"Process modeling and first version of TCO evaluation tool"

D5.2

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UNIVERSITY OF ESSEX	UESSEX	UK

Abstract:
This deliverable presents a detailed description of the cost models of capital and operational expenditures for Next-Generation optical access networks as well as the implementation of the proposed TCO tool. The deliverable has three main parts: (i) the first part focuses on the important aspects of Next Generation Optical Access (NGOA) networks which will impact the total network cost; (ii) the second part focuses on the considered models, which are: operational process modelling, infrastructure and equipment models; and (iii) the third part presents the tool implementation and gives the particular example of Gigabit-capable Passive Optical Networks (GPON) and Active Optical Networks (AON) which have been used as benchmark. The considered models cover the characteristics of the proposed NGOA networks that will impact the total cost. Hence, the cost comparison of the anticipated NGOA solutions and the study of the impact that aspects such as node consolidation, resilience and "zero-touch" have been foreseen.

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Executive summary

One of the objectives of the OASE project is to perform a techno-economic evaluation of different proposed solutions for Next Generation Optical Access (NGOA) Networks. This evaluation comprises a cost assessment of infrastructure, equipment and operational processes, which are dependent on the network dimensioning and the area where they will be used. Hence, the steps that will be followed for our studies are:

- Network dimensioning: based on the area, user distribution, existing infrastructure, expected take-rate, etc., this step calculates the investments required in terms of infrastructure (cable/fibres) and of equipment (at user, remote locations or central offices).
- Based on the network dimensioning, the costs of infrastructure and equipment can be calculated, as well as the power that will be consumed per year and the required floor space to place them.
- The cost of operational processes such as network maintenance, failure reparation and service provisioning can be then computed. However, these costs depend on other parameters that vary with the area/country such as salaries, travelling time, etc.
- At this stage, the business models presented at D6.1 [12] can be applied. In this case, the cost of different providers (i.e. Physical Infrastructure provider or Network provider) as well as the separation of different providers in the same area should be considered and delivered to WP6.
- Sensitivity analysis should be also performed to evaluate the impact of cost and other parameter variations to the total final cost, and as such this deliverable serves as an important input towards T5.3. This analysis will also identify the key cost parameters which any operator should pay special attention to avoid rising costs.

This deliverable presents the aspects of NGOA networks that are expected to have big impact of the total cost, which are: zero-touch operations, node consolidation, network resilience and network migration. Afterwards, the deliverable presents in detail the models considered for the infrastructure, equipment and operational processes. As operational processes, five processes have been described in detail (when needed for clarification, Business Process Modelling Notation (BPMN) was used): Failure Management and Troubleshooting, Service Provisioning, Maintenance, Power consumption and Floor space.

Additionally a general modelling approach for the network migration is presented. The main aspects to be considered are presented.

The equipment, infrastructure and operational models are being integrated within the TONIC tool, which is the frame tool chosen within OASE D5.1. It is shown how this integration is performed and how it can be used by GPON and AON benchmarking scenarios. The first results of these solutions compare cost for Greenfield and brownfield scenarios in terms of infrastructure and equipment total cost and cost per line.

The document is structured as follows: Section 1 provides a general description of this deliverable. In Section 2 the NGOA characteristics that will influence the total cost are presented. Section 3 describes the considered operational models. In Section 4 the outside plant estimation models are presented which are: the existing TONIC model (so-called geometric model), and other proposed analytical models. Section 5 introduces the considered equipment model. Section 6 addresses the operational aspects of the network migration towards NGOA architectures. Section 7 focuses on the integration of all these models within the TONIC frame tool and the first results for GPON and AON solutions. Section 8 concludes the document.

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Abbreviations

ABC	Activity Based Costing
AC/DC	Alternating/ Direct Current
AON	Active Optical Network
AWG	Array Waveguide
BF	Building Fibre
BPMN	Business Process Modelling Notation
BSA	Bit Stream Access
CAN	Consolidated Access Node
CAPEX	Capital Expenditures
CC	Cable Cut
Cd	Consolidation degree
CO	Central Office
CPE	Customer Premises Equipment
CPU	Central Processing Unit
DIY	Do It Yourself
DF	Distribution Fibre
DT	Down Time
DU	Dense Urban area
E2E	End to End
EMS	Event Management Systems
FCAPS	Fault, Capacity, Account, Performance, Security
FF	Feeder Fibre
FIT	Failures In Time
FTTB	Fibre to the Building
FTTH	Fibre To The Home
FMDB	Failure Message DataBase
GIS	Geographic Information System
GPON	Gigabit-capable Passive Optical Networks
HH	Households
HPON	Hybrid PON
HVAC	Heating, Ventilation and Air Condition
HW	Hardware
I/F	Interface
IT	Information Technology
MDT	Mean Down Time
MTBF	Mean Time Between Failures
NGAON	Next Generation Active Optical Network
NGOA	Next Generation Optical Access Network
NGPON	Next Generation Passive Optical Networks
NE	Network Element
NMS	Network Management System
OAM	Operations, Administration and Maintenance
ODF	Optical Distribution Frame
ODN	Optical Distribution Network

OF	Outage Frequency
OLT	Optical Line Terminator
O&M	Operations and Management
ONT	Optical Network Terminal
ONU	Optical Network Unit
OPEX	Operational Expenditures
OSM	Open Street Map
P2P	Point-to-point
P2MP	Point-to-multipoint
PCP	Physical Connection Point
PHY	Physical
PON	Passive Optical Network
R	Rural area
RE	Reach Extender
RN	Remote Node
SLA	Service Level Agreement
SME	Small and Medium Enterprises
SPOF	Single Point-Of Failure
SW	Software
TCO	Total Cost of Ownership
TDM	Time Division Multiplexing
TONIC	Techno-Economics of IP Optimized Networks and Services
TRX	Transmitter
TT	Trouble Ticket
U	Urban area
UDWDM	Ultra-Dense WDM
UPS	Uninterruptible Power Supply
WDM	Wavelength Division Multiplexing
WSS	Wavelength Selective Switch
XGPON	10G PON

1. Introduction

This document presents the continuation of the work in WP5 based on the results obtained in the first deliverable D5.1 [1]. This deliverable D5.1 presented the general framework for the techno-economic assessment of next generation access networks and concluded with the proposal of the tool to be used within the OASE project. This tool uses the TONIC-tool as the frame tool because it is available, it can be used by all partners, other home developed tools can be integrated in the cost computation and sensitivity analysis can be performed. This document also presents the first steps towards the integration of the presented models as well as the implementation of the TCO tool.

The objective of this deliverable is to give an overview of the considered cost modelling of Next Generation Optical Access (NGOA) networks as well as the implementation and first studies for Gigabit Passive Optical Networks (GPON) and Active Optical Networks (AON). This deliverable is structured as follows: Section 2 presents the challenges of NGOA that are expected to influence the total cost. One of these aspects is the node consolidation which is considered by network operators as a way to reduce costs by decreasing the number of sites. However this is only possible when considering NGOA solutions, that is, access solutions reaching up to 100 kilometres reach and 1000 clients. Other aspects are “zero-touch” capabilities, network resilience and smooth network migration.

Sections 3, 4 and 5 introduce the models that have been used or developed for the operational processes, outside plant infrastructure and equipment respectively. Special attention is given to five operational aspects: Failure Management and Troubleshooting, Service Provisioning, Maintenance, Power consumption and Floor space. Section 6 gives an overview and first steps towards the network migration model to NGOA implementation; and finally Section 7 shows the integration of all these models within the TONIC frame-tool and the particular implementation of GPON and AON as benchmarking.

Strong collaboration has been required to align the cost models with the work done in other Work packages:

- WP3: the modelling of the network architectures had to be coherent with the architectures proposed in WP3 (e.g. taking into account protection)
- WP4: the component modelling and the definition of the required values for each element were agreed between WP4 and WP5.
- WP6: the cost differentiation for the different business scenarios to be evaluated by WP6 were differentiated

This document is the working document of Task 5.2 and will be the basis for milestone M 5.3 “TCO modelling and proposed TCO evaluation tool” where the final migration cost model as well as the last description of the tool implementation will be presented. This deliverable also serves as input for the further work within Task 5.3 since this task will use the implemented models and tool to perform the required case studies.

2. NGOA challenges influencing cost

Many opportunities for reducing TCO for NGOA networks are under investigation, e.g. node consolidation, open access networks, zero touch operations, etc. Moving along the path of such TCO optimization will also pose different requirements on the NGOAN than currently exist on access networks which have been identified in OASE WP2. Many of these requirements are expected to influence the total cost of ownership (TCO). The key operation requirements for network and Network Management System (NMS) design are:

- Aiming at zero-touch operations
  - Technology neutral End-to-End (E2E) provisioning of multiple services for residential, business, mobile
  - Support of auto-configuration, remote-management and network monitoring to automate operational processes (provisioning, maintenance, fault management)
  - Simplifying operational processes by suitable network design, e.g. Do It Yourself (DIY) installable and wavelength unspecific Optical Network Terminators (ONTs)
- Co-operation support with seamless interoperability across different carrier networks
- High E2E network availability and low failure penetration ranges to minimise service impacts, requiring network redundancy and protection mechanisms
- Information Technology (IT) supported optical diagnosis and measurement solutions for fault localisation
- Next Generation naming and numbering addressing schemas in multi-service/-provider environments
- Multi-Vendor capable, allowing seamless interworking of network and IT
- “Green network operation and IT” with reduced power consumption and clean technologies
- Likely higher requirements on hardware (HW) and facilities in consolidated larger locations have to be considered.

Based on these requirements, NGOA have special characteristics that will influence the total cost. These characteristics are presented in more detail in the following sub-sections. The first subsection will discuss in more detail the impact of customer installation and especially all possible applications of zero-touch will have on the costs. The second subsection will show how node consolidation is an important factor which might be used for reducing costs of an NGOA network. NGOA are also expected to require more stringent resilience and especially in case of higher node consolidation. Clearly node consolidation, resilience and traffic locality will have a trade-off for which an example is sketched in the fourth subsection. The fifth subsection puts the focus on migration and points out where the boundaries in migration are found. Finally the section ends with a small conclusion.

2.1. Zero-Touch versus One-Touch operations

Zero-touch are operational activities with minimal or zero human action (human effort). Zero-touch activities are expected to decrease Operational Expenditures (OPEX) e.g. by speeding up processes (decrease process time), automation of processes incl. technical documentation and minimisation of human mistakes.

In real network rollouts, “Zero-touch” is hard to achieve, especially during the network setup phase. Basic network rollout usually reaches less than 100% coverage, typically justified by economic reasons. For the service provisioning process this means that a so-called “One-touch” network extension up to the customer flat (final drop) may be required. “One-touch” is an operational activity which is only one time. All subsequent activities are then done either from a central desk with minimal effort or even fully automatically. Also other activities like fault identification and localisation or network control may improve over time depending on learning effects, resulting in minimised touches on the network.

“Zero-touch” capabilities are expected to decrease the cost of fault management (fault identification, isolation, and activation of fault reparation); service provisioning (faster user connection, service changes, etc.); control activities (F.C.A.P.S. – Fault, Capacity, Account, Performance, Security), etc.

A particular example of the “One-touch” activity (Figure 1) versus “Zero-touch” (Figure 2) for the service provisioning process is presented below.

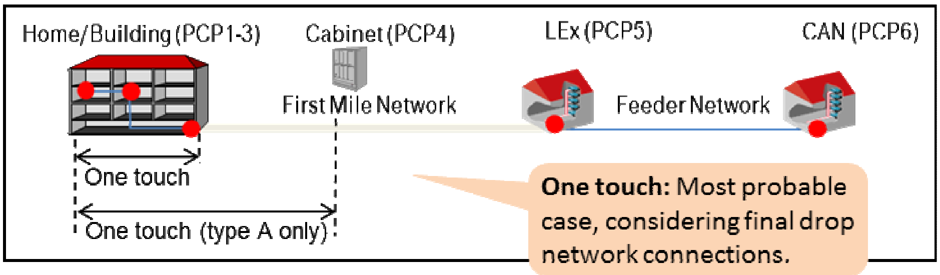


Figure 1 "One-touch" example

“One-touch”: Considers all for provision required network extensions after network basic deployment as for example a fibre connection from the already prepared building connection point to the customer flat. Those activities belong usually to the provision process because they are mainly driven by customer requests. For the so-called final drop extension, four building types will be differentiated.

- Building Type A - without fibre connection during basic rollout
  - Either with (1) or without (2) prepared micro-duct connection
  - First customer request triggers fibre blowing (1) from the cabinet to the building for all potential customers (fibre patch panel used in the cabinet and fibre termination point used in the building).
  - In-house cabling individual per customer
  - Required micro-duct extension in case (2) belongs not to the provision process
  - Typically relevant for very small buildings (1 – 3 customers)
- Building Type B - with fibre up to the building basement during basic rollout
  - First customer request triggers in-house cabling (in larger building vertical stand-pipe up to the floors).
- Building Type C - with fibre up to the floor(s) during basic rollout

- Customer request triggers final drop cabling individually per flat
- Typically relevant for large buildings

- Building Type D - Fully prepared during basic rollout with fibre up to the flats

In T5.3 deployment scenarios will be defined considering a certain percentage of the above mentioned building types that will be determined by the network basic rollout.

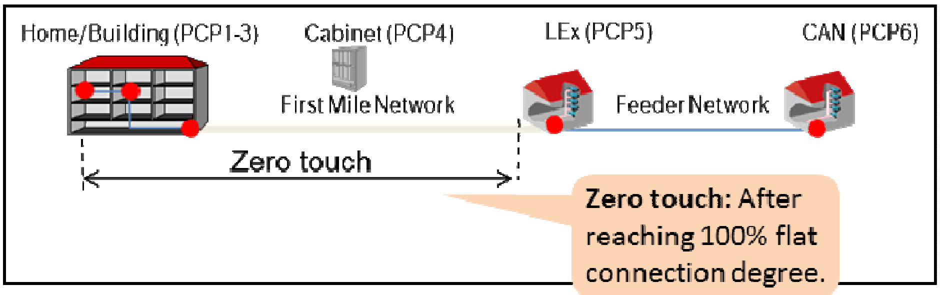


Figure 2 "Zero-touch" example

"Zero-touch": Provision after reaching full network deployment up to the flat.

- 100% of the buildings are fully connected with fibre up to the flats.
- Service activations and changes possible for individual customers without any further field work in the network section between PCP1 and PCP5.
- Service activations and changes are allowed at the PCP5 location, e.g. the installation of transceiver modules and patch fibres for individual customer connections or provider changes.

2.2. Node consolidation

One of the targets of NGOA is to reduce the number of required central offices (as presented in D5.1 [1]) in order to minimize the cost associated to them. This approach is called node consolidation and is specified by a consolidation degree which is the reduction ratio of central offices. For each consolidation degree, network scenario (area, user distribution, etc.) and architecture, the network dimensioning is performed. Differences between the technical architecture variants concerning the demands for space (e.g. smaller ODF size), power supply and climate facilities in the consolidated access nodes (CAN) will be evaluated. The total savings in number of Cos depend on the node consolidation degree of the different topology scenarios.

Figure 3 shows on the left side the potential real estate savings which could be realised at the old CO location (CO old) and on the right side the cost items which have to be considered to determine the real estate demand in the CAN (= CO new). The real estate model considers buildings that are owned by the operator (primary rural areas) and buildings that are rented. In case of rented CO old, 100% of the rents would be considered as savings. In case of owned CO old it will be assumed, especially in rural areas, that some buildings cannot be sold and that the others can only be sold on bad conditions.

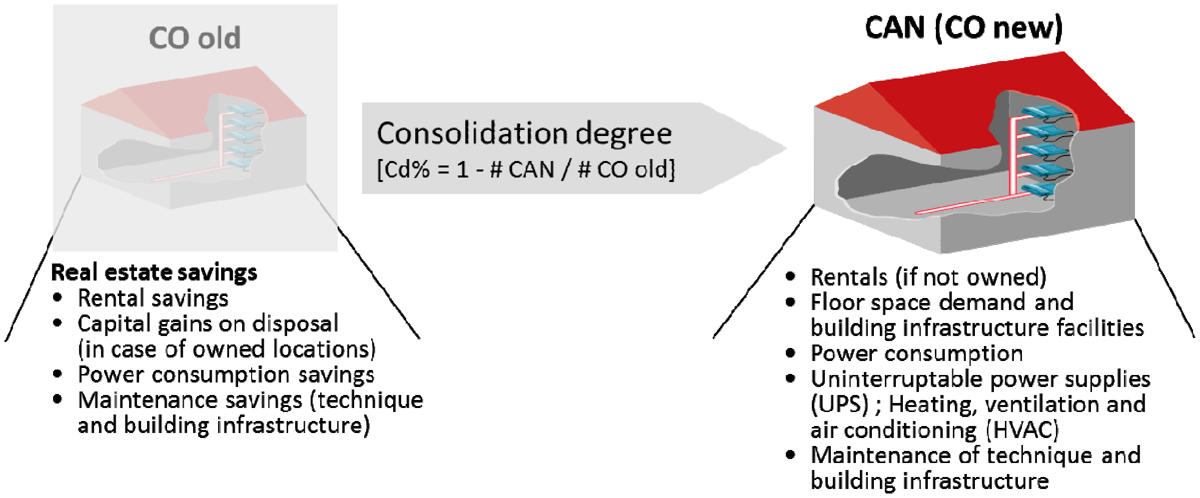


Figure 3 Impact of node consolidation

Beside the architectural and topological requirements, business cooperation related aspects have to be considered for the real estate concept. In real deployment scenarios it is most likely that cooperation partners and competitors may wish access at a network location which is planned to be consolidated by the incumbent operator. In those cases interconnection interfaces have to be provided, and OAM support is needed at these locations. Depending on the cooperation or regulation contract agreements, the OAM support will most likely be imposed on the incumbent operator, i.e. those network locations have to be considered for the evaluation of the operational costs, but on the other side the payments from the other providers for OAM support can be considered as revenue in the value chain model.

One enabler for node consolidation, beside the technology capabilities, is an adequate design of the hardware and facilities aiming at higher compactness and improved system utilisation with resulting lower floor space demand. To achieve this, the following high level guidelines have to be observed.

- Scalable and upgradable NE regarding new service requirements and demands
- Support of modular HW and pluggable optical modules (ONT only if economically)
- Interoperable network elements (protocols; standardized interfaces)
- Small sized systems and optical components (esp. OLT, ODF), retaining operation ability, e.g. easy fibre patching
- High packing density per system rack to reduce the floor space demand
- Passive network elements should be operable indoor and outdoor
- Active network elements should also be operable outdoor, if economically, to allow a higher flexibility regarding node distribution (e.g. partly deployed as remote nodes)
- Efficient power supplies and optimized climate solutions with high cooling efficiency
- “Green network operation” with reduced power consumption, e.g. support of “power sleep" mode, and “Green IT” using clean technologies with e.g. eco-friendly materials
- Support of TL9000 Quality Management System in general.

2.3. Network resilience

Resilience in NGOA architectures is becoming increasingly important due to two main reasons. First, higher reliability requirements have to be fulfilled in support of business access, backhaul and some high quality consumer applications, such as remote surgery and healthcare. Secondly, access networks are evolving towards reduced number of nodes where multiple central offices (COs) are being replaced by a single CAN covering larger service areas. This evolution is driven by operators in order to reduce operational cost. Due to a large number of subscribers and long reach between the legacy local office and the new central access node, an efficient resilient mechanism is required to avoid service interruption in case of a failure. On the other hand, resilience affects OPEX, such as costs related to failure management, service provisioning, maintenance, energy consumption, and real estate.

Failure management is one of the most costly operational processes. Mainly, two operational costs are related to the failures in the network:

1) Failure reparation cost, which includes the personnel cost for the time period of reparation and travel, the required spare components, etc.
2) Penalty cost which is proportional to the number of disconnected services for each failure of an unprotected component during the period of total time to repair (which also includes the time for fault detection and localisation and the time to wait for available resources, e.g. spare components and personnel). Typically, the penalty is paid to the business users and specified in service level agreement (SLA), whereas in most cases no penalty is given to the residential users.

Obviously, due to higher risk of service interruption, the unprotected access network architecture always has much larger penalty cost than the protected one. On the contrary, because of the larger number of equipment (and failures) the protected architecture has reparation cost higher than the unprotected one. Furthermore, efficient network recovery strategies and monitoring techniques are able to quickly detect and locate the fault and hence decrease the service interruption time. Therefore, impact of resilience on the total failure related OPEX is dependent on the scenario parameters, e.g. number of business users, penalty unit specified in SLA, type of resilience schemes, etc. Typically, for the urban area with large number of business users, total failure related OPEX can be reduced by providing appropriate resilience mechanisms to the network [2].

Compared to failure management, impact of resilience on service provisioning, maintenance, energy consumption, and real estate is less complicated. Typically, extra hardware as well as software is required to provide resilience, which may increase the complexity of service provisioning and maintenance and consequently result in higher personnel cost. Energy consumption is only related to active components. Some studies [3, 4] have shown that power usage only has minor increment in protected PON-based access solutions, but obvious increase in protected AON. Regarding resilience impact on real estate, hardware redundancy for protection provision may need additional floor space. Among different NGOA solutions the increase of space due to resilience is similar at CO, but should be quite different at the remote node (RN). This is caused by duplicates of active RN typically taking more space than of passive RN.

2.4. Trade-off between node consolidation and resilience (Example for NG-AON)

Whereas the main trend for NG-PON is towards consolidation of central offices in the access network, the focus for NG-AON is towards utilizing the inherent possibility of resilience in mesh and ring topologies from access to core network as it shows in
Figure 4, whilst new locality paradigms in content distribution networks (CDNs) are also in focus (see details in [1] Section 8.4.1).

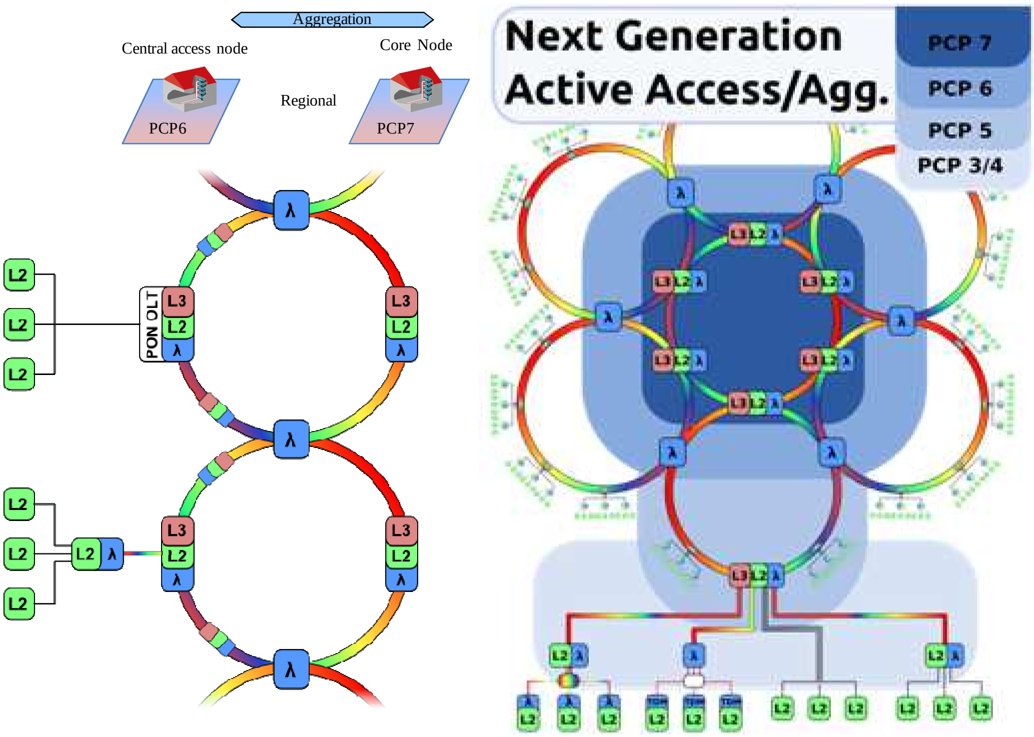


Figure 4 Example of end-to-end NG.AON topology

In such a scenario, the cost saving is not associated with the reduction of number of old COs in the access network and related cost saving of real estate and management of old CO nodes. Instead the potential benefits (and cost savings) of such mesh and ring topologies will be through new resilience opportunities and through network equipment and power savings etc. in the aggregation and core network. By utilizing the locality in the traffic patterns, the active equipment in the mesh and ring nodes can keep some data traffic locally and hence offload the aggregation and core network, which will potentially result in a net saving in total cost of expenditure of the whole network

2.5. Migration boundaries

The migration towards a new technology generation may have various drivers, for instance End-of-Life of the existing technology (which may result in higher operational costs), omitted vendor support, new service features and traffic evolutions with missing scalability and upgradability on the existing technology, new world-wide mass-market evolutions and standardisations resulting in lower price level (lower cost per bit) as well as competitiveness imposing short time-to-market requirements.

Key operator requirements on migration are minimal service impact on existing subscribers and minimal migration effort (minimal personnel demand and investment). Especially the first point leads usually to an overlay migration approach considering a smooth customer driven switchover. The experiences show also that an overlay migration often allows a reduction of the complexity and less IT adaptation effort for migration. However, parallel operations of the platforms have to be considered during the time period of the overlay migration.

The migration scenarios in this document describe brownfield situations considering existing infrastructure of the reference access areas (ODN), topology parameters from the geometrical model as well as the reference start architectures, as shown in
Figure 5.

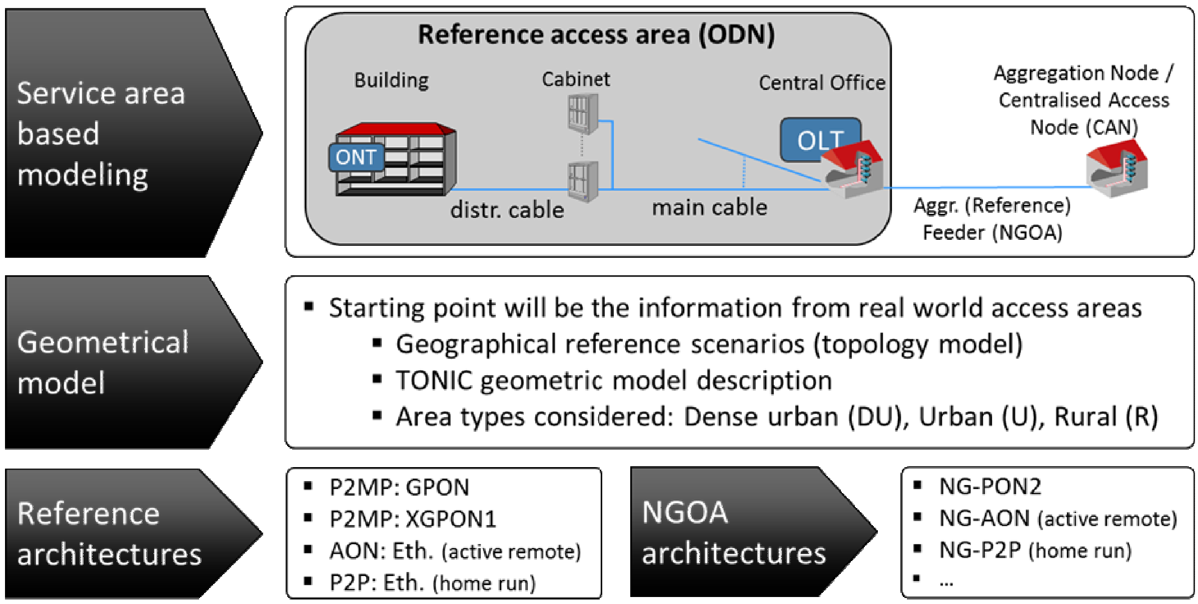


Figure 5 Some important aspects to define the migration process

As studied within WP3, the migration from deployed systems towards NGOA systems should be as smooth as possible and therefore, the following guidelines should be considered:

- Overlay migration approach, e.g. on a dedicated wavelength (instead of a singular network swap)
- Before the migration of the individual customers, the new NGOA network architecture will be deployed as overlay (realistically >1 year per access area needed)
- The NGOA system has to work on the existing first mile infrastructure, aiming minimal demand for additional infrastructure components (ducts, cables, fibres etc.)
- The NGOA system should not affect the deployed system and the existing spectrum.

- Operation of maximal two system generations in parallel in order to avoid operational complexity. Both system generations will operate in parallel over a certain time period (e.g. 1 - 2 years)
- The customers will be migrated smoothly, e.g. by connecting a new ONT which is compatible with the NGOA system
  - For the migration of the individual customers, the services will be reconfigured and routed from the service creation platform to the over-layed NGOA system
  - The customers can use the services via a new NGOA-compatible ONT
  - The customers must be informed and will get a new ONT before the migration
  - Customers from other providers can only be migrated if the providers agree, and have prepared for migration (e.g. SCP, IT ...).
- To avoid long parallel platform operation, remaining copper customers (incl. single play) will be “hard” migrated to FTTH after reaching a penetration threshold.

As shown in Figure 6, the migration assessment should consider several start technologies and evolution steps, as they might occur in reality. For the GPON reference, two migration options will be distinguished in Section 6.2. GPON Option 1 with direct migration towards NGOA and GPON Option 2 with intermediate step XGPON1 towards NGOA.

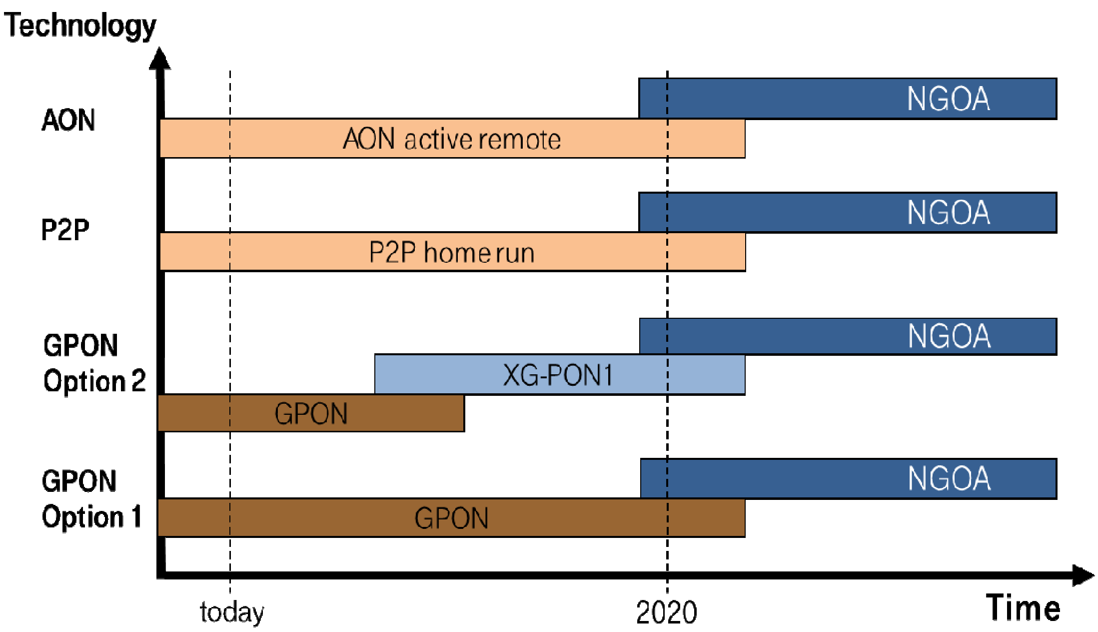


Figure 6 Exemplary migration scenarios

2.6. Conclusion

The economic questions to be answered with the total cost of ownership (TCO) tool are a combination of all the NGOA aspects presented in this section. For example, node consolidation is expected to reduce the number of rented or owned locations (i.e. lower total footprint) and could reduce operational expenditures in this way. It will also accommodate more customers per location, so failures can impact more customers at once. Hence, network resilience should be considered carefully. Traffic locality will also impact this trade-off between node consolidation and resiliency. Further influences on cost are imposed by e.g. the ONT requirements (standardization, design universal vs. per customer class etc.), technical and operational migration efforts, zero touch vs. one touch provisioning, as well as different technology characteristics.

3. Operational Models

The focus of the OASE OPEX assessment lies on the main cost driving processes such as service provisioning, fault management, maintenance and power consumption. As shown in Figure 7 the different operational aspects depend on different parameters. Therefore, the modelling of these operational aspects will rely on them and a sensitivity analysis will be performed to evaluate their impact on the final cost. The required floor space demand will be outlined as square meter per network location in this document. A monetary evaluation of the floor space and real estate demand will be performed in Task 5.3.

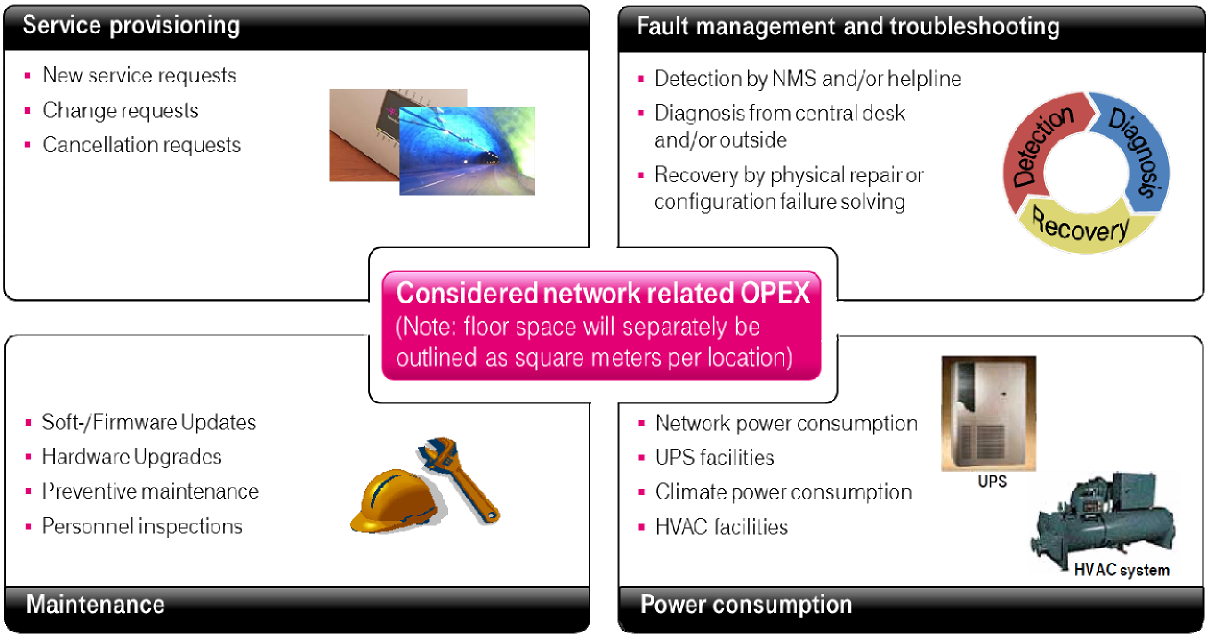


Figure 7 Main operational aspects of a NGOA network

Next to the impact of different architecture designs on operational expenditures, the impact of node consolidation, business co-operation and deployment strategies should also be investigated.

Existing background on the operational processes is found in the work of the different project partners and various other projects. Exemplarily, a comprehensive background on operational processes can be obtained from the former MUSE project as listed here:

- Fault Repair and Troubleshooting
  - Outage frequencies (FIT rates)
  - Impact of resilience concept
  - Failure penetration ranges
  - E2E network availability
  - Network monitoring (e.g. performance, quality, incidences etc…)
- Service Provisioning
  - Manual switching effort (e.g. fibre patching at ODF for new provision, provider change, user move)
  - Network and service configurations
  - ONT post delivery
  - ONT installation support at user site

  - ONT remote configuration support from central desk
  - Costs of automated provision functions
- Maintenance (usually contracts with system vendors)
  - Maintenance of system hardware and passive infrastructure
  - Software release updates (incl. licences etc.)
  - Inventory management etc.
- Energy Efficiency
  - Power consumption and price mix
  - Climate concept
  - Power supply and climate facilities (UPS, HVAC)
- Real Estate
  - Location consolidation potential
  - Power savings, maintenance savings
  - Rental savings, capital gains on disposal
- Business Cooperation
  - IT Support
  - Operational support (OAM)
  - Provision of open access interfaces

In the following subsections each of the aforementioned operational processes (except the last process of business cooperation which is left outside the scope of this deliverable) will be presented in detail while having in mind the key requirements indicated by WP2. The final operational process is drawn in BPMN format when required for clarification and discussed in detail in the second part of each subsection.

3.1. Failure Management and Troubleshooting

The failure management and troubleshooting process (refers to the MUSE "Fault Repair and Troubleshooting" process) is concerned with capturing all kinds of failures in the network – equipment failures, cable breaks, CPE failures, software failures, etc. From literature some processes are already available and can be used as a starting point for the construction of the process for the different NGOA network architectures and systems. In [5] an overall failure management process is introduced as show in Figure 8. It contains the necessary administrative steps to perform before the actual repair, followed by the repair steps, typically going to the location of the failure and repairing this failure. Finally, the process is closed with some additional administrative steps.

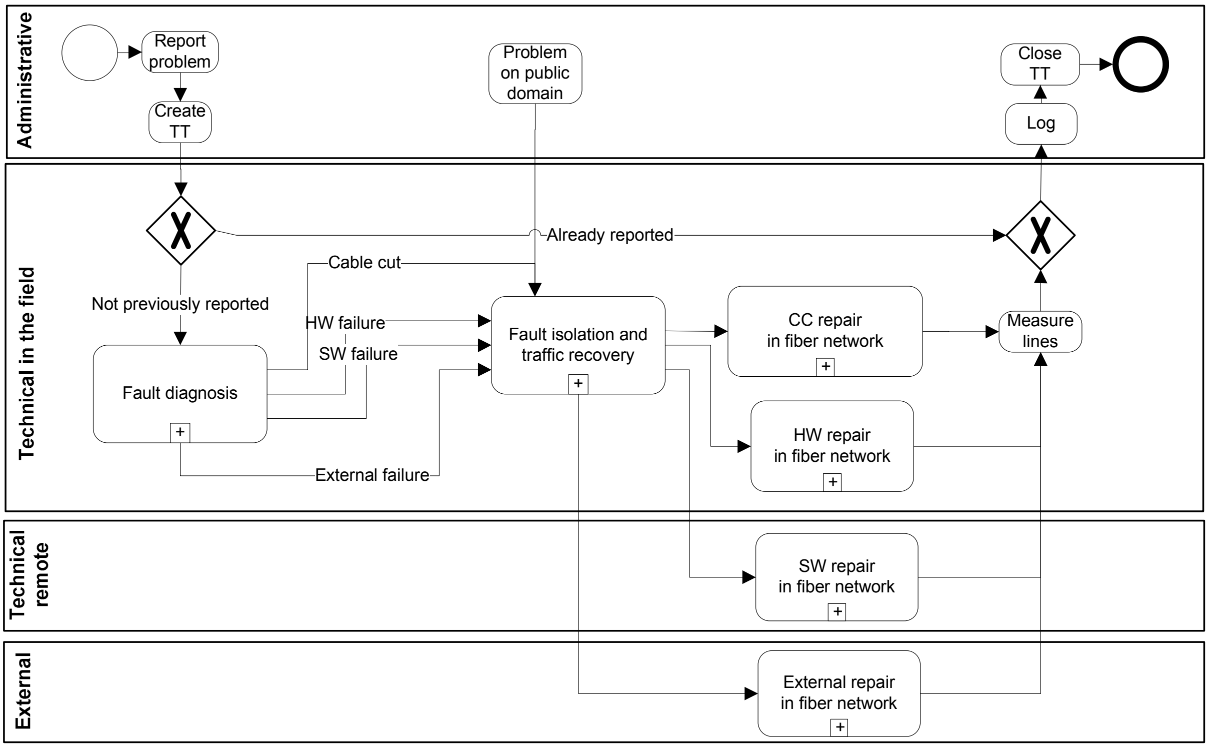


Figure 8 High level overview of the repair process

It also couples to more specific processes for hardware and software repair, cable cut repair, failure diagnosis, etc. From these the most useful (in the context of an NGOA network) is the cable cut repair process which is shown in Figure 9.

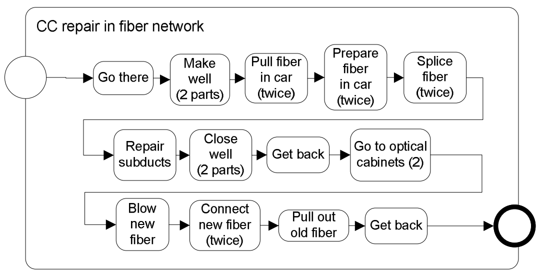


Figure 9 CC Repair sub-process

These processes and sub-processes will be used as a construction basis for the failure management and troubleshooting process in an NGOA network.

The fault management and troubleshooting process comprises three major sub-routines: prevention, detection and reaction/troubleshooting. The main goal of the proposed process model is the identification of the most costly activities or sub-processes, which will help decreasing the total process cost.

- **Prevention** against network failures requires the support of redundancy and protection mechanisms to minimise service impacts (e.g. support of automatic re-connections with short re-routing times),but also preventive diagnoses of link quality with outage prediction as well as customer impact analyses with focus on service impact and failure ranges are required in order to trigger appropriate preventive tasks.
- **Detection** of network failures can be recognised by customer calls (helpline trouble shooting), NMS alarms or personnel inspections. In case of a network failure (i.e. excl. customer troubles without network relation) a fault diagnosis with identification of the faulty network elements will be performed. For this, IT supported optical diagnosis and measurement solutions for localisation of passive infrastructure faults up to the home as well as higher layer system measurement solutions for localisation of active system failures are required. An extended fault diagnosis is needed in some cases, if the initial diagnosis shows no results (e.g. outside measurement in the first mile loop).
- **Troubleshooting** deals with both, solving of customer troubles and recovery of network failures, aiming a high "first solving rate" through measurements and configurations from central NMS/IT locations as well as minimal effort for reparations, configurations or technique changes at remote locations (requires a highly automated, highly available and robust network).

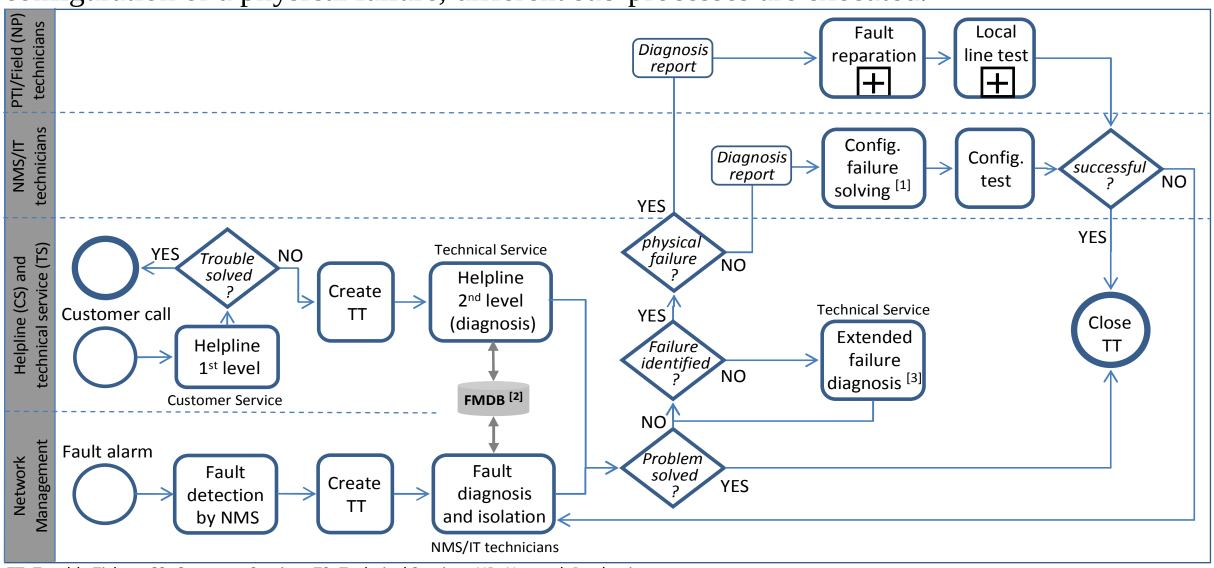
Availability requirements per customer class*

Customer class	E2E Service Availability	OF [1/a]	MTBF [a]	MDT [h]	DT [h/a]	Max. failure penetration range
PSTN today	99,983%	0,135	7,4	10,9	1,47	1000
Residential (drivers Voice & IPTV)	99,98%	0,128	7,8	13,6	1,75	One failure does not affect more than 1000 customers
Wholesale / Wholebuy	99,98%	0,128	7,8	13,6	1,75	
Business	Option 1: 99,5% Option 2: 99,95% Option 3: 99,99%	1,825 0,547 0,219	0,55 1,83 4,57	24 8 4	43,8 4,38 0,876	
Backhaul of mobile base stations	99,95%	0,547	1,83	8	4,38	

*) OF = Outage Frequency per anno; MTBF=Mean Time between Failures; DT=Downtime per anno; MDT=Mean Downtime
OF = DT/MDT
DT = OF*MDT
MTBF = 1/OF – MDT ; MTTF > MTBF (MTTF = "mean time to [first] failure")
Availability = 1 – DT/(365*24h)

Figure 10 Exemplary market availability requirements for different customer classes

The major target of fault management is to minimise the service related "Down-Time" (DT) per year. The service DT per year is mainly determined by the network components quality (robustness and life-cycle behaviour) as well as the network redundancy degree (see resilience chapter, Section 2.3). The network components quality is expressed by the "Mean-Time-Between-Failure" (MTBF) as key-parameter for the determination of the E2E service availability. Beside the DT per year, also the minimisation of the "Mean-Down-Time" (MDT) per individual failure is a key target of the fault management aiming fast failure recovery. Figure 10 shows exemplarily market quality requirements on DT and MDT per customer class and the corresponding MTBF and E2E availability. The Fault management process, depicted in Figure 11, is triggered either by alarms received by the Network Management System (NMS) or by the contact of the customer service line by customer(s). In the first case, a Trouble Ticket (TT) is created and a *Fault Diagnosis and isolation* is performed. If the failure is not identified, an extended failure diagnosis will be performed until the failure is identified. After this, *fault isolation and traffic recovery*, shown in Figure 12 will be performed to minimize the service interruption times. This sub-process consists of isolating the failure and, in case no automatic protection is implemented, the protected lines are re-routed via the back-up lines. Depending on the nature of the failure, whether it is a configuration or a physical failure, different sub-processes are executed.



TT: Trouble Ticket ; CS: Customer Service ; TS: Technical Service ; NP: Network Production
***Fault detection** is the process of receiving alarms and knowing that there is a network problem that should be identified.*
***Fault diagnosis** is the process of identifying a set of candidates to be faulty and have caused the received alarms.*
***Fault isolation** is the identification from the set of candidates of the faulty element after some remote tests.*

[1] Mostly from a central NMS/IT location without traveling
[2] FMDB: Failure Message Data Base
[3] e.g. outside failure localisation by technical service

Figure 11 Fault management and troubleshooting process model

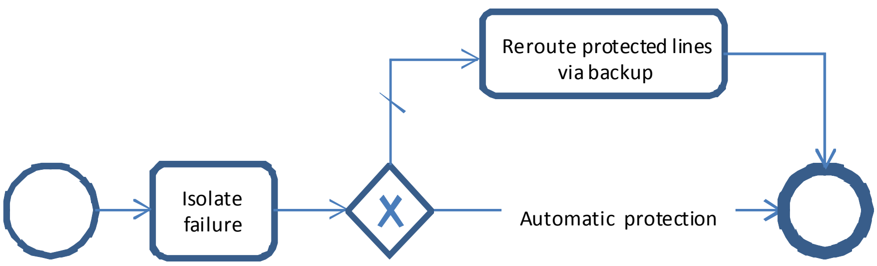


Figure 12 Fault isolation and traffic recovery sub-process

If it is a configuration failure, then the *configuration failure solving* is performed, and a test is executed to verify that normal functioning has been correctly restored. If it has been repaired, the TT will be closed and the process ends. Otherwise, the *fault diagnosis and isolation* will be performed once again.

If it is a physical fault, a physical fault repair sub-process is executed, which is shown in Figure 13. This sub-process first distinguishes whether the repair is outsourced or not. If it is outsourced, a failure report is submitted to the outsourcing company. This company processes the report and repairs the failure within the agreed time and quality. If the repair is not outsourced, the operator has to diagnose whether it is a cable or an equipment failure. If it is a cable cut (CC) failure, the sub-process CC failure repair is performed for which a detailed description is shown in Figure 9. If it is an equipment failure, the operator has to check whether the required manpower, material, spare components and mobility means for the failure repair are available. Furthermore, if digging is required, it is subcontracted and the repair has to wait until the pavement is open. When all the prerequisites are accomplished, the technicians travel to the failure location and they repair or replace the failed component. Once the failure has been repaired, a line test is performed (shown in Figure 14) to check whether there is connectivity and the signal quality is above the required value. If the quality is good, the TT can be closed. Otherwise, the components and lines are checked again. If the problem continues to be unsolved, the fault diagnosis and isolation is performed once again.

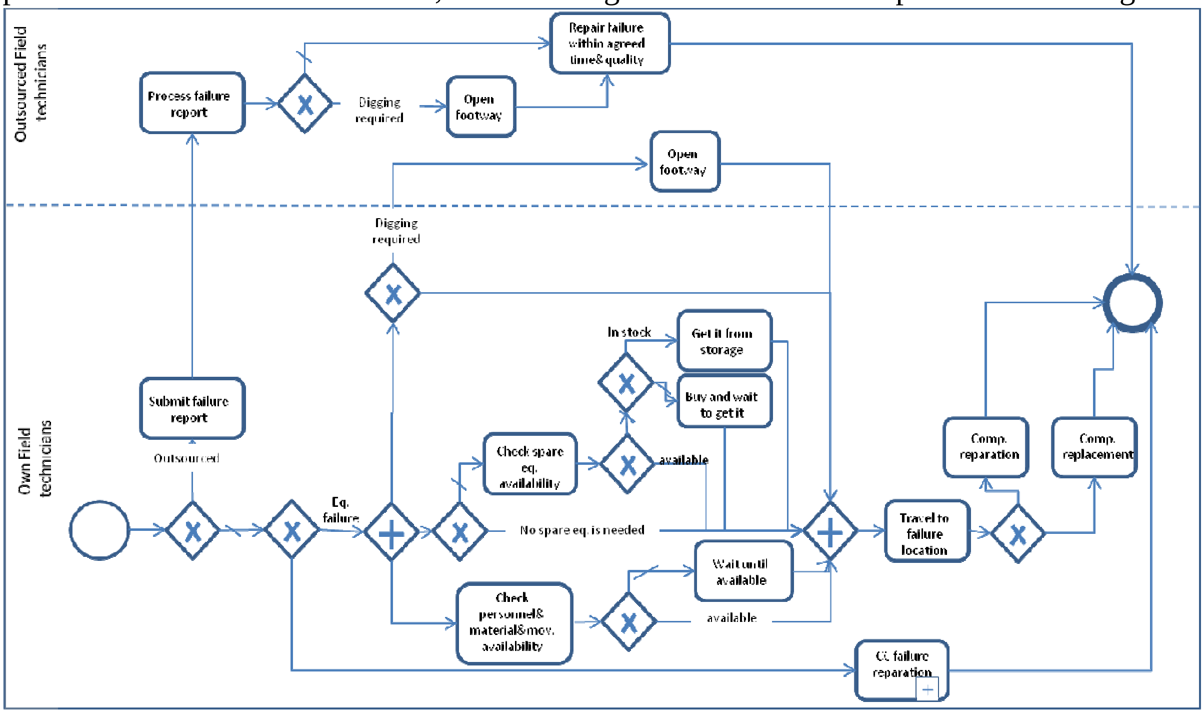


Figure 13 Fault reparation sub-process model

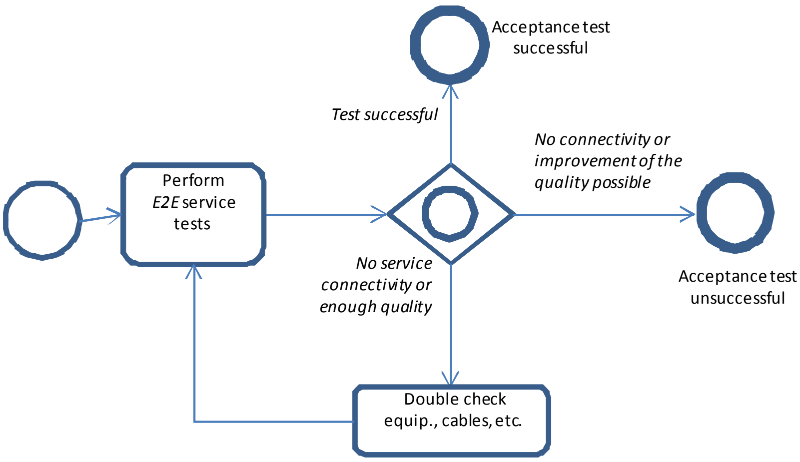


Figure 14 Line test sub-process

The fault reparation sub-process will be considered in more detail as shown in Figure 13. It is expected to cause the highest delta on operational expenditures between the different architecture designs. The process chart differentiates between self-realisation and outsourcing. Digging work will always be outsourced. In case of self-realisation, the check and gathering of available personnel and equipment, the travelling to the failure location as well as fault reparation, or if not possible, component replacement will be considered. For this, required labour time as well as cost for repair material and spare components has to be taken into account for detailed modelling.
The cost evaluation of this process depends on the number of faults occurred in the network. Customer troubles not caused by the network, as for instance CPE configuration problems, are not in the scope. For the estimation of the amount of failures network component specific parameters like FIT rates and MDT have to be determined. Resilience concepts of WP3 have impact on the E2E network availability and failure penetration ranges. However, at higher number of network components that is required for the realisation of resilience concepts will likely result in a higher amount of network failures in total, except when having automatically service re-routing without customer impact and thus less helpline received calls. The E2E availability is service specific and depends on the path through the network (e.g. voice versus client server applications). The maximal failure penetration range will be determined by the single-point-of-failure (SPoF) element with the highest customer aggregation and may also vary for different services if a certain service does not flow through this element (it depends e.g. on service creation and content distribution architecture).
After the reparation, a fault recovery acceptance test will be performed before sending a ready message back to the customer relationship and/or network management department.
For architecture differentiation of the fault management cost, the different failure types must be distinguished. These are for instance hardware failure (e.g., I/F, fabric, WSS, RE …), configuration and software failure (e.g., DCN, EMS, NMS) and failures of the passive infrastructure (e.g. splitter, AWG, fibre cable, patch connectivity failures).

3.2. Service Provisioning

This section introduces the modelling for service provisioning which includes any activity related with adding, changing or cancelling customer services. For service provisioning, no fully detailed processes exist in literature.

Service provisioning is expected to be an operational process that will differentiate the operational costs of different NGOA solutions. The required fibre or equipment to connect a new customer, the possibility of remote configuration, the type of required ONT, etc. will impact the final cost. In this section, the general requirements for service provisioning for NGOA as well as the proposed service process model are presented.

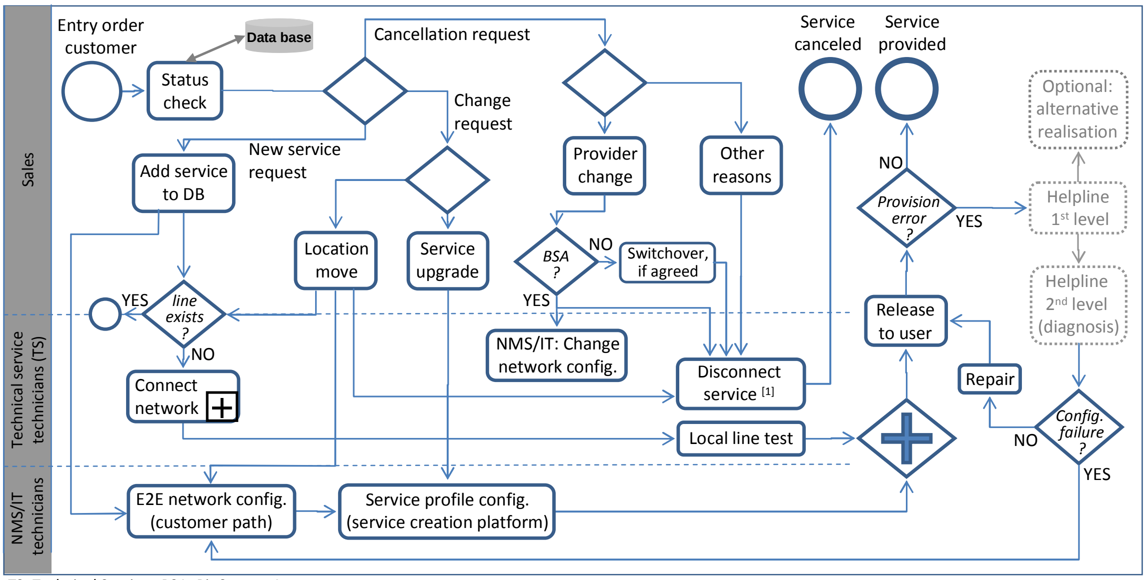
The NGOA operation capabilities that are expected to impact the service provisioning are:

- The possibility of "zero-touch provisioning" after initial roll-out
    - Physical network to be prepared up to the homes during basic roll-out, if economically viable
    - DIY installation of ONTs (plug & play capable)
        - Auto-configuration of ONTs up to the Service Creation Points
        - Single-sign-on for service connectivity
    - Non-disruptive service changes and service upgrades have to be supported including web-based customer self-provisioning and self-configuration
- Portability of customer identification data, e.g. for location move (nomadic services)
- ONTs within a customer group should not be customer specific (means e.g. "colourless")
    - However, the potential of a universal ONT needs to be analysed.
    - Customised ONTs for residential users, business users as well as mobile and wireline backhaul are likely to be required in order to meet the different needs.

The service provisioning process deals with the overall order handling procedure of adding, changing or cancelling services of the customers. The process model is shown in
Figure **15**.

- Add service: In order to add a new service, two activities are triggered in parallel: the first one deals with the physical connectivity, and the second one is related to the configuration of the customer service profile and service path through the network. The service is not to be released to the customer until both activities are successfully completed. In particular, the first activity checks whether there is physical connection and available capacity or not. If there is not enough capacity, a new physical connection has to be added (called "connect network" sub-process). The detailed model of this sub-process is shown in
- Figure **16**. It can be observed that the connection can be outsourced or done by the own technical personnel. In the latter case, the connection will be done once the personnel and resources are available at the connection location. Once the connection is done, tests to guarantee a good signal quality are performed before this activity is successfully completed. The second activity configures the service from a central NMS desk. A detailed description of the configuration tasks is not the focus of this document.
- Change service: A customer may request a change of a service because of his/her new location or because the customer wants an upgrade of the service (e.g. more bandwidth). If there is a new location, the operator has to check whether there is physical connection with enough available capacity or not. If there is capacity, the service has to be re-configured to the new customer's location. Otherwise, new physical connection has to be added before configuring the service.

- Cancel service: A customer may request a cancellation of his/her service because he/she wants to change provider. In this case, the operator has to check whether there is a bit-stream access. If so, the service can be re-configured through the NMS. Otherwise, the service is switched over to the new provider and removed from the current one.



TS: Technical Service ; BSA: Bit Stream Access
Connecting is the process of establishing the physical e2e connectivity incl. optical splices, connectors, fiber patching, …
Configuration is the process of establishing the logical e2e service connection through network and IT.
Testing is the process of testing the physical and logical connectivity before release of the service to the customer.

[1]: WP2 req.: zero touch after initial rollout → therefore no network disconnection

Figure 15 Service Provisioning process model

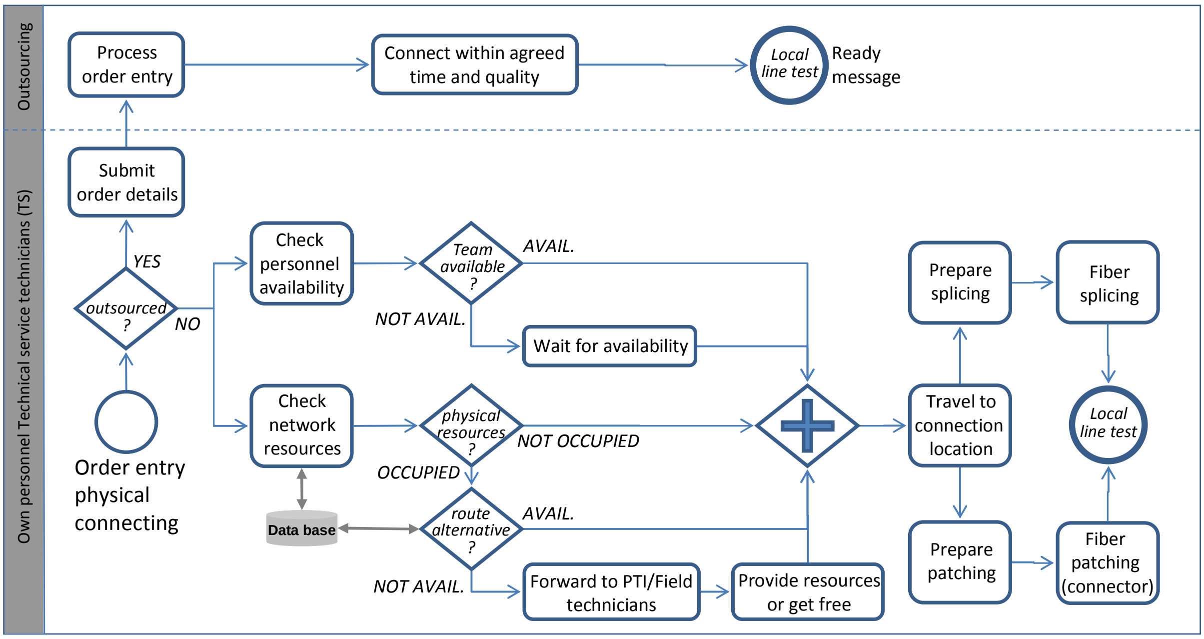


Figure 16 Connect network sub-process model

3.3. Maintenance

The maintenance process comprises all tasks which are required to keep the network up and running. This includes also software release updates and hardware upgrades (e.g. new controller line cards). However, the hardware upgrades do not comprise any migration towards new technical architecture generations. The three main process tasks are:

Updates & Restoration

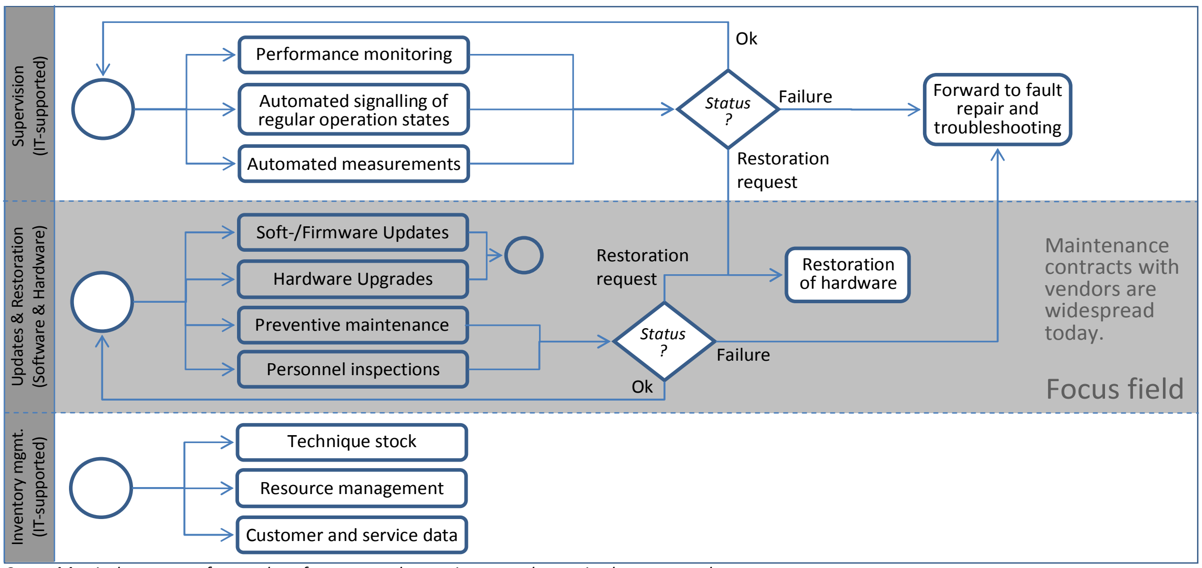
- Periodic, proactive and preventive preservation of network elements & support equipment
- Battery reloads, filter changes, …
- Software release updates
- Hardware upgrades
- Personnel inspections
- Change of technical components in case of incorrect functioning

Inventory-Management

- Technique stock with allocation to storage locations
- Resource management (personnel capacity, materials, reserve planning, …)
- Customer profile data incl. SLAs

Supervision

- Performance monitoring
  - SLAs are target parameters for performance monitoring
  - Availability, QoS performance,
  - Threshold, Trend analysis, …
- Automated signalling of regular operation states
- Automated measurements



***Supervision** is the process of network performance and operation state observation by automated measurements.*
***Updates & Restoration** is the process of software and hardware upgrades as well as preventive maintenance and restoration.*
(Note: The hardware upgrades do not comprise any migration towards new technical architecture generations.)
***Inventory management** is the process dealing with the management of technique and service inventory data and resources.*

Figure 17 Maintenance process model

NGOA networks should be highly automated and manageable for simplified and less time consuming work in the field (without special tools). This includes for instance remote manageability of active network elements, remote auto-configuration and management of customer equipment and optical layer management where technically viable. Also seamless software (SW) upgrade without service interruptions has to be supported (e.g. firmware updates on NE or CPE). Supervision and monitoring capabilities ensure E2E service/traffic performance monitoring per customer and per service (supervision), detection of service quality degradations ahead of time in order to be able to trigger preventive maintenance before customer/service impact. Personnel intensive periodical maintenance actions such as inspection, remote testing, cleaning, adjustment etc. should remain minimal. The maintenance deals also with the renewal of supporting components such as filter mat etc., and the restoration or replacement of defect network elements which are not (yet) recognised as a failure by interacting with the fault management. Maintenance contracts especially with active system vendors have widely used today.
For the TCO assessment, a simplified calculation approach will be considered taking into account the following assumptions:

- 2 maintenance orders per year per fully equipped OLT equivalent
    - 8 Person hours per year (incl. maintenance of shelf facilities and SW updates)
    - 400 € material (e.g. filter mat change etc.)
    - SW licence (once per year for all systems per system class)
- 1 maintenance order per year per fully equipped active RN equivalent
    - 4 Person hours per year (incl. maintenance of shelf facilities and SW updates)
    - 100 € material (e.g. filter mat change etc.)
    - SW licence (once per year for all systems per system class)
- For infrastructure components like fibre cables and optical splitters, a maintenance-free operation is required and will be assumed in failure-free situations. The cost impact of infrastructure failures will be considered in the fault management process.

3.4. Power Consumption

Optical integration and node consolidation will allow higher compactness, better utilisation of active systems and fewer powered locations with expected positive effect on power consumption. Although the number of consolidated access nodes is less than the number of traditional access nodes, the total power consumption depends on the real system design and the support of power-saving modes such as power down and sleep modes. The total power consumption at each consolidated access nodes might become higher (than at the former access nodes) due to the fact that it will serve a higher number of users and therefore, it will needs a higher number of components. This will be compared with the power consumption savings at all former access nodes[1].
The power consumption will be calculated per base system (OLT, RE, ONT), per line-card and per pluggable as well as for climate facilities. The OLT power consumption will be differentiated by shelf/backplane and L2-switch unit. The price per kWh usually depends on the consumption volume per location type (small, medium, large) as well as the price mix and tariffs of the power supplier.
The number of network locations with required power supply and climate facilities depends on the topology scenario. Figure 18 and

[1] Power consumption values and the impact of power-saving modes are defined by WP4.

Figure 19 show exemplarily a power supply for the OLT in the CO and in the field e.g. for a Reach Extender.

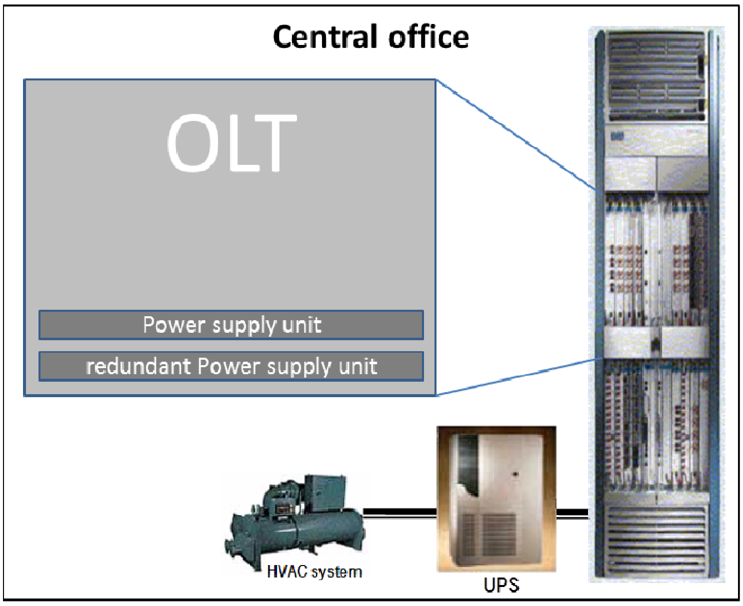


Figure 18 Power supply in CO

Contracts with power suppliers often comprise an annual payment fee per provided connection power [€/kW p.a.]. This payment fee includes, in addition to the pure power consumption [kWh] per system as defined by WP4, all costs for power supply and climate facilities as well as its maintenance and operation.

Central Office (CO) power supply considerations

- Investment for protected power supplies (UPS)
- Investment for required climate facilities (HVAC)
- Required reserve capacity of power and climate facilities, e.g. for overlay migration
- Effort for maintenance and operation of power and climate facilities

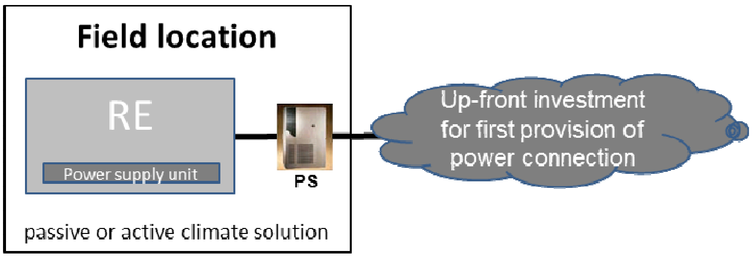


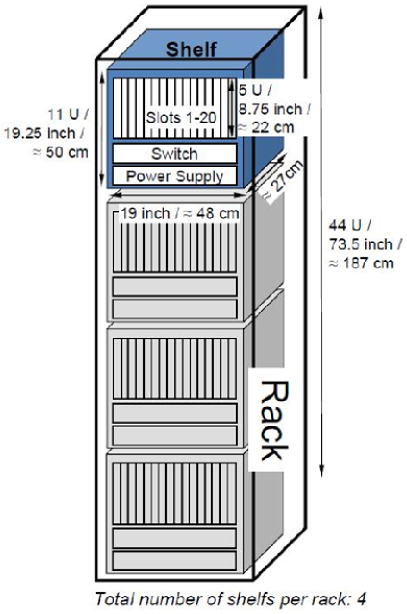
Figure 19 Power supply in the field

Field location power supply considerations

- Up-front investment for first provision of power connection in the field (one-time)
- Investment for power supply termination unit (e.g. for RE)
- Investment for passive or active climate facilities (depends on implementation scenario)
- Required reserve capacity of power and climate facilities, e.g. for overlay migration
- Effort for maintenance and operation of remote power supply

3.5. Floor Space

Floor space means the space demand that is needed to install, operate and manage the system technologies (switches, OLTs, WDM coupler) which are typically installed in shelf racks. In addition to the active system racks, some architecture variants require pure passive shelf racks e.g. for WDM couplers. Also the space demand for the termination of the fibre cable infrastructure at the Optical Distribution Frame (ODF) and the through-connection to the systems racks via in-house cabling have to be considered.
Figure 20 shows exemplarily the space demand calculation from WP4 for the model 19" system rack which can accommodate up to 4 system shelves, depending on the varying power consumptions and heat conditions of the different NGOA architecture variants. This model defines the maximal power consumption per rack to 6 kW, which potentially limits the number of shelves and ports per rack.



- 4 shelves per rack (19 inch)
- Number of ports per shelf depending on the system technology
- Footprint per rack: 0,6 m x 0,3 m = 0.18 m²
- Work space per rack: 0,6 m x 1,0 m = 0,60 m²
- Footprint per rack incl. work space: 0.18 m² + 0,60 m² = 0,78 m²

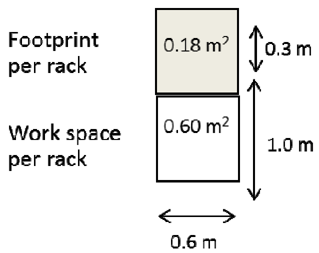


Figure 20 Floor space model

Details of port-density, power consumption and heat loss per system have been described in WP4 for the regarded NGOA architecture variants.

4. Outside Plant Estimation Models

This section introduces different models that can be used to dimension the network infrastructure. The first one is the Geometric model, which is the one used by TONIC [6]. However, other tools can also be used as presented in Section 8.2.

4.1. TONIC (Geometric) Model

The TONIC model follows the approach as described in the Deliverable 7 of the IST TONIC project [6]. Within OASE, the reference architecture point model is the basis for a work package overarching discussion and TONIC was adopted accordingly. More details can be found in the following paragraphs. The reference architecture point model is described and documented in D3.1 [7] Section 2.
The geometric model distinguishes between three different area types, dense urban (DU), urban (U) and rural (R). Each of this area types differs in certain aspects like number of customers and related households/business offices, number of buildings, different fiber and trenching lengths etc. The businesses are split in-between SME and even larger companies, which are expected to be high bandwidth demanding customers. For large The detailed numbers can be found in Table 1.

	Dense Urban	Urban	Rural
Area size km²	5	24	57
Buildings	2.400	3.456	2.040
Households (HH)	14.500	8.400	3.035
SME business	1.100	240	25
Large business	5,5	1	0,05
Total subscribers	15.600	8.640	3.060
HH density / km²	2.900	350	53
SME density / km²	220	10	0
Large business density / km²	1	0	0
Total subscriber density / km²	3.120	360	54

Table 1 General parameters describing area types

The number of required connections is based on the total number of households and businesses. It is assumed that the business customers (high bandwidth business) demand a higher connectivity which could be provided by a single, not shared, fibre only. Overall, this special group of customers does not have a huge effect on the model and a number of additional fibres are included to serve them (which is calculated as an additional number of fibres per building).

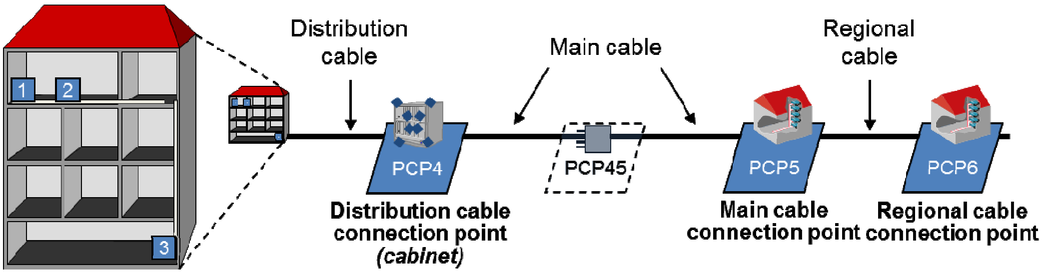


Figure 21 Adopted Reference Architecture Points

The reference architecture model was adapted to the geometric model used in TONIC. So far, only PCP2 to PCP5 were included but the model will be extended with PCP6 later. After feedback from different operators, an additional PCP had to be included between PCP4 (distribution cable connectivity point) and PCP5 (main cable connectivity point). This additional point (PCP45) is a branching box point and bridges in the main cable section from PCP5 to PCP4 between two different deployment strategies, a combined bus-star structure (see Figure 21). A complete duct is not required at each PCP4 and therefore a sharing of ducts between different PCP4 is organized. The most effective way to do so is to aggregate ducts at each point where full ducts could be combined to duct bundles in trenches. So there are two bus structures, one connecting the outer PCP4 with each other to a more centralized PCP4 and a second bus structure between the different, more centralized PCP4. This point is by itself a branch and PCP4, but at the duct layer it is an additional point, the PCP45. The respective main cable section is split into main cable 1 and main cable 2. Overall, the different numbers for the PCP could be found in the Table 2 below.

Area	PCP2	PCP3	PCP4	PCP45	PCP5
Dense Urban	15600	2400	100	20	1
Urban	8640	3456	64	16	1
Rural	3060	2040	30	6	1

Table 2 Number of physical connection points (PCP) in OASE area types per PCP5

It was decided to use an infrastructure model based on the following assumptions:

- Fibres are aggregated in cables
- Cables are placed into micro-ducts
- Micro-ducts are aggregated in micro-duct bundles
- Micro-duct bundles are placed into multi-tube of duct
- Multi-tubes are placed into ducts
- Ducts are placed in trenches

It should be noted that various options exist and a concrete model / implementation is required. Based on different cost calculations, the optimal solution for the OASE area types was developed and can be found in
Table 3. Cables are required to be either laid into a tube directly (building cable section) or in a micro-duct. Micro-ducts are always used as micro-duct bundles only and these bundles need to be installed in the multi-tube or buried directly in the underground (respective in trenches).

Infrastructure	Building	Distribution	Main cable 1	Main cable 2
Fibre	X	X	X	X
Cable	X	X	X	X
Micro-duct		X	X	X

Micro-duct bundle		X	X	X
Multi-tube			X	X
Duct / Tube	X	X*	X	X

Table 3 Infrastructure implementation in cable section

In the distribution cable section, the ducts are only used if they are already available (brown field scenario), otherwise the micro-duct bundles are laid directly into the ground. This is marked by (*) in Table 3.
Due to the constraints of available cables, micro-duct bundles and tubes, the following infrastructure equipment could be used:

- Fibre cable with 4 fibres
- Fibre cable with 12 fibres
- Fibre cable with 16 fibres
- Fibre cable with 24 fibres
- Fibre cable with 48 fibres
- Fibre cable with 72 fibres
- Fibre cable with 96 fibres
- Fibre cable with 128 fibres
- Fibre cable with 144 fibres
- Micro-duct bundle with 1 x 7mm micro-ducts
- Micro-duct bundle with 6 x 7mm micro-ducts
- Micro-duct bundle with 10 x 7mm micro-ducts
- Micro-duct bundle with 20 x 7mm micro-ducts
- Micro-duct bundle with 3 x 10mm micro-ducts
- Micro-duct bundle with 5 x 10mm micro-ducts
- Fibre termination box large (Cross-connect for max 50 fibres)
- Fibre termination box small (Cross-connect for max 10 fibres)
- Duct multi-tube 4
- Duct 100mm
- Branching box for 192 fibres
- Optical Distribution Frame (ODF) for max 2000 fibres (calculated per fibre only)

In addition, there are some constraints regarding the infrastructure which could be used with each other. The combination of duct, multi-tube, micro-duct bundles and micro-ducts can be found in Figure 22 below.

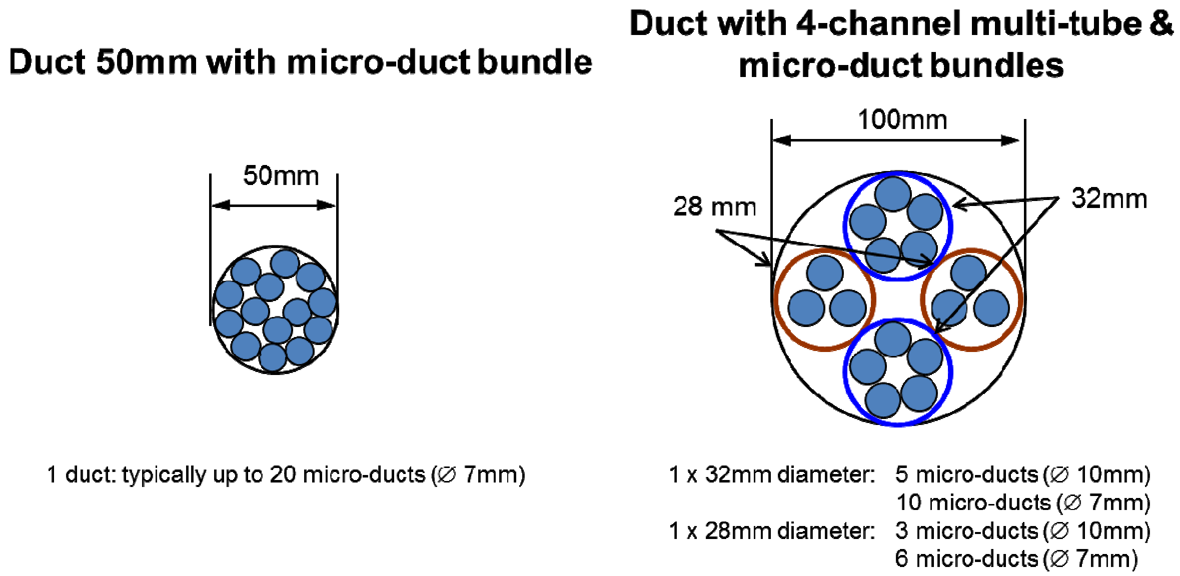


Figure 22 Combinations of infrastructure equipment

The duct of 50mm size is only available in brown field scenarios and cannot be used in new deployments. If this infrastructure equipment is available, it is possible to deploy a micro-duct bundle with 20 x 7mm micro-ducts inside. The duct with 100mm provides more options:

1. Duct is split into four with a multi-tube
2. Multi-tube provides option for 2 x 28mm tube and 2 x 32mm tube
    a. A 28 mm tube provides sufficient space for a micro-duct bundle with 3 x 10 mm or Micro-duct bundle with 6 x 7mm micro-ducts
    b. A 32 mm tube provides sufficient space for a micro-duct bundle with 5 x 10 mm or Micro-duct bundle with 10 x 7mm micro-ducts
3. Micro-duct provides a capacity depending on the diameter
    a. 7 mm micro-duct provides sufficient space for a cable with up to 96 fibres
    b. 10 mm micro-duct provides sufficient space for a cable with up to 144 fibres

In order to analyse the impact of our infrastructure component model, different availability scenarios of ducts have been taken into account. These scenarios reflect no general information of deployed networks today as a deployment of infrastructure is typically heterogeneous and depends on the desired number of buildings and customers to be connected.
Figure 23 shows the four different models with the related availability of 1, 2 and 3 ducts, buried and aerial cable for the different OASE area types and the main and distribution cable section. It is always assumed that highest number of deployed ducts is closest to the PCP5, followed by the second highest and so on.

Empty conduit diameter

100mm
50mm

			++			+			-			--		
			DU	U	R	DU	U	R	DU	U	R	DU	U	R
percentage of main cable duct length	duct Ø100mm	1 empty duct	30%	25%	50%	15%	20%	20%	5%	15%	15%	30%	20%	8%
		2 empty duct	34%	33%	5%	39%	18%	5%	49%	23%	5%	14%	5%	2%
		3 empty duct	30%	15%	0%	25%	10%	5%	15%	5%	5%	5%	3%	0%
	Buried cable		5%	25%	40%	20%	50%	65%	30%	55%	70%	50%	70%	85%
	Aerial cable		1%	2%	5%	1%	2%	5%	1%	2%	5%	1%	2%	5%
percentage of distribution cable duct length	duct Ø50mm	1 empty duct	40%	20%	10%	20%	10%	5%	2%	3%	3%	7%	5%	1%
		2 empty duct	30%	10%	5%	20%	5%	3%	20%	5%	3%	5%	3%	0%
	Buried cable		27%	63%	71%	57%	78%	80%	75%	85%	80%	85%	85%	85%
	Aerial cable		3%	7%	14%	3%	7%	14%	3%	7%	14%	3%	7%	14%

Figure 23 Availability of ducts in OASE area types and cable sections

In addition to ducts and cables, there are some additional infrastructure components needed for various PON scenarios:

- Power splitter 1:4
- Power splitter 1:8
- Power splitter 1:16
- Power splitter 1:32
- Power splitter 1:64
- AWG 1:80

In case of AON scenarios, there are two technology options which influence the number of fibres required in the cable sections (and therefore for certain components carrying infrastructure in the PCP, e.g. number of required branching boxes): the single- or dual-fibre option. The single-fibre technology is using one fibre for sending and receiving light and is a more costly than the dual-fibre options which uses separate fibres for sending and receiving.
Overall, for the dimensioning of the infrastructure components in the PCP and cable sections, the combination of the different components is required. In the following, no detailed dimensioning will be presented as the model is scenario selective and depends on a number of parameters. Results should thus be understood as case sensitive.
The bridging between the cable sections is organized in the PCP and different kinds of activities are required. This includes

- Termination of fibres
- Splicing of fibres
- Preparation of cables for termination
- Termination of micro-ducts / micro-duct bundles
- Interconnection of micro-ducts / micro-duct bundles
- Termination of ducts / multi-tubes
- Interconnection of ducts / multi-tubes

Individual fibres or micro-ducts are not installed separately. Micro-ducts are terminated in the building (PCP3) and cabinets (PCP4), but interconnected in PCP45 only. All details can be found in the Table 4. If certain equipment is required at a location, this is noted too.

Area	PCP2	PCP3	PCP4	PCP45	PCP5

Termination of fibres	X	X			X
Splicing of fibres	X	X			
Preparation of cables	X	X			X
Termination of micro-ducts / bundles		X	X		X
Interconnection of micro-ducts / bundles				X	
Termination of ducts / multi-tubes			X		X
Interconnection of ducts / multi-tubes				X	
Required Equipment		Fibre termination box	Branching box		(ODF)

Table 4 Activities in PCP for integration of infrastructure components

Based on this information, the number of required infrastructure components and activities can be calculated. However, for cables, fibres, ducts etc., the length is required too. The modelling of this parameter is described in the upcoming paragraphs and figures below.

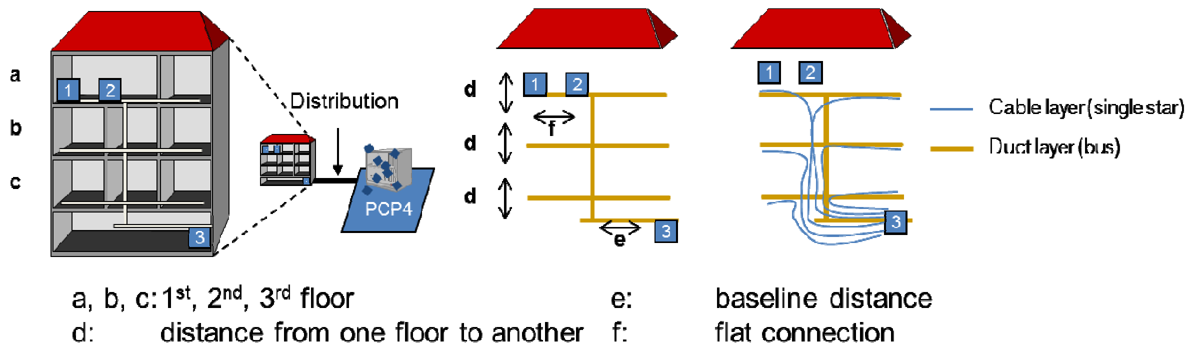


Figure 24 Calculation of length of infrastructure components in building cable segment

The calculation inside the building is rather simple and illustrated in Figure 24. The following aspects are calculated:

- Number of floors per building (Figure 24 “a”,” b”, “c”)
- Distance between floors (Figure 24 “d”)
- Number of flats per floor (e.g. 2)
- Distance between flat and duct (Figure 24 “f”)
- Distance to bridge between lowest floor and basement connection (PCP3) (Figure 24 “e”)

The duct length is calculated based on an assumed tree structure (star at each floor, bus between PCP3 and the highest floor) and the cable length on a single star model between PCP2 (each flat) and PCP3 (building connection in the basement).
The second part right outside the building is the distribution cable section between PCP3 and PCP4. Lengths are determined by the following aspects:

- Number of deployment directions per PCP4 (Figure 25 “a”)
- Number of buildings per deployment directions (Figure 25 “b”)
- Distance between buildings (Figure 25 “c”)
- Distance between duct route and building (Figure 25 “d”)

Similar to the building cable segment, the micro-/duct length is calculated based on an extreme scenario of a tree structure (bus structure for main duct route and for each building a separate small bus) and the cable length is based on a single star model between PCP3 and PCP4.

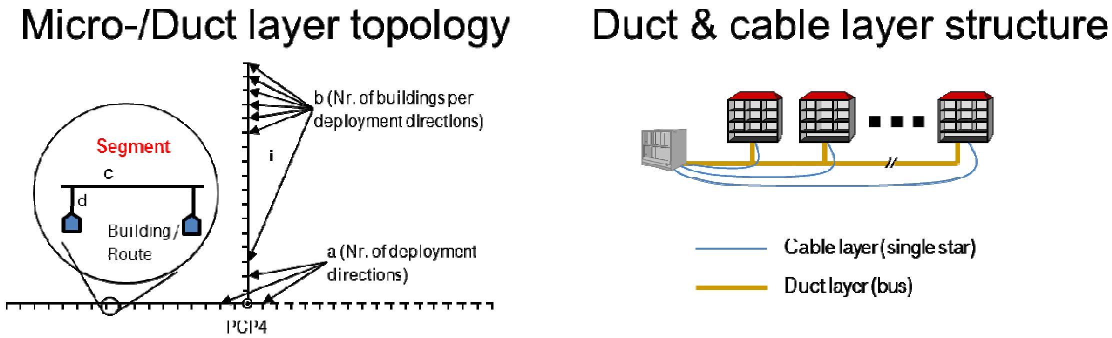


Figure 25 Calculation of length of infrastructure components in distribution cable segment

The third and last part for the calculation of the length is the main cable segment. As already discussed, this segment is more complicated due to a mixture of different infrastructure hierarchies and related deployment structure. A graphical model can be found in the Figure **26**.

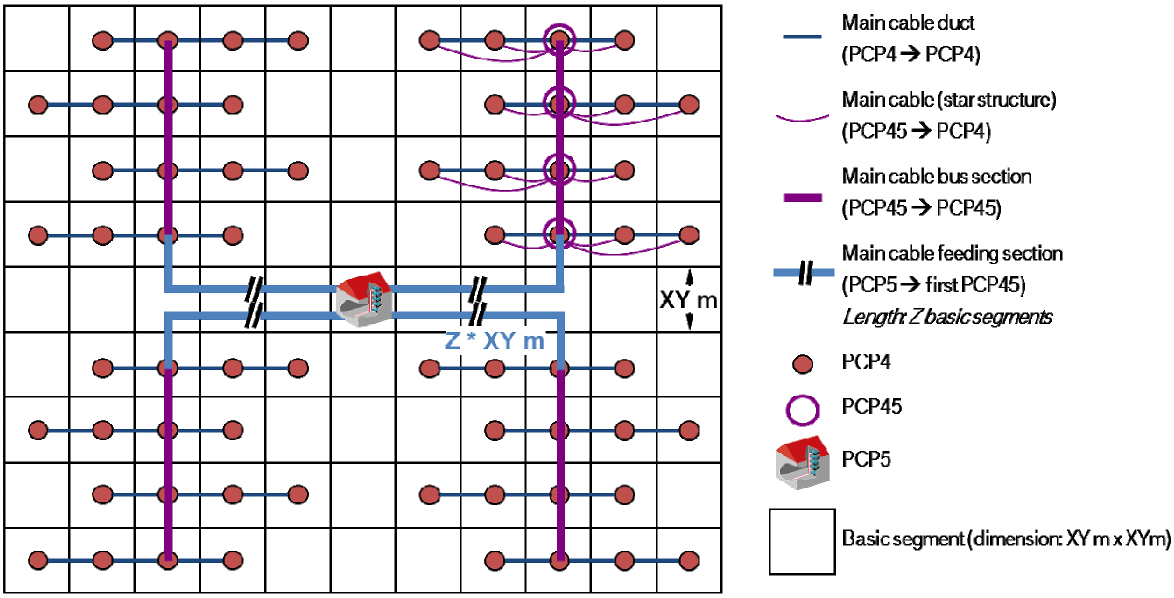


Figure 26 Calculation of length of infrastructure components in the main cable segment

First, an area and its related size in km² is split into basic segments of equal size, each basic segment representing the coverage area of one PCP4 (it should be noted that the PCP4 covered by PCP5 are not shown in
Figure 26). The basic segment is represented by a square with a size of XY m * XY m and it is assumed that the PCP4 is in the center of the basic segment. The PCP4 are organized in the following ways:

- A number of deployment directions exists from PCP5
- The main cable feeding section is Z multiples of the segment, representing the fact that PCP3/PCP4 close to the PCP5 are connected directly to the PCP5
- These deployment directions (main cable bus section) are represented by a bus structure, connecting several PCP45 (which by itself represent a PCP4)
- At each PCP45 an additional bus structure organizes a second level of PCP4 (main cable duct)
- The micro-duct / cable layer is organized as a star structure between PCP5 and PCP4; no intersection at PCP45 (one OASE model assumption, other models are possible) only interconnection from one micro-duct to another

The detailed calculation requires the following steps:

- Calculation of number of terminated fibres per PCP4
- Calculation of number of micro-ducts per PCP4 to carry terminated fibres (based on the available infrastructure equipment, see Figure 22 and related explanations)
- Calculation of number of required micro-ducts in main cable duct
- Calculation of number of required ducts in main cable duct
- Calculation of number of required micro-ducts in main cable bus section
- Calculation of number of required ducts in main cable bus section
- Calculation of length of cable(s) per PCP4 to PCP5

Based on these numbers and the desired infrastructure model (including the duct availability), the length for the different layers (cables, duct, etc.) can be calculated per segment.

4.2. Alternative Analytic Models

Alternative models are possible and under investigation in the OASE project. This section shows two alternatives to the TONIC geometric model and their extensions with consideration of resilience which are used as standard and benchmark in the TONIC implementation.

4.2.1. Block clustered customers

This model dimensions access networks using the Manhattan network model for urban areas and distributing users along rings for rural areas as shown in Figure 27.

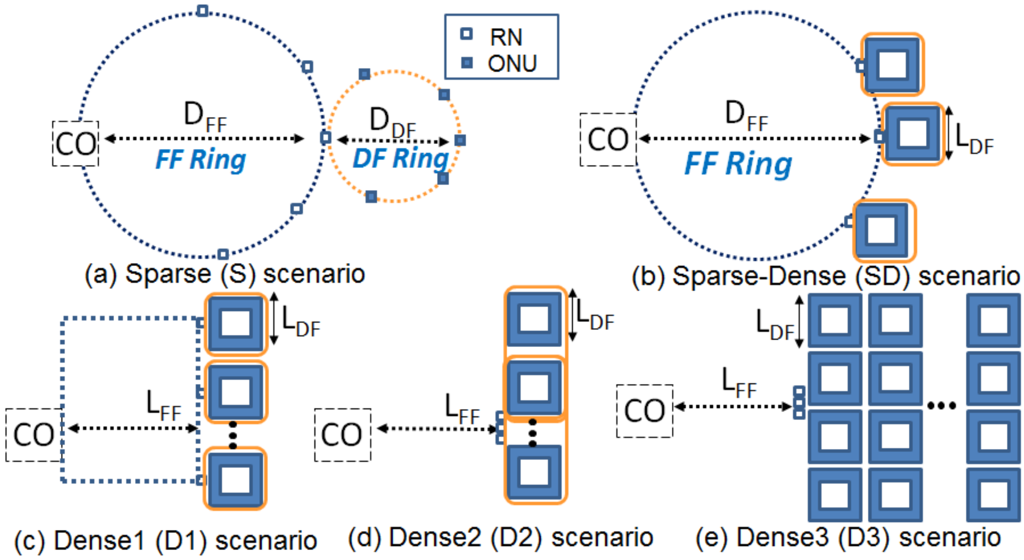


Figure 27 Fibre layout configurations for different populated areas

For rural areas:

Two different variants have been considered:

- ***Sparse (S) scenario:*** This scenario corresponds to the areas where both ONUs and RNs are sparsely populated and can be distributed along a ring (Figure 27a). An operator would dig along the partial ring adding RNs to the FF and ONUs to DF. The FF ring has a diameter of D_{FF} and the DF ring has a diameter of D_{DF}. Our proposed protection will be offered by closing the FF and the DF rings and burying the protection fibre in the opposite direction.
- ***Sparse-dense (SD) scenario:*** This scenario combines the sparse RN distribution with a higher concentration of users (e.g. residential/business clusters). The RNs are distributed along a partial ring similarly to the previous scenario. The users are distributed following the Manhattan network model, which is a square grid distribution of users. L_{DF} denotes the length of block and street side (see Figure 27b). We take the value from [2] and set L_{DF}=0.133km. In this case, in order to serve all the users of the same block, a DF duct around the block has been assumed (Figure 27b). The protection is achieved by closing the ring and burying protection fibres in the opposite direction.

For urban areas:

This scenario assumes that RNs and ONUs are located in a network compatible with the Manhattan network model. Three different variants have been considered:

- ***Dense1 (D1):*** The RNs are located in the same "vertical" street, each placed at the block they are serving. We let L_{FF} denote the distance from the CO to this vertical street for FF length calculation (see Figure 27c). The unprotected FF connects CO with each RN, whereas the protected proposed scheme closes the FF ring following the street distribution (Figure 27c).
- ***Dense2 (D2)***: The RNs are co-located at the closest point to the CO, whereas the ONUs are distributed similarly to D1 scenario (Figure 27d). The FF follows a straight line from CO to RNs and the protected solution installs a protection FF through the parallel street. The DF rings are designed to achieve fibre disjoint rings.
- ***Dense3 (D3)***: This scenario (Figure 27e) is identical with D2 scenario except that the DFs are required to serve multiple arrays of blocks. The protected DF rings can have different layouts to achieve fibre disjoint rings while using as much common ducts as possible.

Input:

Number of users	integer value
splitting ratio	integer value
protected or unprotected	choice
ring or Manhattan network structure	choice

Calculations:

Based on the maximum allowed transmission distance, homogeneously distribute users along the ring or in parallel blocks (Manhattan network model) as shown in the figure below

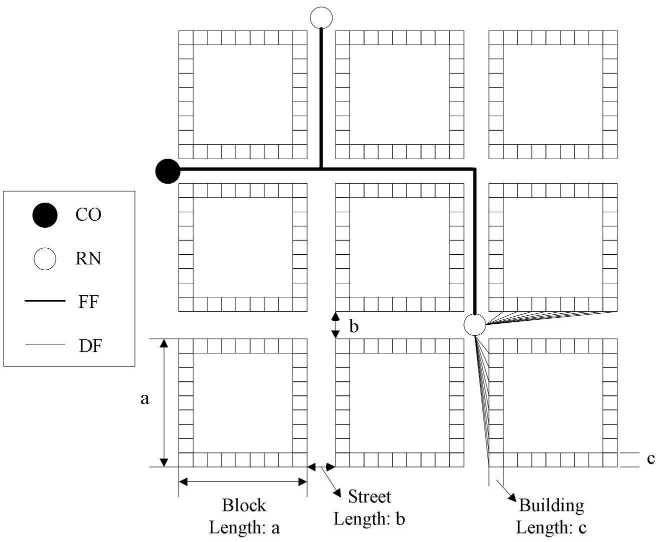


Figure 28 Manhattan network model

Output:

number of remote nodes	integer value
trenching length in km	real value
fibre length in km	real value
travel distance from OLT to any equipment in the network, avg in km	real value

4.2.2. Customers evenly spread over the area

Another approach for analytically approximating or estimating models for both installation length (e.g. trenching) and fibre length consider a given area expressed in terms of customer count and area size. The customers are assumed to be evenly spread over the full area as shown in Figure 29. This figure also shows how different connection types can be used for connecting all customers to the central physical connection point. For all these connection options, the analytical calculation formula is shown in what follows taking you from input to the calculation and rendering the output in terms of trenching and fibre length.

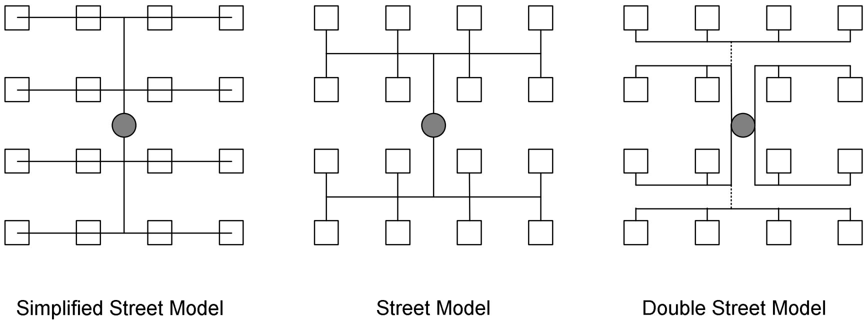


Figure 29 Analytical installation models for customers evenly spread over the area

Input:

Total number of customers	integer value	C(ustomers)
Area size in squared km	double value	A(rea)
Selection of the model	choice	
Width of the street	integer value	W(idth)

Calculations:

A full description of the calculations can be found in the Appendix.
The following models and calculations can be used:

Simplified street model:

Installation length $$(C-1)\cdot\frac{A}{C}$$

Fibre length $$4\cdot\frac{A}{C}\cdot\sum_{1}^{\sqrt{C}-1}\left[\min(i,\sqrt{C}-i)\cdot(\sqrt{C}-i)\right]$$

Street model

Installation length $$(C+\frac{\sqrt{C}}{2}-2)\cdot\frac{A}{C}$$

Fibre length $$4\cdot\frac{A}{C}\cdot\sum_{i=1}^{\sqrt{C}/2-1}\left[2\cdot\min(i,\sqrt{C}/2-i)\cdot\left(\left(\sqrt{C}/2-i\right)\cdot 4+1\right)\right]$$

Double street model

Installation length	$\left(3 \cdot \frac{C}{2} + \sqrt{C} - 4\right) \cdot \frac{A}{C} - \left(\frac{C}{2} + 2 \cdot \sqrt{C} - 4\right) \cdot W$
Street Crossing length	$\left(\sqrt{C} - 1\right) \cdot W$
Fibre length	$4 \cdot \frac{A}{C} \cdot \sum_{i=1}^{\sqrt{C}/2-1} \left[2 \cdot \min(i, \sqrt{C}/2 - i) \cdot \left(\left(\sqrt{C}/2 - i\right) \cdot 4 + 1\right)\right] - \frac{C}{2} \cdot W$

Output:

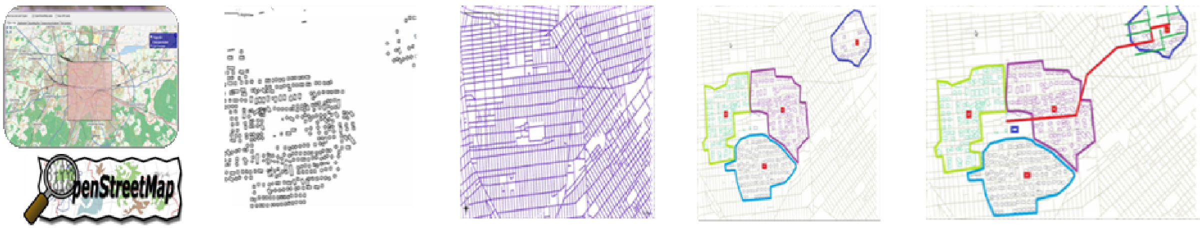
Trenching length (km)	double value
Fibre length (km)	double value
Street crossing length (km)	double value

4.2.3. Model based on real street map

This model is based on real topographical and demographical data which is publicly available. In order to obtain and analyse the required topological data, geographic information systems (GIS) had to be used based on the OpenStreetMap (OSM) project [8]. Based on this data, the following steps are followed:

1. Import into the postgesql database, the .osm data containing the Geo coded information of the area's buildings and the respective street network
2. Based on these data, construct a weighted graph of the street network, on which routing algorithms can be applied
3. Assign ONUs to buildings with respect to their size
4. Apply a clustering algorithm, that clusters ONUs into groups of size determined by the splitting ration of the used technology (e.g. number of AWG ports), assigns them to a respective RN, and estimate the optimal location for that RN as to minimize the distribution cabling.
5. Facilitate the routes. Determine the distribution cabling paths connecting the ONUs to their remote nodes, and the feeder cabling paths connecting the RNs to the central office as well as their protection paths. The cabling layout is computed based on a modified Dijktra's shortest path algorithm whose target is to minimize the cabling length since it is related to the high trenching cost. The same applies for the computation of the feeder protection fibre which is routed through disjoint but existing cables.

The procedure is shown in Figure 30.



Select area | 1. Import database | 2. Construct weighted graph | 4. Clustering algorithm | 5. Feeder Fibre (red) and Distribution Fibre (green) layout

Figure 30 Network dimensioning procedure

Figure 31 shows an example of the impact of the splitting ratio on the number of clusters and the feeder cabling. It can be observed that with a higher splitting ratio, the less clusters are needed and less feeder fibre is required. However, an increase of distribution fibre is expected.

DWDM-PON 80λ | DWDM-PON 160λ | DWDM-PON 320λ

Figure 31 Impact of splitting ratio (in number of wavelengths λ) on number of clusters (i.e. RNs as green points) and feeder fibre (as red lines)

4.2.4. Resilient structures for block and evenly spread customers

In order to reduce the number of users affected by a single failure, protection is required, in particular in a large city with more than one million inhabitants. It has been shown [5, 9] that with a proper fibre layout design, minor extra investment for protection of optical access networks can make a significant saving on failure related operational cost.

In the fibre layout model for block clustered customers (see Subsection 4.2.1), buildings are grouped in blocks, which are arranged in an array (see

Figure 32 below). We assume blocks with several buildings on each edge. Based on the technological reach limitation, the maximum number of blocks that can be covered by one central office can be computed. For instance, UDWDM PON can cover 100x170 blocks whereas hybrid WDM/TDM PON (HPON) can cover 100x90 blocks [5]. Moreover, for PON based NGOA architectures we consider two stages of remote nodes (RNs). The first stage, i.e. RN1 could locate at PCP5 while the second stage, i.e. RN2 at PCP4. In fibre to the building (FTTB) scenarios, optical fibre should reach any single building and therefore, all streets are assumed to have one duct containing any required fibre. The feeder fibre (FF) failure will affect a high number of users and therefore, its protection is crucial and a second disjoint FF is considered for protection. A protected FF layout has been proposed that minimizes the FF length as shown in

Figure 32. The working FF (i.e. FF_w) interconnecting the OLT and RN1 is depicted as a green line. The FF protection (i.e. FF_p) uses a disjoint duct (depicted as dashed green line) which just requires connecting existing dark fibre (or pumping fibre when no dark fibre is available) while avoiding any extra trenching. The distribution fibre (DF) which connects RN1 to RN2 is depicted as a blue line. The last fibre section called building fibre (BF) interconnects RN2 with each building and is depicted as a dash dotted red line.

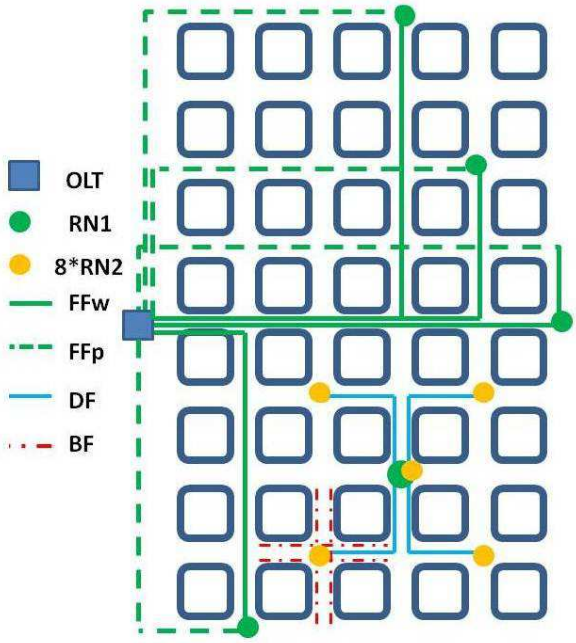


Figure 32 Fibre layout model for block clustered customers with feeder fibre protection

For this resilient fibre layout design, the added development cost related to the feeder fibre protection is trivial, due to high sharing factor of duct in the considered protected FF layout.

Regarding the OPEX, protection significantly reduces the penalty cost, especially in the case with high penalty rate. Offering protection increases failure reparation costs due to the extra fibre required, but it decreases significantly the penalty costs. Furthermore, special attention should be paid by operators when offering high penalty rates since it may become an important expense factor.

Considering evenly spread customers, the trenching and fibre length can be analytically estimated, considering the case in which the central physical connection points are connected to each other and all customers are connected by means of dual homing with two fully disjoint fibres to two separate physical connection points. The evenly spread structure containing the necessary additional trenching and fibre to make this resilient is shown in
Figure **33** and the additional trenching is shown in thicker lines and a cut-out for one area (spread over four) on which the analytical calculation is based, is shown in the rectangle.

The same input and output can be used for the calculation of the trenching and fibre in the resilient case. For calculating the additional trenching length, we clearly need to count the number of connection points to the left and right of the network for any street based analytical model. This means that we will need an extra $n \cdot l$ in length in case of a simplified or double street topology or $\left(\frac{n}{2}\right) \cdot l$ in length in case of a street topology.

For calculating the cabling length we refer to Figure **34** which gives a view on the two first quadrants of the square shown in the previous figure. For adding a redundant cable for a house in quadrant A, we can envisage this as installing a cable up to point a' and from there install a cable up to the redundant connection point b which takes an extra length of $n \cdot l$ per customer. This same reasoning holds for all customers in the four quadrants. As such the extra cable length to install the redundancy in the network is the same as the original cable length for the topology with an additional length of $n^3 \cdot l$.

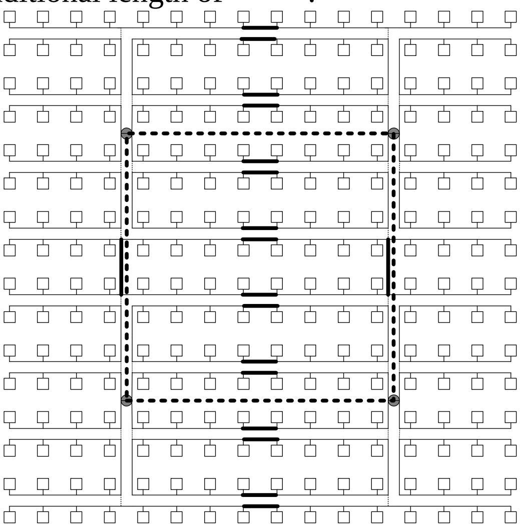


Figure 33 Resilience structure with dual homing towards four subareas connected to the central point with customers evenly spread over the area

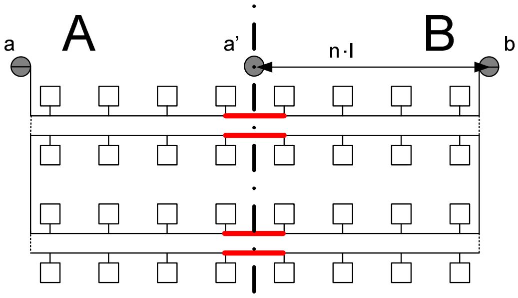


Figure 34 Detail of the resilient structure for the calculation of the cabling or fibre length

5. Equipment Modelling

With the term equipment in the cost models, we pinpoint all passive and active equipment placed in the different physical connection points. As such this is clearly split from all cabling and all passive installation blocks required for placing the cabling into the ground.
Equipment can be modelled and calculated in a very structured hierarchical manner. For instance, when taking a look at the central office in a current AON (P2P) or GPON (P2MP) situation – location is typically PCP5 – we can structure this as shown in Figure 35.

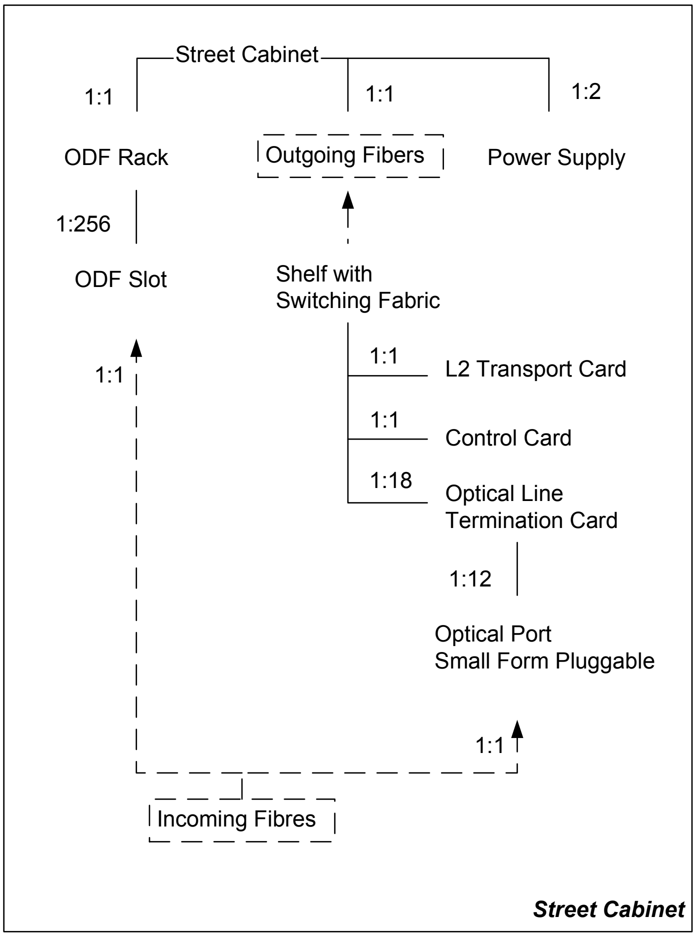


Figure 35 Equipment Model

Calculating the amount of required ODF slots comes down to calculating the amount of incoming fibres (from the geometric model). For each incoming fibre there is one ODF slot required and for each block of 2048 ODF slots an ODF rack is required.
As such:

$$Amount\ of\ ODF\ slots = amount\ of\ incoming\ fibres$$

$$Amount\ of\ ODF\ racks = \left\lceil amount\ of\ ODF\ \frac{slots}{2048} \right\rceil$$

The same structured calculation can be used for the remainder of the central office installation and lead to a given amount of equipment of the different types.

Examples for the OLT and ONT equipment

The network equipment model as described in WP4 consists of an OLT at the Central Office (or local exchange office) side and an ONT at the end-user side. Generic models for OLT and ONT are described in Figure 36 and Figure 37 respectively.

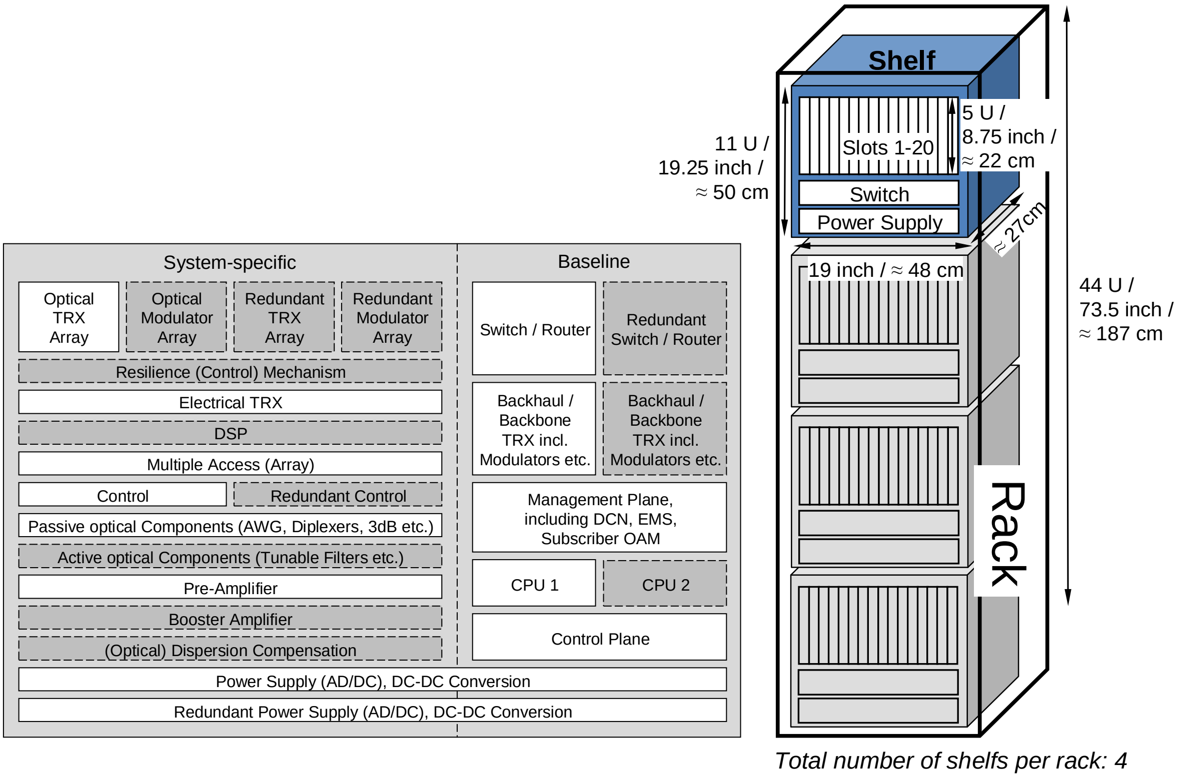


Figure 36 OLT Model

The rack consists of 4 OLT shelves; each of the shelves has 20 linecard slots, with 2 reserved for uplink. The shelf includes some baseline elements, e.g. CPU, mechanics, backplane, power supplies (redundant), Ethernet switching modular, and control and management system etc., that are common for all NGOA systems. The NGOA systems differ in components and subsystems that are listed as system-specific elements in the figure. The detailed information can be found in OASE D 4.2, Section 4.

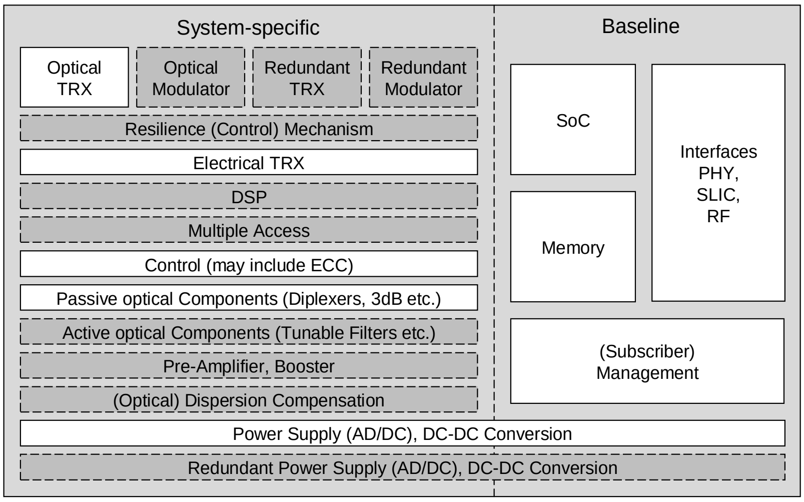


Figure 37 ONT model II

The CAPEX parameters for the network equipment are categorized as component level and subsystem level; and consider a price of a certain category (depending on list market price or large volume price) and reference year. The OPEX parameters include power consumption of components, maintenance and repair cost, etc.

6. Migration Models

This chapter addresses the operational aspects of the network migration towards NGOA architectures. The technical migration aspects are described in WP3 for the different architecture types. The migration process comprises all activities which are needed to switchover customers from the reference architecture to a new NGOA architecture. The basic rollout of the NGOA architecture itself is not part of the migration process. The migration process will be distinguished between migration planning and preparation activities and customer individual migration activities. The first part includes the migration planning, the installation & commissioning of migration specific equipment such as wavelength filters that will be removed after migration and general IT/NMS adaptations for migration. The second part comprises physical switchover of the individual customer lines as well as customer specific network and service configurations.

6.1. High level migration model

The proposed high level model of the migration process is shown in Figure 38. It is aimed at being general enough to cope with any migration scenario and consists of:

- Planning of the migration: e.g. deciding which links/nodes/components should be changed first
- Installation and commissioning: This sub-process is shown in
- Figure 39. It distinguishes between the installations of equipment and the infrastructure itself
- Physical switchover (e.g. manual fibre patching at ODF)
- NMS/IT update and reconfiguration of services from the “old” to the over-layed NGOA service creation platform

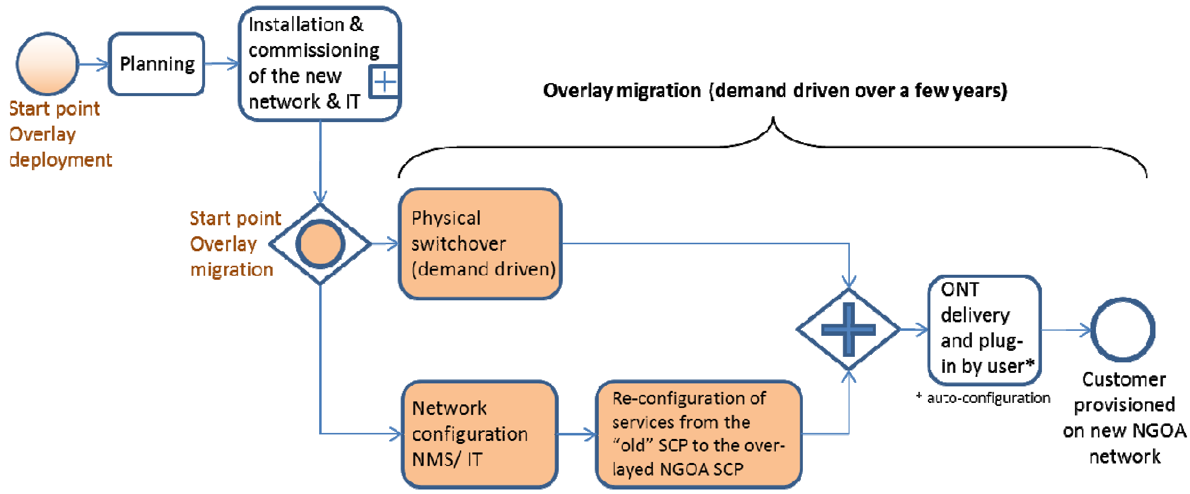


Figure 38 High level migration process model

Figure 39 shows the required installation and commissioning activities for the rollout of the new NGOA overlay system architecture and infrastructure considering all migration specific equipment.

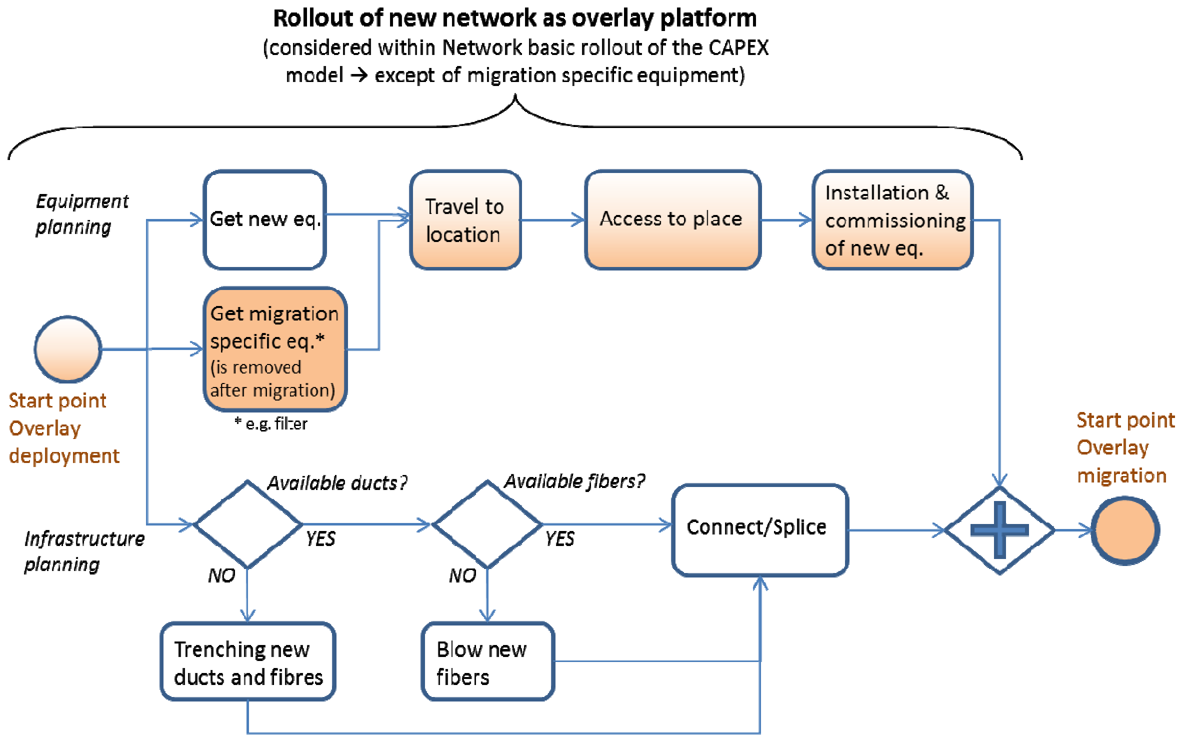


Figure 39 "Installation and Commissioning" sub-process model

6.2. Particular migration example

This section presents two general migration approaches starting from the GPON reference architecture, which differ on the NGOA target architecture type. A detailed description of the migration activities and their cost impact as well as the consideration of other start architectures (e.g. AON/P2P) will be considered for further work.

1) Migration from GPON towards NGOA Hybrid architectures using power splitter

For NGOA architectures which support the existing GPON power splitter infrastructure, most of the network related migration activities can be executed in the CO without the need for parallel ODN infrastructure, resulting in minimal field work. Sample architectures which support a power splitter infrastructure are: XGPON1; Hybrid-PON; UDWDM-PON

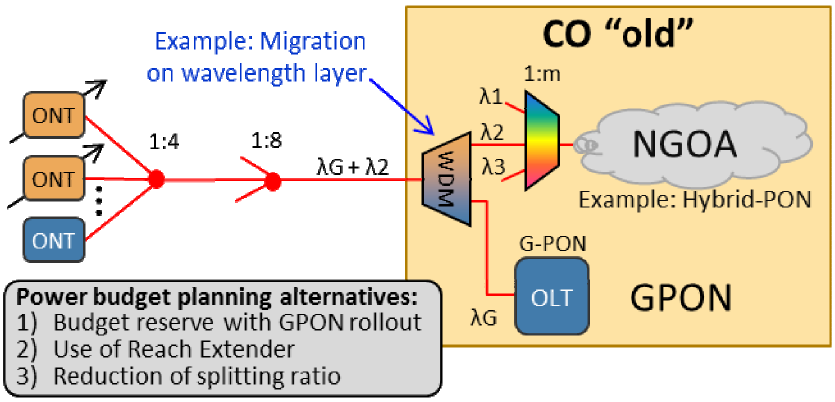


Figure 40 Migration towards NGOA Hybrid architectures using power splitter

<u>General Migration activities:</u>

- Basic installation of the NGOA system
- Introduction of a migration specific WDM coupler per GPON during the maintenance window (usually overnight). Requires adaptation of the NMS configuration and test routines (Customer impact possible)
- Customer flow point and service profile configuration
- Demand-driven migration through ONT delivery and plug-in by user (auto-configuration)

2) Migration from GPON towards NGOA Architectures not supporting power splitter

For NGOA architectures which do not support the existing GPON power splitter infrastructure, a parallel ODN overlay infrastructure up to the “last” GPON splitter (e.g. up to the building in dense urban or cabinet in rural areas) is needed. This results in additional effort in the field and/or in the customer buildings. Sample architectures which do not support a power splitter infrastructure are: DWDM-PON; P2P; AON.

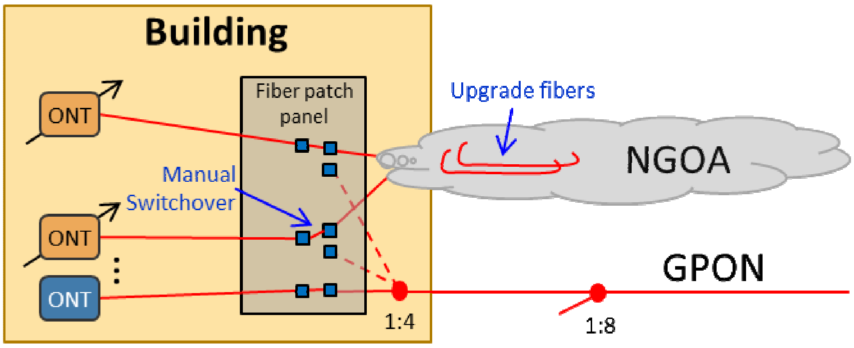


Figure 41 Migration towards NGOA architectures without power splitter

<u>General Migration activities:</u>

- Basic installation of NGOA system and through-connection of parallel ODN infrastructure using upgrade fibres
- Fibre termination at fibre patch panel
  - in the building for buildings with existing splitter
  - in the field for buildings without splitter (e.g. at cabinet)
- Demand driven switchover of user lines at patch panel.
- Customer flow point and service profile configuration
- ONT delivery and plug-in by user (auto-configuration)

7. Integration within TONIC

An important aspect in this deliverable is the implementation of the models into one frame tool, which is based on the TONIC tool as has been the outcome of D5.1. Different of the aforementioned high level modelling approaches should be added and linked into the TONIC structure in order to build this benchmarking tool. first we describe how the equipment modelling is adapted for the real equipment and in the consecutive chapters this is applied to two reference scenarios: GPON and AON. In the fourth subchapter the implementation of the operational expenditure calculation and how this is linked into the TONIC tool is detailed. Finally the last subchapter concludes with an overview of the preliminary results for both reference implementations – GPON and AON.

7.1. Equipment modelling

The models used for the calculation of the equipment installation in the first implementation of the TONIC tool are based on the GPON and AON installation. Figure 42 shows the models for all PCPs for both technology stacks. It considers 5 major elements of the system. The "shelf" defines the dimension and capacity of the OLT equipment; it includes backplane and Ethernet switching, etc. The "OLT line card" is the element which can be directly plugged into the shelf slots, and the "OLT pluggable" refers to the optical interfaces connected to the line card. These two elements are responsible for the communication between the end-users and the OLT. The "10G XFP uplink pluggable" and "10G Line card" are responsible for transmitting or receiving data from the aggregation network equipment.

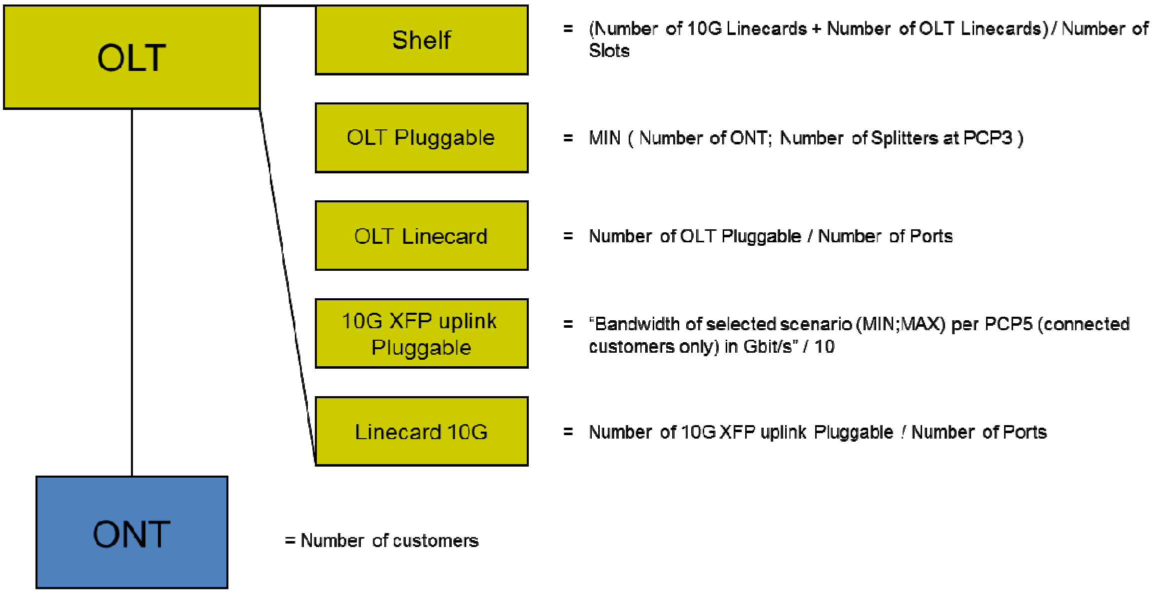


Figure 42 TONIC Equipment Model Implementations

The dimensioning of the OLT differs for each network system. For an Ethernet P2P system, the number of the OLT pluggable optical interfaces and total ports count on the linecard is same as connected subscribers, since every end-user has a dedicated fibre link to the CO (except for NG-AON cases using compact SFP with 2 subscribers per pluggable). For a GPON system, a group of end-users is bundled together in one power splitter, where the size of the group depends on the splitting ratio of the power splitter. On the OLT side one pluggable optical interface (one port) on the linecard correspond to a group of customers, and therefore the number OLT pluggable interfaces equals the total number of splitters used in the network (when one stage power splitting is applied between the customer and CO). The number of required linecards depends on the port density of the linecards. The dimensioning of shelves depends on the number of slots for the linecard. Once the number of connected customers and provisioned service bandwidth are decided, the corresponding backplane capacity, switching fabric, number of uplink linecards and optical interfaces can be calculated.

7.2. GPON reference implementation

Beside a point-to-multipoint infrastructure, a technology scenario based on GPON has been implemented in the TONIC tool as one of the two reference scenarios. Figure 43 presents the high level structure of the GPON scenario. Each customer at his home location (PCP1) is connected to a power splitter in PCP4, which is connected to PCP5, the local exchange from the copper world. By definition of the technology, each customer can have a connection of up to 2.5 Gbit/s, but in practice this depends on some constraints like performance of the CPE connected, number of attached customers per GPON (on average in the order of 75-80% - 20-25% of available splitter ports could not be used), number of parallel active customers in the respective GPON, etc. Therefore it can be assumed that a similar performance as in the AON reference implementation can be achieved for the guaranteed throughput between PCP1 and PCP5, with a higher available peak rate (most probably limited to 1Gbit/s per CPE).

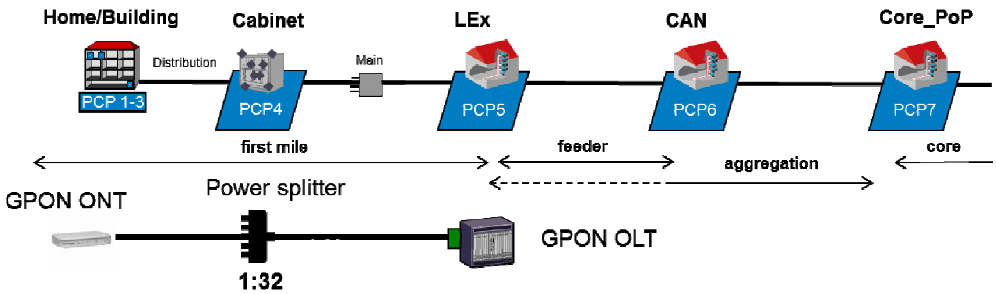


Figure 43 GPON scenario in TONIC implementation

The fibre infrastructure of the GPON implementation is assessed according to the TONIC geographical model as detailed in Section 4.1. It should be noted that it was decided against a cabinet, but similar to the AON case a branching box is included where drop cables are spliced to splitters and splitters spliced to main cables. Compared to AON, the GPON case requires fewer fibres in the main cable section and therefore less infrastructure components like micro-ducts or ducts.
The detailed equipment model can be found in
Figure 44. Beside active equipment, the power splitter at the PCP4 location is included, too. The OLT is equipped with GPON line cards, each able to carry up to 8 GPON interfaces, which means up to 256 customers could be concentrated on one line card.

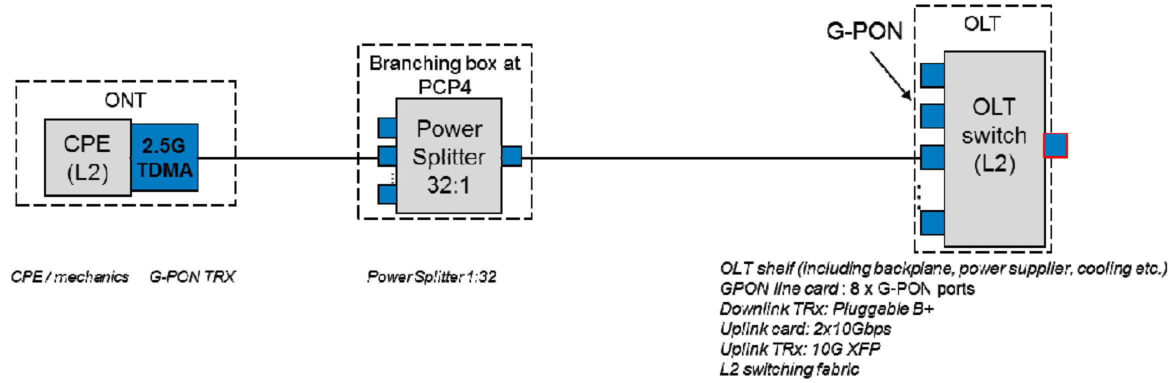


Figure 44 Network equipment model of GPON deployment

Based on the geographical model, the required components could be calculated, as shown in Figure 45.

Equipment and components	Location	Dense Urban	Urban	Rural
GPON shelf (15 tributary slots)	PCP5	21	12	4
GPON line card 8 ports	PCP5	77	43	15
GPON Plugable B+	PCP5	609	338	120
Infra - ODF - connected fibre	PCP5	609	338	120
Infra - ODF - terminated fibre	PCP5	1.200	768	360
Infra - Splitter 1:32	PCP4	609	338	120
GPON ONT	PCP1	15.600	8.640	3.060

Figure 45 GPON dimensioning for different area types

The calculated results are presented in Section 7.5. They include price references for the year 2010.

7.3. AON reference implementation

An Active Optical Network (AON) with its point to point (P2P) Ethernet access scenario has been implemented as a reference study in the TONIC tool. As shown in
Figure 46, every subscriber at location PCP1 is connected with 1Gb/s (peak rate) fibre link individually to the local exchange office (PCP5). The distance between PCP1 and PCP5 varies from 1.3 km in a dense urban to 2.7 km in a rural scenario.

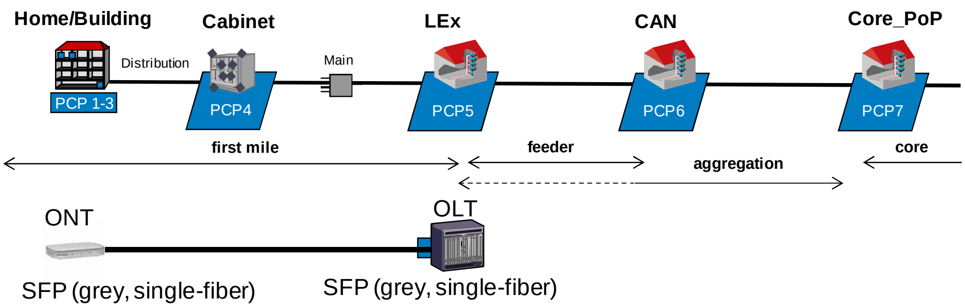


Figure 46 AON scenario

The fibre infrastructure of the AON implementation is assessed according to the TONIC geographical model described in Section 4.1. Compared to the GPON implementation, AON P2P Ethernet does not need any passive splitter and cabinet in between the PCP1 and PCP5, However, it is inevitable to have some cable interconnection points where trunk fibre cables are spliced into smaller distribution and drop cables.
The network equipment model of AON is shown in Figure 47 according to the TONIC equipment mode. Both GPON and AON system dimensioning are based on the same sustainable service bandwidth to the subscribers, however both of them could have peak bitrate up to 1Gb/s.

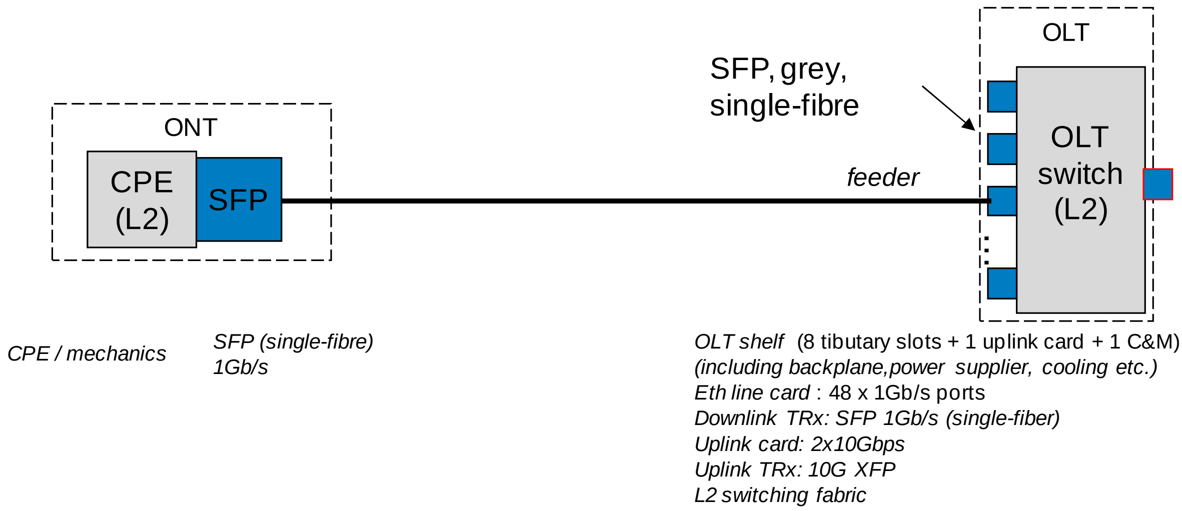


Figure 47 Network equipment model of AON

By applying the equipment model into the geographical model we can get detailed dimensioning of network equipment and components needed in the AON P2P reference scenario as shown in Section 7.5. All equipment costs are based on 2010 reference prices.

Equipment and components	Location	Rural	Urban	Dense Urban
AON 10G XFP 40KM 1550	PCP5	2	4	6
AON ETH Line card 6 x 10G aggregation uplink	PCP5	0,3	0,7	1
AON ETH Line card optical 48Portx1Gbps	PCP5	60	180	325
AON ETH shelf (160G / 8 slot)	PCP5	8	23	41
Infra - ODF - connected fibre	PCP5	3060	8640	15600
Infra - ODF - terminated fibre	PCP5	3840	9216	16800
SFP BiDi 1.25G LC 3.3V SM 1550T/1310R LX 20KM	PCP5	3060	8640	15600
AON ONT	PCP1	3060	8640	15600

Figure 48 AON P2P dimensioning for different types of areas

7.4. Coupling the operational expenditures

The BPMN models as defined in the previous chapters, and more in general annotated flowchart diagrams, can easily be accommodated to be used in cost calculations. It suffices to associate an execution cost to each activity and associate information on the statistical occurrence to each branch at a gateway[2]. The cost of executing the process once is then calculated by summing up the weighted cost of each of the activities. The weight is the total statistical occurrence of the activity, as shown in
Figure **49**. In case a process contains a loop, this can be analytically removed from the process by altering the entrance probability (or occurrence) of the first and consecutive activities in this loop and beyond[3]. The entrance probability is multiplied by a factor as shown in
Figure **49**.
Finally the total cost of executing the process once is multiplied by the number of occurrences of this process, leading to cost estimation over a given planning horizon (e.g. 1 year).

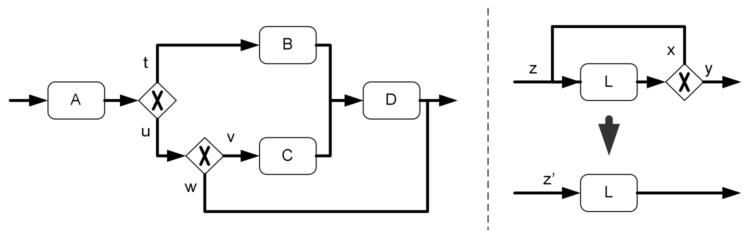


Figure 49 Simplified processes used in examples for the cost calculation

$$Cost_{tot} = Cost_A + t \cdot Cost_B + u \cdot v \cdot Cost_C + (t + u \cdot v) \cdot Cost_D$$

With: Cost = The cost of executing a specific activity or the total process (left part of the figure). Note how the statistical occurrences t and u.v are summed for the calculation of the cost of executing activity D.

$$z' = z \cdot (1 + x + x^2 + \ldots) = z \cdot \sum_{i=0}^{\infty} x^i = \frac{z}{1-x}$$

[2] The statistical occurrence indicates how many times this path will be taken for one execution of the process.
[3] This approach is able to remove a loop from the process in case this loop completely covers a separate part of the process with no paths running to parts outside this loop and a full probability at the exit (here x + y = 1). This has always been sufficient for the analysis of processes in our research.

With: z' = The new entrance statistical occurrence (i.e. replacement for z) when removing the loop link from the process. This will alter the statistical occurrence of all consecutive activities and gateways in the process.

The cost of executing an activity can be closely reflected by detailing which type of personnel is required and what time it (statistically) will take to execute the activity. This approach is suggested in activity based costing (ABC) [11].

In this way the costs of the operational processes are calculated. In order to make this interact with the cost calculation in the TONIC tool, a tool is constructed which is able to translate the content from a BPMN model into a spreadsheet calculation with formulas in the sheet as indicated above. The algorithm followed (in pseudo code) is:

1. Point at start event of the process
2. Read next step in the process
3. Depending on the type
    a. Gateway
        i. Read the name
        ii. Store the parameters of the occurrences of the different outgoing paths
        iii. For each path go to step 2
    b. Task
        i. Read the name
        ii. Store the parameters of execution time and type of personnel
        iii. if not already visited
            1. make new entry for storing occurrence tree of this task
        iv. if already visited via the current path
            1. break loop by changing occurrences of incoming path
        v. if via new path
            1. update statistical occurrence of this task with reference to the incoming path
    c. Subprocess
        i. Read the name
        ii. Go to step 1 for this subprocess
        iii. End event - STOP

At the end of this process, the tool has stored information on the following data:

1. All personnel types used in the tasks
2. For each gateway and each outgoing path the statistical occurrence of this path
3. For each task the time and personnel required
4. For each task the statistical occurrence of this task linked to the different paths leading to this task

For each of these sets of data a separate sheet is written in the output spreadsheet with links between the different sheets and formula for the calculation of the statistical occurrences of all tasks, their statistical resource consumption and their associated cost based on the input from all other sheets. Clearly the summation of all task costs (statistically for one run of the process) multiplied with the amount of occurrences over a given time period (for instance per year) will give the cost of the process.

Linking the sheets into the TONIC tool is first a matter of copying the sheets into the same spreadsheet and linking the amount of process executions to the right driver.
In case of the failure management and troubleshooting processes, this is the aggregated amount of failures to be expected in the network for each year and can be calculated by means of the amount of installed equipment and their mean time between failures. In order to calculate the difference in repair time and the impact of placement of the different types of equipment on the process cost in more detail, we split the calculation in two parts: the generic administrative process and the equipment specific repair actions. The first part is calculated by means of the process indicated in Section 3.1 where we leave out (or set at zero cost) the actions of going to the location, repairing and returning. The second part is a per equipment calculation of these steps and is calculated by estimating the distance from the repair team to the placement of this equipment – we expected the repair team to be located at the PCP6 (or at a comparable distance on average from PCP5 and downwards – and from this deriving the driving time (twice – hence and forth) with an addition of the actual repair time. Multiplying this with the statistical per equipment failure rates for each year will give for each equipment the repair time and cost of personnel.
The service provisioning process is linked into the TONIC tool. It should be fed with the data on the adoption of the customers which is an outcome of the Task 6.2.

7.5. Preliminary Results

The total cost of investment of AON Ethernet P2P is shown in
Figure **50** (left) in contrast with GPON case for a brownfield deployment. This figure distinguishes infrastructure costs from equipment costs (as dashed and plain colours respectively). Infrastructure costs distinguish costs of different links LLx: LL1 in-house cable, LL2 Distribution cable, and LL3 and LL4 Main cables as shown at the bottom of the figure. Equipment costs distinguish equipment at Flexibility Point (FP) 0: flat; FP1: building; FP2: cabinet; FP3: branch; and FP4: Main cable connection point. We can see that fibre infrastructures weight more than network equipment, and especially the distribution cable section is the most costly.
Figure **50** (right) shows the cost per subscriber. Rural area deployment has the highest cost per user, whereas dense urban area has the lowest due to the high number of users sharing costs. Main difference between GPON and P2P is on the main cable LL4 and local exchange office FP4 cost due to the high number of fibres required by P2P.

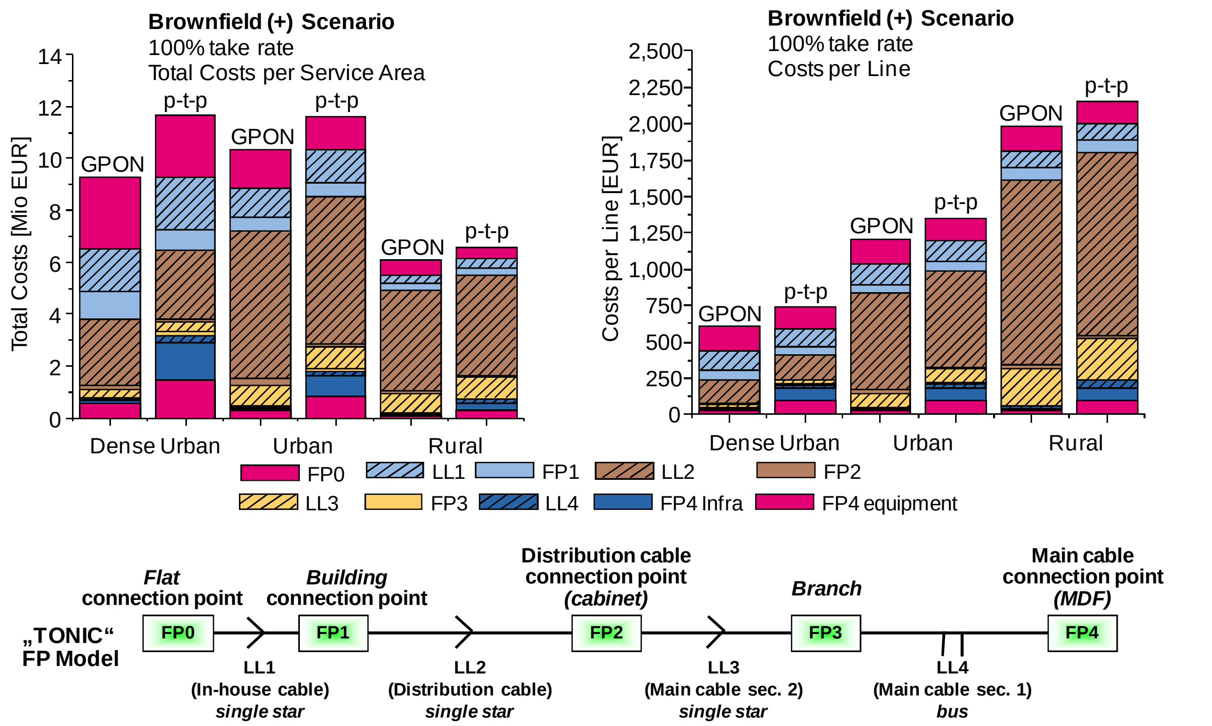


Figure 50 Comparison of GPON and P2P network in a brownfield scenario study. Left: Total cost of investment; Right: cost per subscriber.

Figure 51 shows a greenfield scenario study on GPON network. In terms of total cost of investment (left figure) GPON has similar costs in dense urban and urban areas. In a dense urban area the higher cost of the drop / in-house cable is due to the higher number of end-users, while in an urban area the higher cost existing in the distribution cable part is due to the longer distribution distance. The impact of greenfield case is the most significant for dense urban area: almost 33% add-on comparing to the brownfield case. From cost per subscriber perspective the investment required to install the missing infrastructure of the greenfield is clearly shown in
Figure 51 right, however the difference between the cost of greenfield and brownfield is less significant.

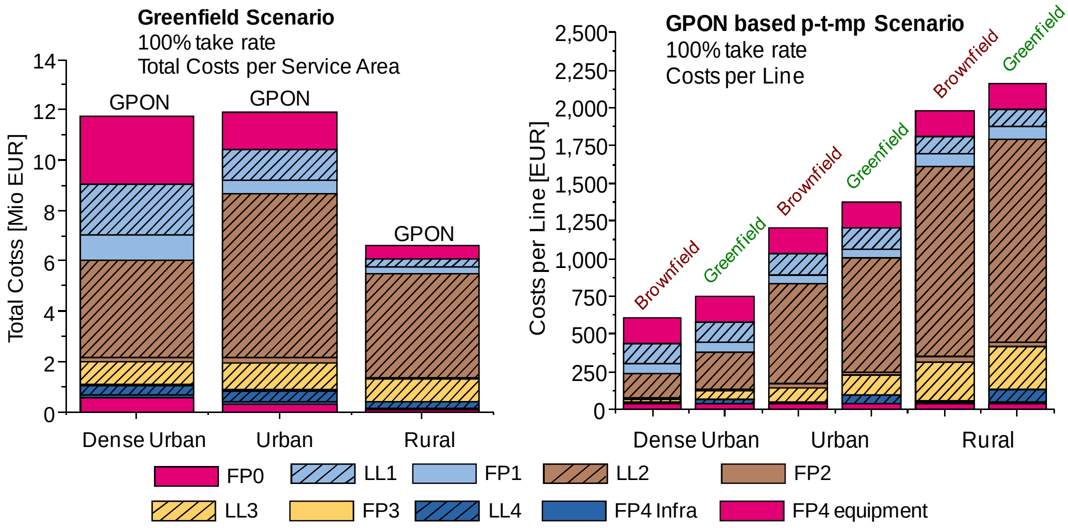


Figure 51 Left: Total cost of investment of GPON for a Greenfield scenario
Right: cost per subscriber of GPON network comparison between brownfield and greenfield

8. Conclusions

This deliverable summarizes the work on the total cost of the ownership tool. The frame tool has been based on TONIC as discussed in D5.1. This deliverable extends the work within D5.1 with details on the models and implementation in TONIC. The aim of this work is to serve as a frame tool for benchmarking and calculation of NGOA network installations.

In order to be capable to calculate the TCO for NGOA networks this tool had to be updated and linked to specific calculations, for instance considering the operational models. This deliverable contains detailed modelling of the operational processes indicating all tasks and possibilities during the execution. The operational processes taken into account are: failure management and troubleshooting, service provisioning and maintenance. Additionally the operational expenditures for energy consumption and floor space have also been described in detail.

Next to the operational expenditures, the deliverable also shows how the installation of the network – in terms of trenching and fibre can be estimated by means of structural or analytical models. Finally the deliverable also proposes a generic approach for modelling the equipment in the different physical connection points in the network.

All models – operational, installation and equipment – are also integrated within the frame tool, build on top of the TONIC basis. The details of this implementation and configuration of everything are described in this deliverable. The TONIC frame tool also had to be configured with the right models and cost values for calculating the operations and equipment required and to estimate the cost of the outside plant (trenching, ducting, cable and fibre). As a test of the implementation and as a means for benchmarking the logical structure of the calculation has been described and implemented in the TONIC tool for both a currently possible AON and GPON solution.

In task 5.3 and deliverable D5.3 the models described and the frame tool will be used to compare different NGOA architecture and system solutions. The main points of interest and areas of investigation have also been highlighted in the beginning of this deliverable.
Finally Milestone 5.2 will present the final tool implementation and the network migration process model.

Appendix - Analytical trenching and fibre length models

This appendix details how the analytical models for trenching and fibre installation in a given area are calculated and as such it links to Section 4.2.2.

As mentioned before, the potential customer base is uniformly distributed over a squared area (see Figure 52). One side of the square contains n houses and the square contains as such n^2 houses. The distance between two houses is indicated by l. When considering only the connection points of the houses, the longest distance horizontally or vertically between the two most distant houses is $(n\text{-}1).l$. When considering a house to have a square perimeter separating this from the neighbouring houses and the graphical model to continue beyond the selected square, the longest distance horizontally or vertically is $n.l$. The surface of the square is at most $n^2.l$. The central office (CO) is always situated in the middle of the square.

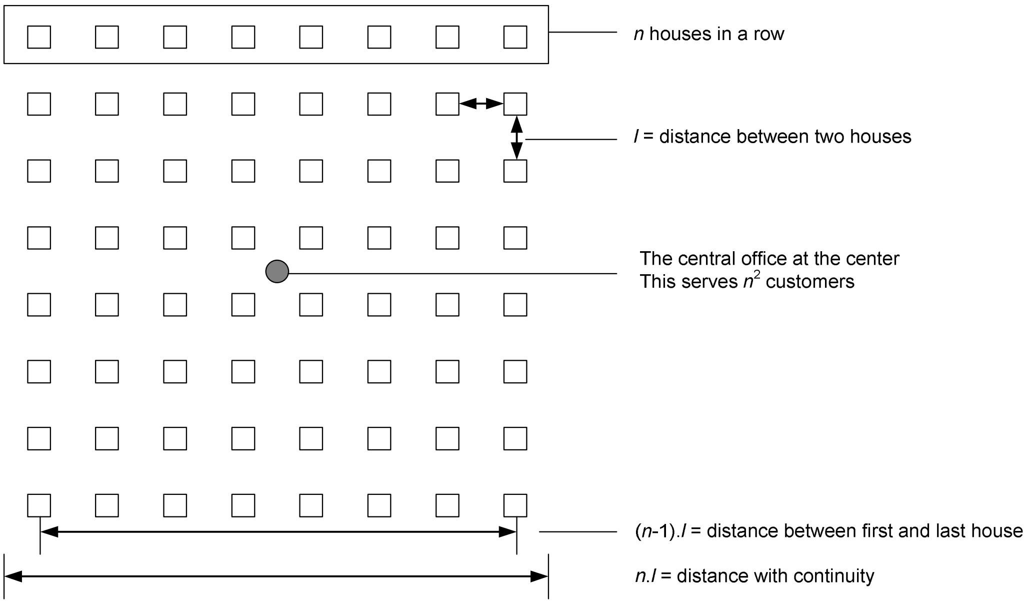


Figure 52 Schematic overview of the logical structure and parameters for the analytical installation and fibre length calculations

The following sections will detail the different analytical models. We start with a graphical representation of the model for n = 8 and indicate the relation of this analytical model to reality. Next, we deduce the installation length (I) and the fibre length (F).

Street Based Models

In a fully buried FTTH installation, the trenching will run along the side of the streets, typically in the pavements. In new installations of residential or industrial areas, the fibre could be run along one side of the street connecting the customers. We distinguish following three street side installations: *simplified streets*, *streets* and *double street*. They are detailed in the following sub sections.

Simplified Street Model

The first model is a very simplified model, assuming that all houses can be connected in one line through the middle of the house (see Figure 53). This simplified Manhattan model is of course not realistic, but could closely resemble a façade installation of the FTTH network. All streets are connected using one divider street.

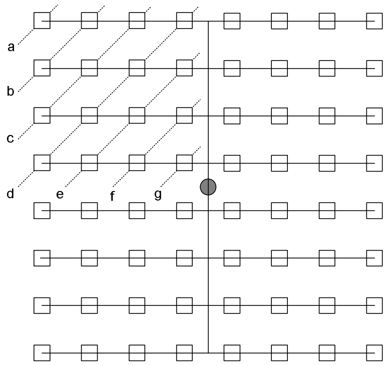


Figure 53 Logical structure for the fibre connections in a simplified Manhattan street length.

Simplified Street Model: Installation Length

Each row requires an installation length of (n-1).l, and there are n rows. The divider street requires an installation length of (n-1).l. Combined this gives an installation length as given in (1).

$$(1) \qquad I = n \cdot (n-1) \cdot l + (n-1) \cdot l = (n^2 - 1) \cdot l$$

Simplified Street Model: Fibre Length

The structure, as seen from the CO is fully symmetric horizontally as well as vertically. As such there are 4 quadrants which result in the same fibre length each. When we focus on one quadrant (see also the first quadrant in Figure 53), we find for the houses in the categories indicated on the figure the following lengths: a=(n-1).l, b=(n-2).l, … g=l. The categories are formed by the intersection of a diagonal line with the quadrant moving from the most distance house up to the CO. At the beginning, the number of houses in each category is increasing with one each step. Once the diagonal line crosses at the half of the quadrant this changes and from there the number of houses per category is decreasing with one each step. The fibre length is as such given by (2). Note that this analytical model will assume a double symmetrical structure (n is even).

$$(2) \qquad F = 4 \cdot l \cdot \sum_{1}^{n-1} \left[\min(i, n-i) \cdot (n-i) \right]$$

Street Model

The street length model will more closely follow one street and connect all houses from one street-wise cable along the street (see Figure 54). Within the calculation of the analytical model, the cable is located at the middle of the street, but could easily be envisaged at one side of the street as well. As such it could consider an aerial installation in which the poles are placed at one side along the street and all houses at both sides can be connected from those poles.

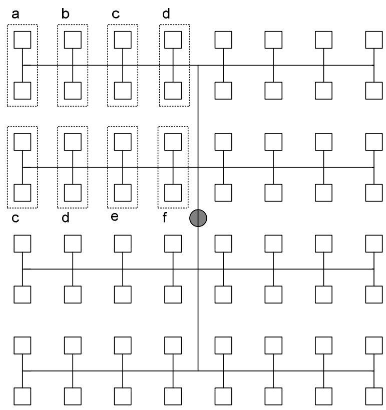


Figure 54 Logical structure for the fibre connections in a street length.

Street Model: Installation Length

In this structure we can group all houses per 2 as indicated in Figure 54. For connecting all couples of houses in 2 adjacent rows (one street) we use an installation length of *n.l*. There are *n*/2 such adjacent rows. For connecting these connected couples of houses into one fully connected street, we need an installation length of (*n*-1).*l*, and again in *n*/2 adjacent rows. Finally the connection to the central office happens in the divider street which has a length of (*n*-2).*l*. Combined this gives an installation length as given in (3).

$$(3) \qquad I = \frac{n^2 \cdot l}{2} + \frac{n \cdot (n-1) \cdot l}{2} + (n-2) \cdot l = (n^2 + \frac{n}{2} - 2) \cdot l$$

Street Model: Fibre Length

For the fibre length we can again follow the same reasoning as in the Manhattan case. Figure 54 shows the structure and the categories in the first quadrant. The distances are the same as in the Manhattan case. The grouping in categories is different and is as follows: a=2, b=2, c=4, d=4, e=2, f=2. The grouping is per two houses and the distance between two consecutive horizontal streets is 2.*l*. As such per two categories we can again group (a+b), (c+d), (e+f). For each of those new groups, the number of houses is the same and the distance is double of the smallest + 1. Finally all this information leads to the following fibre distance in the structure (4). Note that this analytical model assumes a symmetrical structure for the horizontal rows of houses (*n*/2 is even).

$$(4) \qquad F = 4 \cdot l \cdot \sum_{i=1}^{n/2-1} \left(2 \cdot \min(i, n/2 - i) \cdot \left[(n/2 - i) \cdot 4 + 1\right]\right)$$

Double Street Model

The double street length considers a street to consist of two sides. Crossing the street is often much more costly than the installation along the street side. This analytical model reduces the number of street crossings to a minimum. As such it closely resembles a fully buried installation in the area (see Figure 55).

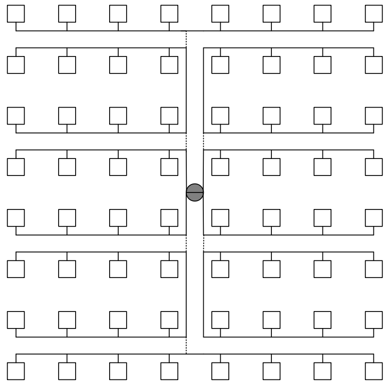


Figure 55 Logical structure for the fibre connections in a double street length

Double Street Model: Installation Length

Again we can make use of the structure mentioned above for the grouping of two houses. In this case the adjacent houses are not directly connected to each other as there is no crossing of the street with distance *w*. As such the installation length in this part is (*l*-*w*) and there are again $n^2/2$ such adjacent houses.
Considering the connecting in the rows, we need an installation length at both sides of the street. In all cases except the upper street side of the upper row and the lower street side of the lower row, we require an installation length of (*n*-1).*l* minus the street width *w* of the divider street which is not crossed here. In the upper and lower street we do not need to take this into account. We have in total *n*/2 streets and as such *n* street sides.
Finally considering the divider street, the installation length at both sides of the street will be the same. Again the horizontal streets are spaced at a distance of 2.*l* and the length at one side to connect two streets is as such 2.*l*-*w*. The number of streets to connect is *n*/2 and the number of connectors (at both sides) is as such 2.(*n*/2-1).(2.*l*-*w*). The resulting installation length is given in (5). In this calculation one should still add the length of installation crossing the streets. We need to do this at both sides for every two streets, except for the top and bottom street, where the street is only crossed at one side. Finally there is also one street crossing for connecting both sides of the street at the CO (6). Note again that the model assumes a highly symmetrical structure in which *n* is even.

$$\begin{aligned} I &= \frac{n^2}{2}\cdot(l-w)+\Big[(n-2)\cdot\big([n-1]\cdot l-w\big)+2\cdot(n-1)\cdot l\Big] \\ &\quad +2\cdot(n/2-1)\cdot(2\cdot l-w) \\ &= \left[\frac{3\cdot n^2}{2}+n-4\right]\cdot l-\left[\frac{n^2}{2}+2\cdot n-4\right]\cdot w \end{aligned} \tag{5}$$

$$I_{SC}=\left[2\cdot\frac{n}{2}-2+1\right].w=(n-1)\cdot w \tag{6}$$

Double Street Model: Fibre Length

The fibre length and cost is independent of the crossing of the street. It will be the same as in the case for the street length with the difference that in half of the houses, i.e. for each of the horizontal streets this is the street side closest to the CO, we can save a fibre distance of *w*. The fibre distance is given in (7).

$$F = \text{Fibre street length - } (n^2 / 2) \cdot w \qquad (7)$$

Aerial Based Models

In an aerial installation the choice of path is completely free. In these analytical models we consider the smallest possible installation length. We consider following two installation models: diagonal tree and simplified Steiner tree.

Diagonal Tree Model

The diagonal tree considers an installation per four houses from the geometrical centre of those four houses (see Figure 56). The difference between the centre and another location will not matter a lot as we will indicate in this section as well.

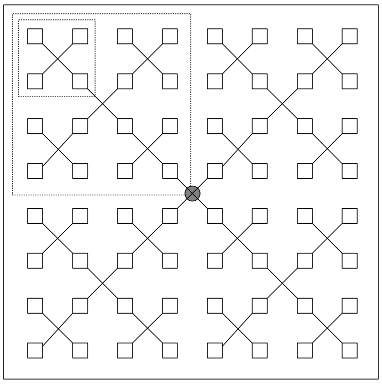


Figure 56 Logical structure for the fibre connections in a diagonal tree

Diagonal Tree Model: Installation Length

The tree structure is a repetitive structure (see also Figure 56). In each block connecting 4 houses, we find one smaller structure consisting of 4 connections from the centre of this structure. Each 4 blocks are again combined by one structure of the same size in the centre of the 4 structures. This aggregation is repeated in different levels combining always by a factor of four. Considering the combination of 4 houses, we need 1 such structure, for 16 we need 4+1 structures, for 64 we need 16+4+1, etc. In general, we will need at the last level always 1, at the last but one level we need 4 and later on we need 4^i structures and we will need $\log_4 n^2$ levels. Note that the last level has 4^0 structures. We need a number of structures as defined by (8). In this the (*) indicates the usage of a partial sum of a geometric series. Although the formula does not indicate the highly symmetrical structure, the model will assume a structure in which n is a power of 2, especially regarding the fibre length.

$$\sum_{i=0}^{\log_4 n^2 - 1} 4^i \overset{*}{=} \frac{1-4^{(\log_4 n^2 - 1)+1}}{1-4} = \frac{n^2-1}{3} \qquad (8)$$

$$a = (l/2)\cdot\cos(45^\circ) = \left(\sqrt{2}/2\right)\cdot l \qquad (9)$$
$$I = 4\cdot a = 2\cdot\sqrt{2}\cdot l$$

$$b = 2\cdot a = \sqrt{2}\cdot l \qquad (10)$$
$$I = 2\cdot l + b = (2+\sqrt{2})\cdot l$$

Figure 57 Installation Length for connecting four houses from one drop box using straight lines

The total installation length is then this number multiplied by the length of the structure for connecting 4 houses. In this case the length of the middle of the houses perimeter to the center of the four houses is equal to $(2 \cdot \sqrt{2}) \cdot l$ (see also (9)). As mentioned before, the longest distance from one house to the other three houses would be $(2+\sqrt{2}) \cdot l$ instead (see also (10)). In case the installation is performed from the center of the four house, the total installation length is given in (11).

$$I = \left(\frac{n^2 - 1}{3} \right) \cdot (2 \cdot \sqrt{2}) \cdot l \qquad (11)$$

Diagonal Tree Model: Fibre Length

The fibre length is calculated in a recursive manner. Figure 58 links to the different steps in this approach. The smallest fibre length that we will need in the calculations is indicated by y and is equal to $\left(\sqrt{2}/2\right) \cdot l$ (see also a in (9)).

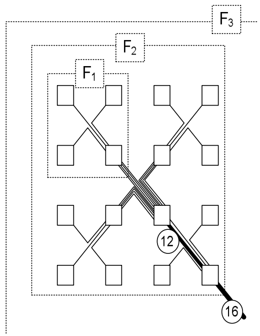


Figure 58 Recursive structure used in the analytical calculation of the fibre length

At the highest level we find four equal blocks, in which each blocks connects $n^2/4$ customers. For connecting those four blocks, we need a fibre length of y dedicated for each customer (from a to b). The total length is then given by $n^2.y$ + 4.(length of each block). We indicate the level of the block by an x which is the number of customers on one side as a factor of 2 ($\log_2$). At all lower levels, we always connect again four smaller blocks. F_0, which contains only one customer, has no extra fibre length and will as such stop the recursion.
At each level we will also need additional fibre for connecting the three most remote blocks to the edge of the block (by which it connects to a larger block). In this manner we lengthen the fibre of 3/4th of all customers residing in the considered block. The number of customers at one side of the block is equal to 2^x and the total number of customers residing in the block is equal to $2^{x.2}$ or 4^x. The number of customers to connect is then 3.4^{x-1}. Finally the fibre length to connect each customer to the edge will also be depending on the size of the block. A block of level x, has a total length of $2.(2^x-1).y$ from edge to edge. To connect all three smaller blocks to the edge we need a length from the edge to the center and one extra y beyond this center to connect to the edge of the smaller block. As such we need a fibre length of $2^x.y$ per customer of the 3 smaller blocks.
The total length is given in (12).

$$\begin{gathered} n^2 \cdot y + 4 \cdot F_{(\log_2 n)-1} \\ \begin{cases} F_x = 4 \cdot F_{x-1} + 3 \cdot 4^{x-1} 2^x \cdot y \\ F_0 = 0 \end{cases} \end{gathered} \qquad (12)$$

Simplified Steiner Tree Model

The simplified Steiner tree uses the optimal structure for the connection of every block of four houses (see Figure 59). It is easy to find a Steiner tree for this structure considering the fact that in a geometrical Steiner tree a Steiner point will always connect three links at an angle of 120° between each two adjacent links. This is the smallest possible connection of the four houses and serves as such as the lower boundary of the installation length. It is hardly useable in a realistic installation as the operator would need to install a dedicated pole for each two houses.

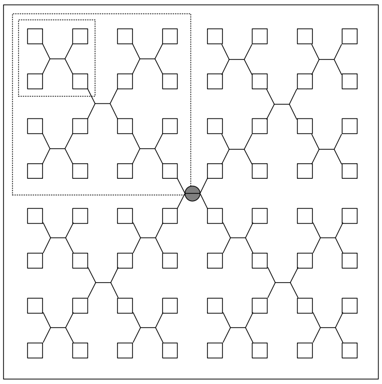


Figure 59 Logical structure for the fibre connections in a simplified Steiner tree

Simplified Steiner Tree Model: *Installation Length*

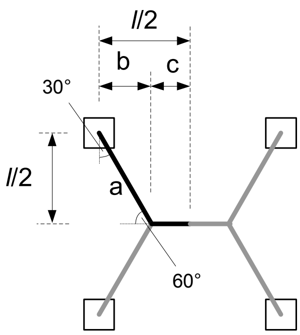


Figure 60 Installation Length for connecting four houses by means of a Steiner Tree

$$
\begin{aligned}
& a=(l/2)\cdot(1/\cos(30^{\circ})=(l/2)\cdot(2/\sqrt{3})=l/\sqrt{3} \\
& b=a\cdot\sin(30^{\circ})=a/2=l/(2\cdot\sqrt{3}) \\
(13) \qquad & c=(l/2)-b \\
& I=4\cdot a+2\cdot c=\left(4/\sqrt{3}+2\cdot\left[1/2-1/(2\cdot\sqrt{3})\right]\right)\cdot l \\
& \quad =(3/\sqrt{3}+1)\cdot l=(1+\sqrt{3})\cdot l
\end{aligned}
$$

In this calculation we used the same tree structure as mentioned before. The length of the installation for the connection of four houses or four sub blocks will in this case be equal to $(1+\sqrt{3})\cdot l$ (see also Figure 60 and (13)), and the total installation length is given in (14).

$$(14) \qquad I=\left(\frac{n^2-1}{3}\right)\cdot(1+\sqrt{3})\cdot l$$

Simplified Steiner Tree Model*: *Fibre Length

The fibre length for this tree structure will follow the same reasoning as in the case of the diagonal tree structure. The smallest length *y* is in this case equal to $\left[(1+\sqrt{3})/2\cdot\sqrt{3}\right]\cdot l$ (see also (13); *a*+*c*). In this calculation we assumed all fibres to be aggregated in the center of the structure. Considering the 3 ways connection to the smaller sub blocks, this assumption disregards a small saving possible by connecting the closest edge over the shortest path (2 times *a* in (13)).