GPON, XG-PON and NG-PON2. In any migration case, legacy ONUs and OLTs must remain unchanged. The attenuation of any additional device must also remain similar to or less than those induced by WDM1r in order not to compromise the legacy optical budget.

Colourless ONUs
The NG-PON2 ONUs should be ‘colourless’, meaning that they are not specific to a certain wavelength. In general, different ONU variants are required for FTTH, FTTB, mobile backhaul etc.

Resilience, redundancy requirements
NG-PON2 should support resilience options for duplex system configuration and dual

parenting duplex system configuration as defined in G.984.1 (03/2008) / appendix II. In addition, NG-PON2 should support rapid restoration. For instance, the service interruption time should be less than 50 ms for enterprise or premium users.

Reach extender requirements

NG-PON2 should support reach options that enable a system reach of at least 60 km. NG-PON2 should support Mid-span reach extenders that must be remotely manageable through an OLT to enable configuration and monitoring functions for maintenance and fault location. The reach extenders should be able to operate over typical temperature ranges in indoor and outdoor and uncontrolled environments.

Power reduction

NG-PON2 systems must be designed in the most energy-efficient way whilst maintaining compatibility with the service requirements

OAM, Provisioning and Management

NG-PON2 systems should be at least as secure as XG-PON1. Extra security should be supported in the event of open access being employed where access to data between operator domains should be restricted, e.g. higher levels of ONU authentication.

The NG-PON2 ONUs must be remotely manageable and support auto-configuration functions. The ONU management must be based on OMCI (G.988) including NG-PON2 specific MEs. NG-PON2 should support PON supervision features that enable enhanced use experience through early identification and location of faults (including splitter) at the physical layer, e.g. ODN monitoring/checking and end-to-end performance monitoring up to the Ethernet layer.

In summary it can be said that the NGOA requirements specified in OASE are basically in-line with the key requirements for the NG-PON2 system defined in FSAN. However, there are some minor deviations, for example regarding the timeframe for the equipment to be available for deployment. FSAN aims at a deployment in 2015 whereas OASE considers NGOA technologies which will be generally available in 2020. That is the reason why OASE specified a more challenging aggregate capacity per feeder fibre and sustainable data rate compared to FSAN.

In 2012 FSAN continued the work on the technology assessment and discussed the following NG-PON2 technology options:

- Forty gigabit time division multiplexed PON (XLG-PON)
- Time and wavelength division multiplexed PON (TWDM-PON)
- Wavelength division multiplexed PON (WDM PON)
    - Externally seeded WDM PON
    - Wavelength reuse WDM PON
    - Tuneable WDM PON
    - Ultra-dense WDM PON
    - Self-Seeded wavelength division multiplexed PON

  - Wavelength routed (WR-) or wavelength selected (WS-) WDM PON realisation in the ODN
- Orthogonal frequency division technologies
  - Orthogonal frequency division multiplexed PON (OFDM-PON)
  - Hybrid WDM/OFDM-PON
  - Wavelength division multiplexed OFDMA-PON (WDM-OFDMA-PON)
  - Asymmetric coherent/envelope-type 40Gbps OFDM/-A PON

FSAN reviewed the remaining in-scope solutions and agreed to include the following in any future studies:

- TWDM-PON as a primary NG-PON2 solution
- With support for (tuneable) WDM overlay if needed
  - Possibly with coherent reception and/or OFDM for enhanced capability (for further study)

TWDM-PON is just a flavour of the Hybrid WDM/TDM-PON solution that has been studied in OASE. The TWDM-PON must support the following mandatory minimum requirements:

- 40 Gbit/s DS capacity with 10 Gbit/s per DS channel and 20 km system reach, 1:64 split
- 10 Gbit/s US capacity with 2.5 Gbit/s per US channel and 20 km system reach, 1:64 split

FSAN will provide contributions to the ITU-T standardisation regarding common operators requirements as the basis of the NG-PON2 specification G.989.1 “NG-PON2 general requirements” (consented in 09/2012).

3. Summary

According to the quantitative OASE results most of the requirements can be fulfilled with some exceptions, as shown in ***Table 3***. There is an issue with the quality requirement: availability one-way ≥99.99% cannot be fulfilled. For the residential market this requirement has been adjusted to ≥99.98% one-way (equates to ≥99.96% E2E resp. round-trip). Another issue is the backhaul requirement: delay < 1ms and jitter << 1ms, especially required for some mobile use cases. This might become critical if one considers extreme node consolidation scenarios where the distance becomes close to the upper end of the protected distance of 90 km. Furthermore, the use of dynamic resource allocation within a concept might seriously compromise fulfilment of the backhaul delay and jitter requirements. Hence, for clients with the most stringent backhaul requirements, backhaul should be based on static resource allocation and preferably utilise dedicated PtP links or wavelengths.

For the architecture requirements, with respect to migration, the studies have shown that three out of the NGOA architecture options (WR-WDM PON, NG-AON, and two-stage WDM PON) could not reuse a power splitter based ODN infrastructure and would also not allow a seamless migration (i.e. no user-wise switchover) on a PtP based ODN infrastructures. A migration starting from a non-coexisting architecture would lead to additional effort in upgrading network infrastructure. For Greenfield scenarios this has no relevance.

However, there are no knock-out criteria that exclude any concept from the technical point of view, because all technical constraints could be overcome with additional measures and money.

Results from the economic evaluation and from the business analyses are therefore of major importance for the adjustment of the requirements. The impact of major cost driving requirements on system and architecture design, network operation and open access has been analysed in a sensitivity study.

From the business perspective, multiple network providers in an area must be supported, taking into account isolation functions and dynamic allocation of resources depending on market share. There should also be a coordinating rule set in place. Furthermore, network interconnection via standardized interfaces and open-access-enabling interoperability across different carrier networks must be supported.

The NGOA requirements specified in OASE are essentially in-line with the key requirements for the NG-PON2 system concepts defined in FSAN as well as with feedback received form the Industry board meetings. The related FP7 projects have, of course, different targets, but in general they are also quite well aligned with the OASE requirements. The technical focus of these projects is in most cases complementary to OASE, and can deliver interesting input on OFDMA-PON (ACCORDANCE), higher network layers (SPARC), and core network aspects (STRONGEST), as well as on low-cost system design (GigaWaM). ALPHA and SARDANA are most in line with the OASE project, and in general their requirements are very similar.

Table 3 Requirements fulfilment by NGOA architectures

<table>
<tr><th></th><th colspan="2">Reference</th><th colspan="5">NGOA</th></tr>
<tr><th>Architecture
Key requirement</th><th>GPON</th><th>XGPON1</th><th>Passive Hybrid PON</th><th>WR-WDM PON</th><th>WS-WDM PON</th><th>UDWDM PON</th><th>AON P2P</th></tr>
<tr><td>Low NPV [CU]</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Availability
99.99% one-way (equates to 99.98% E2E resp. round-trip)</td><td colspan="7">Even with protection of OLT, feeder fibre and aggregation,
99.99% (one-way) will <u>not</u> be reached (except of WR-WDM PON in Dense Urban)</td></tr>
<tr><td>Service quality
1) Delay < 1ms
2) Jitter << 1ms
3) BER: < 1,0E-07; PL: < 1,0E-05</td><td colspan="7">Fulfilled by all architectures</td></tr>
<tr><td>Wavelength OA
1) λ per NP
2) User reachable by λ</td><td colspan="2">NA#</td><td>1) λ range per NP using band filter
2) λ per PS-PON using cyclic AWGs</td><td>1) λ range per NP using band filter,
2) λ per user using cyclic AWGs</td><td colspan="2">1) λ range per NP using band filter,
2) λ per user</td><td>1) λ backhaul per NP at AON switch</td></tr>
<tr><td>Reach
1) 20-40 km passive (working)
2) 60-90 km extended passive preferred (backup)</td><td colspan="3">1) Fulfilled,
2) Reach extender required</td><td>60km passive only in 80ch. & preamp config. with APD ONT</td><td>1) Fulfilled,
2) Reach extender required</td><td>60km passive only in 40ch. & booster config. and 1:8 PS</td><td>Not passive</td></tr>
<tr><td>Fan-out/split
1) 256 - 1024 users
2) 128 - 500 Gbit/s
on single feeder fibre</td><td colspan="2">No</td><td>Fulfilled</td><td>Only in 320λ config. fulfilled</td><td>No</td><td colspan="2">Fulfilled</td></tr>
<tr><td>Traffic
1) 1G peak/user, 1:2 symmetry
2) 500 Mb / user sustained
3) 10G peak, 1:1 symmetry for business or mobile backhaul</td><td>2) Reduced power split Ø 1:5
3) NA#</td><td>2) Reduced power split Ø 1:20
3) NA#</td><td>Fulfilled
2) Reduced power split Ø 1:20</td><td colspan="3">Fulfilled
3) additional 10G upgrade required</td><td>Fulfilled</td></tr>
<tr><td>Migration coexistence
1) Seamless migration on PON based ODN (i.e. no user-wise manual switchover)*
2) Spectrum coexistence</td><td>Reference</td><td colspan="2">Fulfilled</td><td>No</td><td colspan="2">Fulfilled</td><td>No</td></tr>
<tr><td>Protection
1) FF + OLT protection
2) E2E protection e.g. for business or mobile backhaul</td><td colspan="7">Fulfilled by all architectures
2) E2E protection requires additional ODN infrastructure upgrade</td></tr>
</table>

* Note: Seamless migration starting from a PtP architecture will not be supported by all architectures, because user-wise manual switchovers are required in all cases.

- End of document -