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SODALES

SOftware-Defined Access using Low-Energy Subsystems

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D5.6 Final report with techno-economics, usage statistics and field trial feedback

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PP	Restricted to other programme participants (including the Commission Services)	
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Deliverable D5.6

Project	SODALES
Doc	Final report with techno-economics, usage statistics and field trial feedback
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Abstract

In this deliverable D5.6 "Final report with techno-economics, usage statistics and field trial feedback" we provide the final techno-economic study of the SODALES concept and the field trial feedback in terms of user characterization.

We show the updated values for capital expenditure (CapEx) costs associated with the SODALES architecture. The results show the effect of the components maturity. We also present the theoretical analysis of operational expenditures (OpEx). We provide an update of the techno-economic analysis of the central office (CO), active remote node (ARN), and customer premises equipment (CPE) components of the network.

As for the deliverable D5.2, the Olsen learning curve model was used to estimate the SODALES component costs in volume production.

Finally, we compare the expected relative costs of the SODALES network to current GPON costs.

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List of Acronyms

ARN	Active Remote Node
BTS	Base Transceiver Station
CAPEX	Capital Expenditure
CFM	Connectivity Fault Management
CFP	C Form-factor Pluggable
CO	Central Office
CPE	Customer Premises Equipment
cSFP	Compact Small Form-Factor Pluggable transceiver
DSL	Digital Subscriber Line
E2E	End-to-End
EFM	Ethernet First Mile
EoS	Ethernet over SDH
EPON	Ethernet PON
EVC	Ethernet Virtual Channel/Connection
FDD	Frequency Division Duplex
FSAN	Full Service Access Network
FTTB	Fibre-To-The-Building
FTTC	Fibre-To-The-Curb
FTTCab	Fibre-To-The-Cabinet
FTTH	Fibre-To-The-Home
FTTx	Fibre-To-The-x
GEM	GPON Encapsulation Method
GFP	Generic Framing Procedure
GPON	Gigabit-PON
GSM	Global System for Mobile
HDTV	High Definition Television
HO	High Order
HQoS	Hierarchical QoS
HSPA	High Speed Packet Access
HW	Hardware
ICI	Inter-Cell Interference
ID	Identifier
IEEE	Institute of Electrical & Electronic Engineers
IETF	Internet Engineering Task Force
iid	independent & identically distributed
IoF	Intermediate frequencies over Fibre
IP	Internet Protocol
IPTV	IP Television
IRN	Intermediate RN
ISP	Internet Service Provider
ITU	International Telecommunications Union
JD	Joint Detection
JT	Joint Transmission
LAN	Local Area Network
LCAS	Link Capacity Adjustment Scheme
LO	Low Order

LoS	Line of Sight
LTE	Long Term Evolution
MAC	Medium Access Control
MEF	Metro Ethernet Forum
MEP	Maintenance End Point
MIMO	Multiple-Input Multiple-Output
MPLS	Multi-Protocol Label Switching
NGPON	Next-Generation PON
NNI	Network Node Interface
O&M	Operations and Maintenance
OAM	Operations, Administration and Maintenance
OBSAI	Open Base Station Architecture Initiative
ODN	Optical Distribution Network
OFDM	Orthogonal Frequency Division Multiplexing
OLT	Optical Line Termination
OMCI	ONT Management and Control Interface
ONT	Optical Network Termination
ONU	Optical Network Unit
OPEX	Operational Expenditure
ORI	Open Radio equipment Interface
P2MP	Point-to-Multi-Point
P2P	Point-to-Point
PB	Provider Bridge
PBB	Provider Backbone Bridge
PDH	Plesiochronous Digital Hierarchy
PHY	Physical layer
PON	Passive Optical Network
POTS	Plain Old Telephone Service
PPB	Parts Per Billion
PTN	Packet Transmission Network
PTP	Precision Time Protocol
PWE	Pseudo Wire Emulation
QoS	Quality of Service
RAN	Radio Access Network
RBS	Radio Base Station
RF	Radio Frequency
RF	Radio Frontend
RN	Remote Node
ROADM	Reconfigurable Optical Add/Drop Multiplexer
RoF	Radio over Fibre
RRH	Remote Radio Head
RSP	Retail Service Provider
RT	Remote Terminal
SCN	Signalling Communication Network
SDR	Software Defined Radio
SME	Small- to Medium-sized Enterprise
SNMP	Simple Network Management Protocol
SoC	System-on-a-Chip
SODALES	SOftware-Defined Access using Low-Energy Subsystems
SOHO	Small Office/Home Office
SONET/SDH	Synchronous Optical Network/Synchronous Digital Hierarchy

SP	Service Provider
SSM	Synchronous State Message
STM	Synchronous Transfer Mode
S-VLAN	Service VLAN
SW	Software
TCO	Total Cost of Ownership
TDD	Time Division Duplex
TDM-PON	Time-Division-Multiplexing PON
TD-SCDMA	Time Division Synchronous Code-Division Multiple-Access
TE	Traffic Engineering
ToP	Time over Packet
TWDM-PON	TDM/WDM-PON
UDWDM	Ultra-Dense WDM
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
UNI	User Network Interface
VCAT	Virtual Concatenation
VDSL	Very-high-data-rate DSL
VLAN	Virtual LAN
VoD	Video on Demand
VoIP	Voice over IP
WAN	Wide Area Network
WCDMA	Wideband Code Division Multiple Access
WDM	Wavelength Division Multiplexing
XG-PON	10-Gb/s capable PON
ZF	Zero Forcing

1   Introduction

In this deliverable D5.6 "Final report with techno-economics, usage statistics and field trial feedback" we provide the final techno-economic study of the SODALES concept and the field trial feedback in terms of user characterization.

In this deliverable we show the updated values for capital expenditure (CapEx) costs associated with the SODALES architecture. As for the deliverable D5.2, we do not explicitly consider the inherent costs of laying optical fibre, e.g. for the WDM-PON between the central office (CO) and active remote node (ARN), since these costs on the one hand are very high and will probably tend to dominate the final figures; and on the other hand, they are fixed and already highly understood by the network operators, and don't enjoy any learning curve benefits from 'volume' deployment. We focused on the specificities of the SODALES architecture. The results presented show the effect of the components maturity and consequent price reduction.

We also present the theoretical analysis of operational expenditures (OpEx). A concrete analysis of SODALES OpEx can only be done on a specific implementation scenario since the values of maintenance, energy and running costs, repairs analysis etc. depend on the location (country or even region within a country) where the infrastructure is deployed.

We provide an update of the techno-economic analysis of the central office (CO), active remote node (ARN), and customer premises equipment (CPE) components of the network.

As for the deliverable D5.2, the Olsen learning curve model was used to estimate the SODALES component costs in volume production.

Finally, we compare the expected relative costs of the SODALES network to current GPON costs.

We have organised the D5.6 deliverable as follows:

- Introductory chapter 1, this chapter is where we describe the differences between this deliverable and D5.2;
- Chapter 2 provides the updated core techno-economic quantitative analysis of the various component parts of the SODALES network: the CO, ARN, and customer premises equipment (CPE). We present the estimate of SODALES component costs in volume production, from 1 through to 100,000 units, according to the Olsen Model;
- In chapter 3, we present a brief theoretical analysis of the OpEx;
- Chapter 4 presents the feedback from the field trial as well as some Internet traffic and customer behaviour data analyses;
- Chapter 5, we conclude this deliverable with some conclusions and closing remarks.

2   Updated Business Evaluation

This chapter presents the final techno-economic analysis for the SODALES network and subsequent implementation cost. This deliverable reflects the changes on the equipment prices over the last two years of the SODALES project, and they present a more accurate and realistic set of prices then the ones presented on the first year of the project.

The cost of each element for different manufacturing volumes was assessed using the Olsen learning-curve model.

For an easier reading of the document, we present here the most important tables used by the Olsen Model:

Table 1 - Learning curve coefficient in terms of the learning curve classes

	TYPE OF COMPONENT	*K%*
0	constant (raw mat., civil works,..)	1.00
1	optical component	0.80
2	advanced optical comp.	0.70
3	optical cable	0.90
4	electronics	0.80
5	installations	0.85
6	software	0.60
7	mechanics	0.90
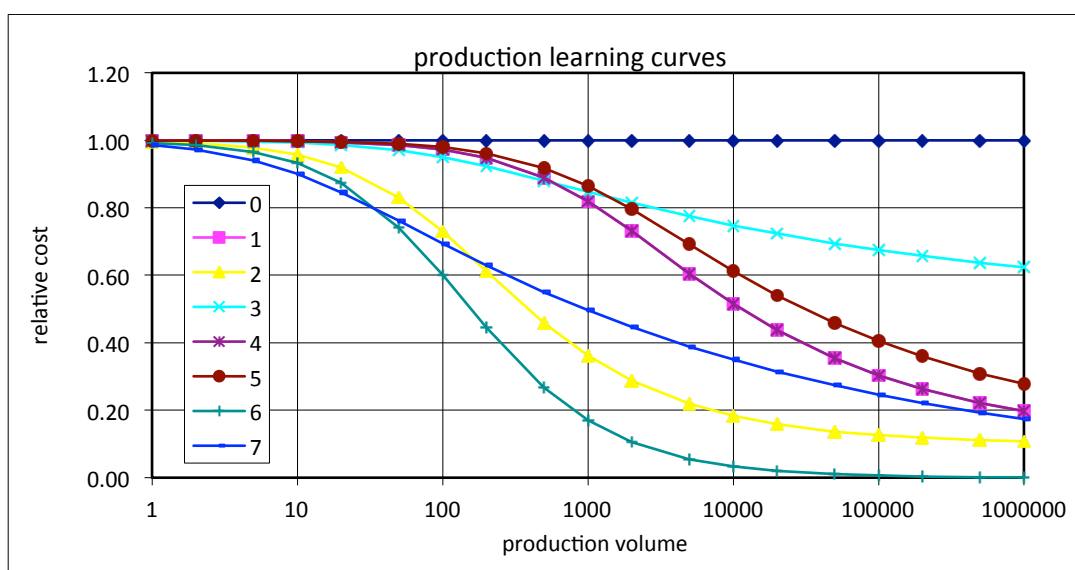
Figure 1: Evolution of the relative cost for each learning category as a function of the production volume.

2.1 Equipment Costs

This section develops the equipment costs for the CO, ARN, CPE and Optical Link, which are implemented using, mostly, off-the-shelf components.

2.1.1 Central Office (CO)

The equipment at the CO provides interconnection with Point-of-Presence (PoP), where each Service Provider will interconnect their equipment to the core network. Thus, the functionality of the equipment at the CO is to aggregate the traffic coming from the different ARNs and distribute it to each Service Provider depending on the labelling of each flow.

As stated in D5.2, the CO equipment is an Ethernet aggregation device, using an off-the-shelf OLT, and it can be seen as an ARN without customer ports but with several 10G/100G interfaces, to interconnect both, uplinks to the PoP/SPs and ARNs.

Depending on where the PoP is located, the OLT will just forward the traffic from the ARNs to the PoP or will aggregate it to deliver it to the different SPs.

The cards that the OLT will have are:

- Switching fabric: a non-blocking backplane is required to interconnect the different ARNs to the PoP;
- Downlink cards: 10/100G interfaces to interconnect the OLT to the ARNs;
- Uplink cards: 10/100 interfaces to connect the OLT with the PoP and deliver the traffic to the different SPs.

As the number of ARNs connected to the CO is predicted to be high, a modular OLT with different cards will be the preferred choice. This allows us to have a scalable platform, which can grow at the same time new ARNs are deployed and also guarantees the investment, as new cards with new features can be installed.

From the powering perspective, the OLT should provide two powering lines for redundancy purposes at 48Vcc.

Mechanically, the form factor of a SODALES OLT will be similar to present GPON/P2P OLTs.

Figure 2: Typical OLT configuration, to interconnect ARNs to the PoP

SODALES proposes several architectures to interconnect the OLTs with the ARNs. The basic one is by means of a WDM-PON. WDM-PON outside plant requires the use of AWGs, which are passive devices that will be installed in the field.
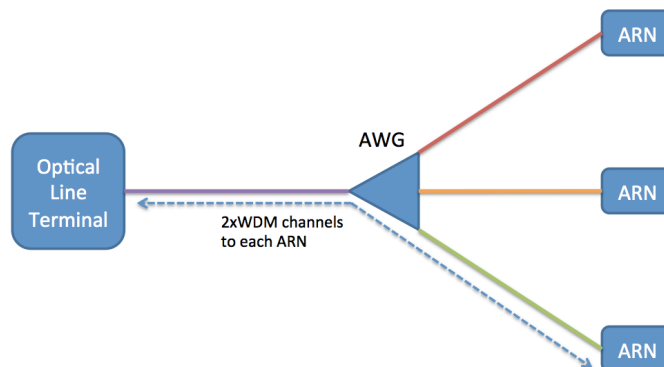
Figure 3: Basic WDM-PON architecture to interconnect the ARNs to the OLT

From the CO perspective, the use of a WDM-PON architecture means that the pluggable optics at the OLT need to be coloured. As is presented in the next section, this will increase the cost of the equipment at the CO but has no other implication regarding the implementation of the solution.

2.1.2   Active Remote Node (ARN)

The SODALES project is using mostly commercial off-the-shelf (COTS) components wherever possible, since this greatly contributes to lowering the cost of the proposed network topology, since we can assume that such COTS equipment is already commercially deployed and the parts are widely available.

The basic ARN hardware solution is provided by PT Inovação (PTI) and comprises four major components the backplane, as indicated in Figure 4, the switch fabric cards Figure 5, the 48x1GbE point-point cards, Figure 6 and a 4x10GbE card Figure 7. The optical components used such as XFP's and SFP's are also provided by PT Inovação.

Figure 4: ARN backplane with tributary cards
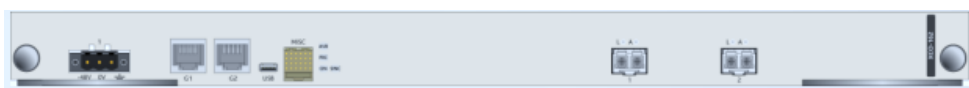
Figure 5: ARN Switch fabric card, featuring 2x10GbE SFP+

Figure 6: 48x1GbE point-point card

Figure 7: 4x10GbE card

In order to present a valid analysis for the ARN, the prices for different boards and optical terminations (XFPs/SFPs) were accessed, using the PT Inovação commercial prices for the boards, and major web retailers for the optical components. In particular, the prices for these latter components can enjoy significant price reductions for high volumes and with appropriate negotiations with the component manufacturers rather than with the retailers. This section presents the updated values of the ARN, which had a significant decrease since D5.2 was produced.

Table 2– Costs for ARN major components

Card	Unit Cost (EUR)	Quantity	Total Cost (EUR)
ARN Chassis with fans and power supplies	1.142,50 €	1	1.142,50 €
CXO 160G Ind. Temp.	3.089,72 €	2	6.179,44 €
TU40G	1.172,78 €	1	1.172,78 €
TA48GE	2.128,16 €	2	4.256,32 €
SFP+ for CXO 160G	-	4	Table 3
XFP for TU40G	-	4	Table 4
cSFP for TA48GE	-	48	Table 5

Table 3 – SFP+ 10GbE quotations for different optical reaches

SFP+ (type/range)	Unit Cost (EUR)
LR (10 km)	122,57 €
ER (40 km)	524,20 €

Table 4 – XFP 10GbE quotations for different optical reaches

XFP (type/range)	Unit Cost (EUR)
SR (300 m)	295,48 €
LR (10 km)	251,71 €
ER (40 km)	683,98 €
ZR (80 km)	1.313,24 €
DWDM (100 GHz spacing)	1.143,62 €

Table 5 - cSFP 1GbE quotation for different optical reaches

cSFP BiDi (type/range)	Unit Cost (EUR)
1000 BASE-BX (10 km)	91,36 €
1000 BASE-BX (40 km)	138,94 €

Table 6 – QSFP 100GbE

QSFP (type/range)	Unit Cost (EUR)
QSFP28 100GBASE-LR4 (10km)	4.750 €

2.2   Price Estimation of SODALES network

2.2.1   Central Office (CO)

As presented in section 2.1.1, the CO (OLT) of SODALES should not differ much from a high-density ARN without customer ports installed in a modular blade configuration. During the last two years of the SODALES project, three new boards were developed and are now available for the CO:

- CXO2T2 – a Switch Fabric and CPU board that is able to switch at a 2.2Tbps rate.
- TU100G – an uplink interface card featuring a 100Gbps interface
- TA12XG – an card with 12x 10Gbps SFP+ interfaces that can be used either as uplink or access.

The expected cost of the cards for volume production would be:

Table 7 - Learning curve parameters for different categories of elements at the C.O. (OLT1T3)

OLT 1T3 (C.O.)	Current unitary Cost (EUR)	Type of learning cost (1-7)	Unitary cost (EUR) 100	Unitary cost (EUR) 1,000	Unitary cost (EUR) 10,000	Unitary cost (EUR) 100,000
OLT Chassis	3.362,31 €	7	2319,99	1681,16	1176,81	840,58
CXO 640G	3.194,32 €	4	3098,4904	2619,3424	1661,0464	958,296
CXO2T2	6.704,46 €	4	6503,3262	5497,6572	3486,3192	2011,338
TU100G	3.091,03 €	4	2998,2991	2534,6446	1607,3356	927,309
TA12XG	2.770,25 €	4	2687,1425	2271,605	1440,53	831,075
TU40G	1.172,78 €	4	1137,5966	961,6796	609,8456	351,834
TA48GE	2.128,16 €	4	2064,3152	1745,0912	1106,6432	638,448
SFP+ for TA12XG (10km)	122,57 €	1	118,8929	100,5074	63,7364	36,771
SFP+ for TA12XG (40km)	524,20 €	1	508,474	429,844	272,584	157,26
XFP for TU40G (300m)	295,48 €	1	286,6156	242,2936	153,6496	88,644
XFP for TU40G (10km)	251,71 €	1	244,1587	206,4022	130,8892	75,513
XFP for TU40G (40km)	683,98 €	1	663,4606	560,8636	355,6696	205,194
XFP for TU40G (80km)	1.313,24 €	1	1273,8428	1076,8568	682,8848	393,972
XFP for TU40G DWDM (100 GHz spacing)	1.143,62 €	1	1109,3114	937,7684	594,6824	343,086
QSFP28 for TU100G (10km)	4.750 €	1	4607,5	3895	2470	1425
SFP for TA48GE (10 km)	91,36 €	1	88,6192	74,9152	47,5072	27,408
SFP for TA48GE (40 km)	138,94 €	1	134,7718	113,9308	72,2488	41,682

For the outside plant, as stated in D5.2, we need to consider the additional price of a AWG, which is the main difference to a GPON/P2P current deployment.

The cost of a 90-port athermal AWG should be below 3,000 EUR in a mass production scenario.

2.2.2 Active Remote Node (ARN)

In order to simplify the estimation of ARN's price for large quantities, the basic SODALES architecture described in D1.1 was selected as the basis for the analysis. This architecture relies on two 10GbE wavelengths for the connection between the ARN and the CO, which is located up to 30 km away from each other. The end-user interfaces consist of: 96x residential homes served with a dedicated 1GbE connection that can be located up to 2 km from the ARN, plus one 10GbE connection for a RBS, and 3x 10GbE connections for up to three SMEs ranging up to 300 metres from the ARN. This architecture is therefore suitable as a representative sample for a mixture of commercial and residential users.
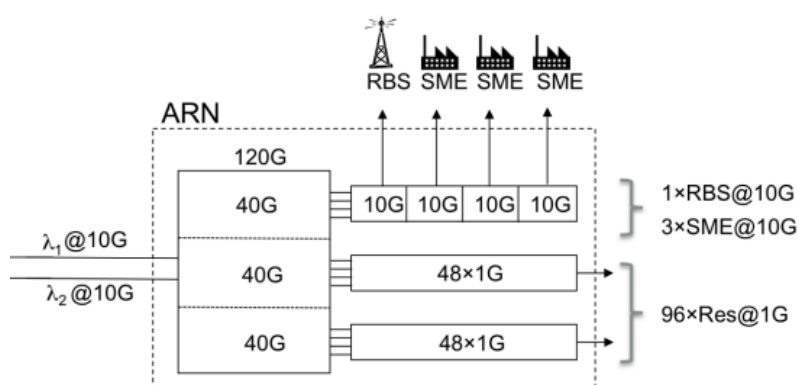
Figure 8: Basic SODALES architecture, serving 96 homes each with 1 Gb/s, and 3x SMEs with 10 Gb/s each, and one remote base station (RBS) with 10 Gb/s bandwidth pipes.

Table 8 presents the unitary cost of each element of the ARN, when the volume number of produced or manufactured units grows by factors of 10, from 100 up to 100,000 in volume production.

Table 8 - Learning curve parameters for different categories of elements at the ARN

ARN	Current unitary Cost (EUR)	Type of learning cost (1-7)	Unitary cost (EUR) 100	Unitary cost (EUR) 1,000	Unitary cost (EUR) 10,000	Unitary cost (EUR) 100,000
ARN Chassis with fans and power supplies	1.142,50 €	7	788,33	571,25	399,88	285,63
CXO 160G Ind. Temp.	3.089,72 €	4	2997,0284	2533,5704	1606,6544	926,916
TU40G	1.172,78 €	4	1137,5966	961,6796	609,8456	351,834
TA48GE	2.128,16 €	4	2064,3152	1745,0912	1106,6432	638,448
SFP+ for CXO160G (10km)	122,57 €	1	118,8929	100,5074	63,7364	36,771
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XFP for TU40G (40km)	683,98 €	1	663,4606	560,8636	355,6696	205,194
XFP for TU40G (80km)	1.313,24 €	1	1273,8428	1076,8568	682,8848	393,972
XFP for TU40G DWDM (100 GHz spacing)	1.143,62 €	1	1109,3114	937,7684	594,6824	343,086
cSFP BiDi for TA48GE (10 km)	91,36 €	1	88,6192	74,9152	47,5072	27,408
cSFP BiDi for TA48GE (40 km)	138,94 €	1	134,7718	113,9308	72,2488	41,682

Table 9 presents the cost reduction for the ARN with the configuration chosen as the number of ARNs purchased. The value considers the cost of each unitary element presented in Table 8 and the number of cards/components necessary for mounting a basic SODALES architecture presented in Table 2.

Table 9 - ARN learning curve cost reductions

Number of ARNs	Total cost per ARN (EUR)	Total Network (EUR)
1	21040,88	21040,88
100	19431,96	1943196,16
1000	15572,34	15572337,60
10,000	9606,86	96068598,00
100,000	5330,70	533070380,00

Table 10 presents the detail of the cost calculation for a full ARN configuration.

Table 10 - ARN cost calculations detail

Number of ARNs	ARN Chassis with fans and power supplies	CXO 160G Comer. Temp.	TU40G	TA48GE	SFP+ for CXO160G (10km)	XFP for TU40G (10km)	cSFP BiDi for TA48GE (10 km)	Total cost per ARN
Quantity	1	2	1	2	4	4	48	
1	1142,5	6179,44	1172,78	4256,32	2897,72	1006,84	4385,28	21040,88
100	78832,5	599405,68	113759,66	412863,04	281078,84	97663,48	359592,96	19431,96
1000	571250	5067140,8	961679,60	3490182,40	2376130,40	825608,80	2280345,6	15572,34
10000	3998750	32133088	6098456,00	22132864,00	15068144,00	5235568,00	11401728	9606,86
100000	28562500	160665440	35183400,00	110664320,00	75340720,00	26177840,00	96476160	5330,70

2.2.3 Customer Premises Equipment (CPE)

Ethernity provides a 10G demarcation device with 10G interfaces towards the network and 1G towards the user, implementing OAM, CFM, clock recovery, switch, MPLs and hierarchical scheduling and shaping. The CPE comes with two 10GE ports (XFP) and 16 GbE ports (SFP), and will cost in the range of 120€ for volume production.

Having support at the CPE for virtual CPE function per each of 16 GbEs, then such CPE can be used as a converged CPE for 16 different customers at a cost of less than 10€ per customer.

Table 11 – CPE production cost reductions

Number of CPEs	Total cost per CPE (EUR)	Total cost per CPE including cSFP for uplink (EUR)
1-999	400	491,36
1000-9999	250	534,77
10,000-49999	180	363,93
above 50,000	120	252,25

On the course of the project, a different version of the CPE was also produced and made available. This new device is a 10G CPE aggregation platform, featuring:

- 16GbE and 2x 10G that can serve to connect 16 x GbE CPEs as a remote aggregation device
- supporting virtual CPE functions, and open access features such as MPLS, hierarchical scheduling and OAM

The cost of this platform is presented on Table 12. As other ARN and CO components, this CPE is optional and will not be used on the CAPEX analysis on the next sections.

Table 12 – 10G CPE Aggregation platform production cost reductions

Number of CPEs	Total cost per CPE (EUR)
1-999	600
1000-9999	400
10,000-49999	300
above 50,000	220

2.2.4 Optical Link

The Optical link provided by HHI has an initial cost of 5.000€ per unit, thus a total of 10.000€ per link.

Table 13 - Learning curve parameters for different categories of elements of the Optical Link

Optical link	Current unitary Cost (EUR)	Type of learning cost (1-7)	Unitary cost (EUR)	Unitary cost (EUR) 100	Unitary cost (EUR) 1.000	Unitary cost (EUR) 10.000	Unitary cost (EUR) 100.000
Mounting kits and housing	2.000,00 €	7	2000,00	1380,00	1000,00	700,00	500,00
VLC with power supply	2.000,00 €	4	2000,00	1940	1640	1040	600
Optics	1.000,00 €	1	1000,00	970	820	520	300

Table 14 – Optical Link learning curve cost reductions

Number of ARNs	Total cost per pair of optical link devices (EUR)
1	10.000
100	8.580
1000	6.920
10,000	4.520
100,000	2.800

With large volume productions it is expected that the link cost will reduce substantially.

2.2.5 Cost analysis per SODALES customer

Taking the ARN estimated volume prices on Table 9 and CPE volume prices on Table 11 (including the uplink cSFP to connect to the ARN), considering that each ARN provides 96 GbE point-to-point links, and considering one CPE per customer, the total cost per customer is then presented on Figure 8.
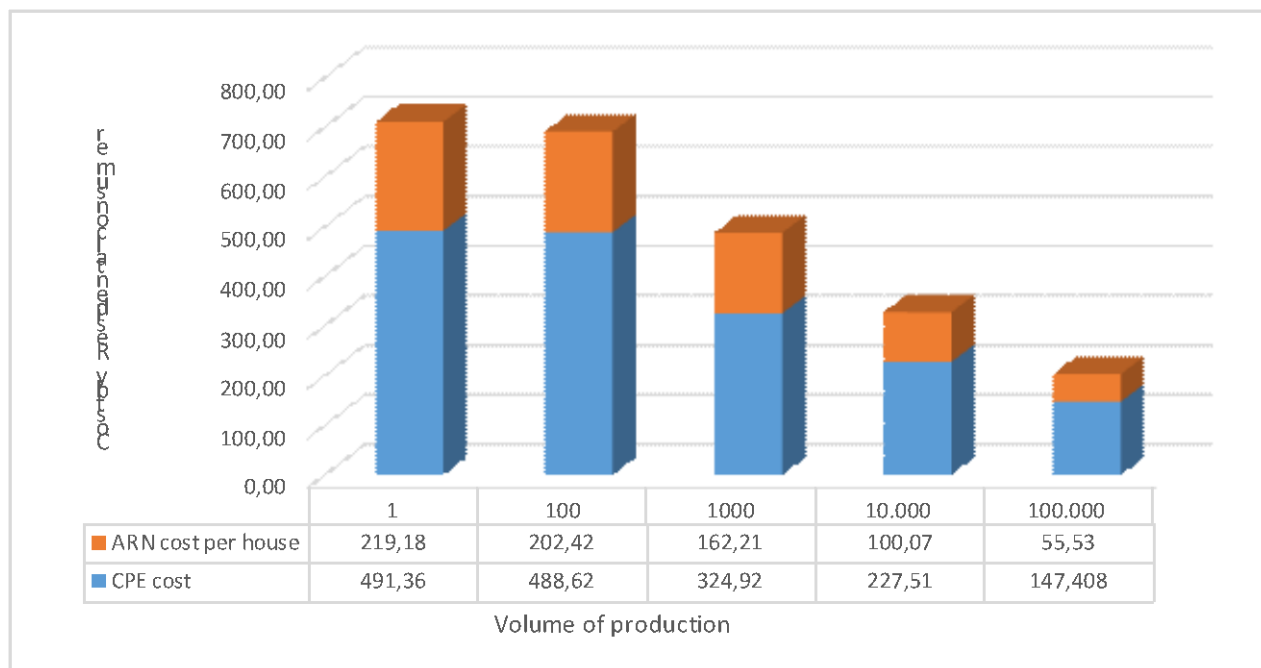
Figure 8: Estimated SODALES cost per residential user

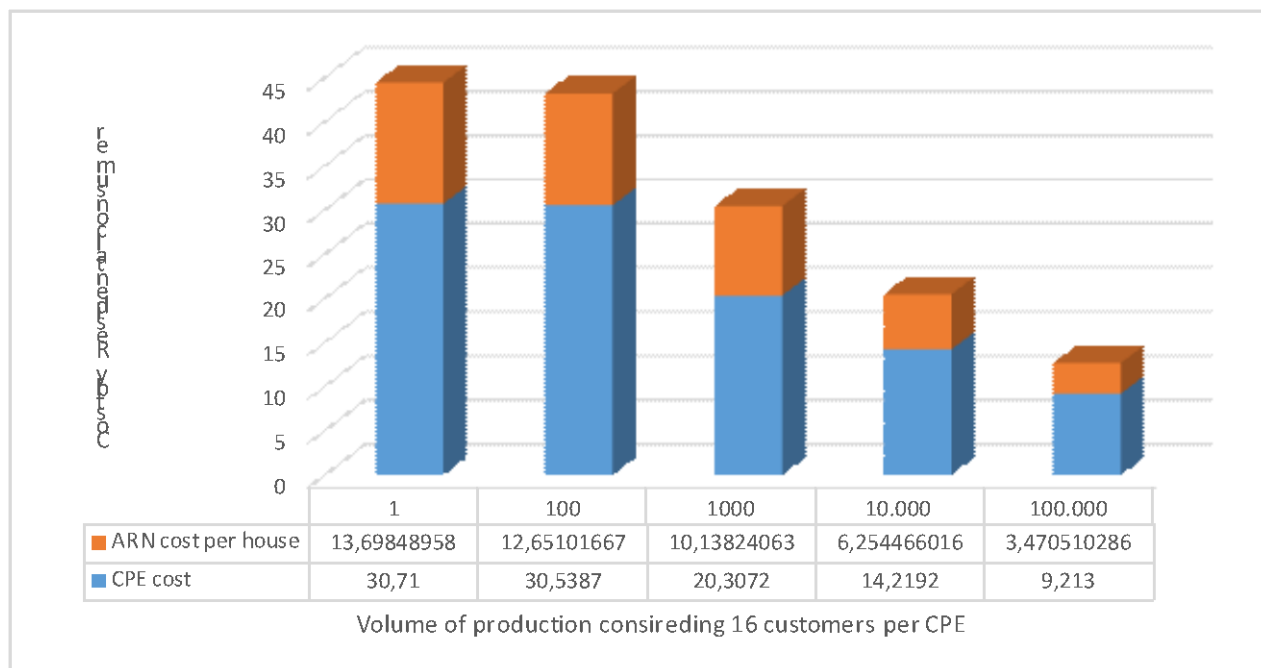However, if we consider that each CPE can connect up to 16 customers, then, each ARN port is able to provide access to 16 customers, decreasing the value per customer on a factor of 16. As we will present on section 4.1, considering this scenario, the available bandwidth per customer is still beyond the present user/customer needs.

Figure 9: Estimated SODALES cost per residential user, considering 16 customers per CPE

On this latest scenario, if more than one Ethernet port is necessary at the customer's premises, and if it is responsibility of the operator to provide it, we need to add the cost of an "of-the-shelf" home router, that would add about 20€ per customer (typical 4 LAN ports plus Wi-Fi gateway).

2.2.6   Cost analysis per SODALES customer, considering volume

The Olsen model [7] also allows calculating the evolution of the cost along the years, based on a certain implementation rate.

$$P(t) = P(0) \cdot \left[\frac{1}{n(0)} \cdot \left\{ 1 + \exp\left[\ln\left(\frac{1}{n(0)} - 1 \right) - \frac{2 \cdot \ln(9)}{\Delta T} \cdot t \right] \right\}^{-1} \right]^{\log_2(K)}.$$

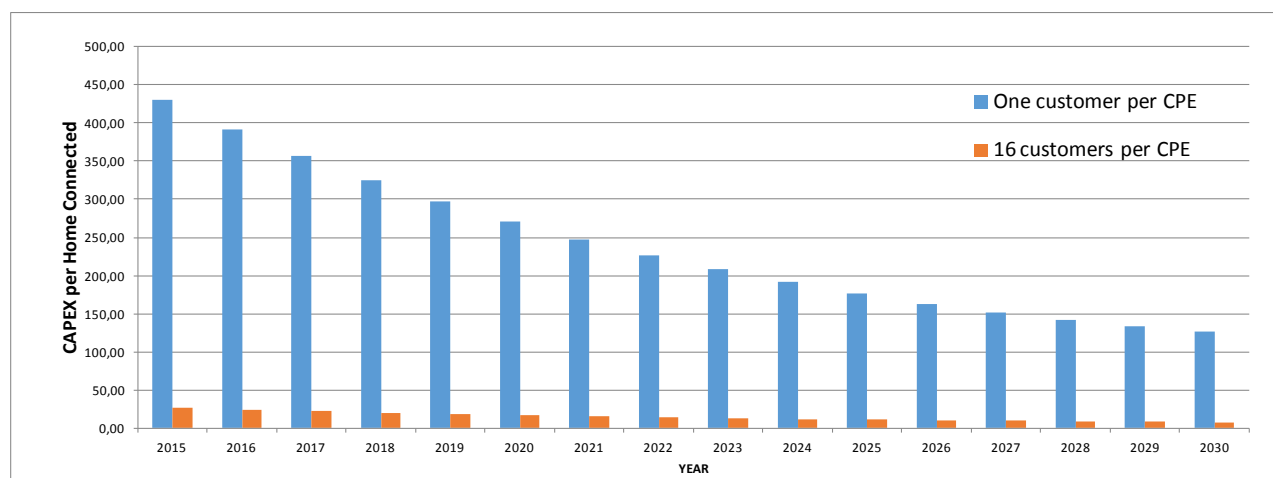**Equation 1: The Olsen model for price estimation over time**

Where
• n(0) is the relative accumulative volume (equal to 0.5 according to statistical data for components that exist in the market and their price is expected to be further reduced due to aging rather than due to production volume: n(0) could be 0.1 for mature products and 0.01 for new components in the market.
• P(0) is the component's price in the reference year 0, ΔT is the time for the accumulated production volume to grow from10 to 90 %,
• K is the learning curve coefficient.
The K factor as well as the actual or forecast ΔT can be obtained from the production industry, mainly the suppliers.

On this scenario, we considered an implementation rate of 100 ARNs per year, thus, we have an initial cost per customer of 430€ (one customer per CPE) and 26,87€ (16 customers per CPE).

We have P(2015) = 430€, ΔT = 15years, n(2015) = 0.01 and K = 0.8.

Applying these values on the above formula, we can calculate the evolution of the price per customer over the next 15 years.

Figure 10: Evolution of CAPEX per user, over the years

3 SODALES OPEX

Accurate calculation of the expected costs of operational expenditure (OpEx) for the SODALES architecture is somewhat out of the scope of the current project, in the sense that although we can fairly straight-forwardly calculate the CapEx costs associated with SODALES (see Chapter 2), calculating the OpEx of the network is unfortunately significantly more complex. This is because a realistic OpEx calculation requires consideration of aspects such as the costs associated with service provisioning, fault management, maintenance, and power consumption as well as migration-specific expenditures. These aspects can only be accurately known in the context of a fully operational (and relatively widely deployed) network infrastructure.

There have been full-scale studies attempted to assess the OpEx costs of next-generation optical access networks, e.g. the FP7 OASE (Optical Access Seamless Evolution) project [1], which undertook a full techno-economic study of next-generation access networking. Indeed, we make use of the results from the OASE study, particularly since at least 1 of the partners (UEssex) from the SODALES project was involved in OASE. However, whereas the OASE project only considered fixed wireline (i.e. FTTx) architectures, the SODALES project is a converged wireless-wireline architecture, and so from that perspective the OASE results are not fully applicable to the SODALES architecture. That said, the OASE methodology is still valid to a degree, and highlights the complexities and multi-dimensional modelling required to credibly assess the OpEx costs of any access network. For example, as already previously discussed, the OpEx is divided into four different cost factors [2]:

- Fault Management, which includes the pre- and post-processing of a failure as well as the failure reparation itself. The cost of this process depends on the failure rate of the network components, the mean time to repair (MTTR) each network component, their location, etc. Clearly, the relative failure rates and MTTRs for each network element need to be known.

- Service Provisioning is the cost associated to any physical installation, service connection and service disconnection required by the users.

- Floor space includes the cost of the floor space required by the OLT at the operator premises as well as any active component required in the field, i.e. at the ARN.

- Energy gives the energy cost of the power consumed by any equipment in the network.

In addition, the deployment context needs to be assessed, as to whether it is in a rural, urban, or dense urban setting. Related to that, is the need to assess what kind of migration strategy is also likely to be required, e.g. for brownfield, greenfield deployment, and whether, looking to the future what kind of node consolidation is likely to be adopted, e.g. non-node consolidation, node consolidation, and aggressive node consolidation. Finally, the rates of penetration and take-up of the architecture by end-users must also be assessed, e.g. (according to the OASE project assumption), a penetration curve of 10% in 2020 rising to 74% in 2030 was assumed. While clearly affecting the CapEx trajectory over time, the take-up curve will also have a strong bearing on the OpEx trajectory over time as well.

Together, the CapEx and OpEx components form the basis of the total cost of operation (TCO) for the SODALES network. Again, from the OASE project, the Figure 11 below shows how the TCO model comprises investments for all active and passive system and infrastructure

components, expenditures for network operations and location infrastructure as well as migration related costs, and indicates the multi-dimensional complexity inherent here.
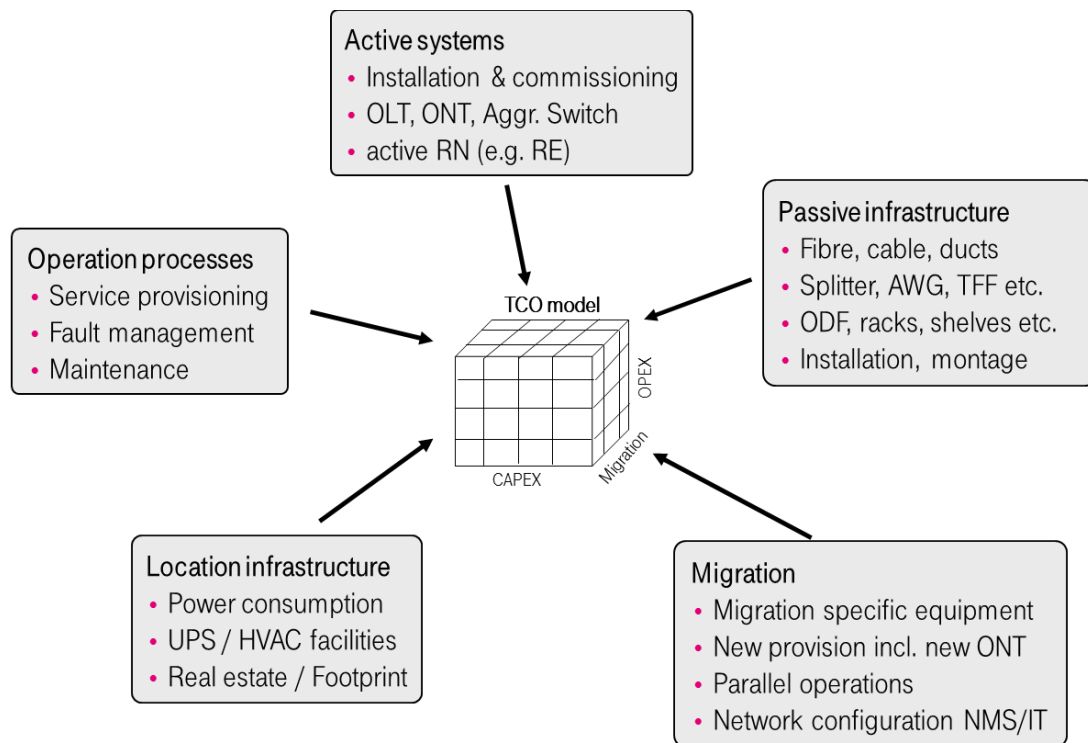
Figure 11: Building blocks of the TCO model [2]

An added ingredient required for an appropriate time-evolution calculation of the OpEx is the assumption of the discount rate, so as to achieve the net present value (NPV). This is also required so as to calculate the required subscription prices, in order to get a positive NPV and achieve a break-even point after a certain number of years, given the CapEx costs, and the ongoing OpEx costs. In this case, the following formula is required to calculate the NPV:

$$NPV = \sum_{n \,\in years} \frac{CF_n}{(1+i)^n}$$

where, NPV = total calculated NPV

years = 0 … planning horizon (e.g. 0-20)

i = discount rate

CF = cash flow for a given year

The speed of any migration process will also have a bearing on when the break-even point can be achieved.

Another important aspect to the SODALES architecture is its open access design, which also has an impact on understanding the OpEx costs of the network, e.g. for co-operation between the various actors and their sharing of part or all of the infrastructure, equipment, etc. With respect to open access, different methods for giving access to the network are possible [3]:

- **Fibre open access:** Fibre open access scenarios consider the possibility of utilising deployed (but unutilised) fibre capacity within the fibre network for any FTTH aspects, i.e. any fibre final-drop from the ARN.

- **Wavelength open access:** Wavelength open access refers to the ability for network providers / service providers to access one or more dedicated wavelengths within individual fibres to reach customers.

- **Bit stream open access:** The implementation of this service-level open access (hereafter referred to as bit-stream open access) may be done in different ways, and also provides opportunities for various alternative scenarios, e.g. see [2].

The equipment related costs for open access or unbundling on different network layers varies for these three layers, and each requires a separate evaluation.

- Open access on the fibre layer provides the greatest degree of flexibility and could result in the largest possible market competition, thanks to the ease of deployment of multiple network providers potentially opting for heterogeneous network technology. However, additional costs would be incurred should end-users decide to switch NPs, which also need to be considered.

- While open access on the wavelength layer is possible and comes for a marginal increase in cost (below 1% if choosing for the right technological solution [2]), diseconomies of scale associated with the use of PON architectures by network providers give a disincentive to utilize such a scheme for small numbers of users.

- Bit-stream level open access is possible for all the various SODALES system variants, and there are small additional overheads associated with providing access at this level, while the actual additional equipment related costs are close to negligible. This can lead to some benefits (for example, optimizing deployment and reducing duplicated equipment), but also reduces the ability to differentiate service between operators.

Open access also entails a management and process related cost, including all the various kinds of patching which are related to the provisioning process of a physical or logical connection for a bitstream product. These patching costs can amount up to €150, but are usually lower due to economies of scale.

Finally, business related costs are the collection of search and information costs (related to the level of standardization and documentation of the requirements of the other actors), bargaining costs (for the negotiation of the contracts) and enforcement costs (ex-post costs to ensure that everything operates according to the agreements). These costs typically range between 8% and 15% of turnover for the PIP and NP.

From the perspective of transaction cost reduction, there is also potential gain in promoting standardization, both at technical and business levels. Such an agreement should probably include all relevant technical (including, for example, resource allocation) processes, as well as business aspects and interfaces required for providing services to the customers. The rule set

should be monitored and coordinated by an independent party; it should definitely not lie with one of several NPs offering service in the same area. The coordinating party can be the PIP or possibly another independent (public) entity.

The key figures for OpEx calculation are energy consumption, reparation and outage time penalty (for business user). The last two relate to network failure and, for these, the operational costs are: the failure repair cost and the penalties that should be paid due to service outage. The failure repair cost depends on the total number of network components (including hardware, software and different parts of the fibre infrastructure) and the network lifetime. For each component, the failure repair cost depends on the Mean time between failures (MTBF), the number of persons required to repair the failure and the Mean Time To Repair (MTTR). For each cost component, only active equipment has effect in duration of 20 years life time, because all passive equipment has MTBF higher than 100 years. MTTR is the average value of total time to repair (TTTR), including travel and the time to wait for the available resources and actual repair time. As stated before, most of these values are strongly dependant on where the network is located.

In particular, the maintenance and repair costs are dependent on the lifetime of the asset and the price erosion of that asset according to the lifetime. Different assets have different expected lifetimes and thus, different price erosions (also dependant on volume productions as shown on the CAPEX analysis section).

Table 15 – Useful life according to asset type

asset		useful life (years)
land and buildings	land	indefinite
	building and constructions	5 to 33
technical and network equipment	switches	3 to 10
	cables and operational support systems	4 to 20
	transmission	4 to 10
	equipment installed at client premises	2 to 5
	equipment for data transfer business	3 to 5
	mobile antennas	6
furniture and vehicles	furniture and office equipment	3 to 10
	vehicles	5
	other tangible assets	3 to 33

Other important factors of OpEx are the maintenance fees. Those values may vary according to the type of component and also specific commercial agreements, but as a general rule, the maintenance fees are calculated respecting the indications of **Table 16**.

Table 16 – Maintenance over lifetime

Equipment type	Maintenance over lifetime
Active Optics	50% (3-5y)
Active Electronics	50% (3-5y)
Passive Electronics	25% (>10y)

In order to calculate the OpEx it is necessary to have the values of MTBF and power consumption of the several SODALES components. At the time of writing this deliverable the available values are presented on the next tables.

Table 17 – ARN MTBF and power consumption

ARN	Temperature (ºC)	MTBF (hours)	MTBF (Years)	Failure Rate (FIT)	Consumption (W)
ARN Chassis with fans and one CXO160 and power supplies	40	3.218,77	367,4	310,7	83,3
CXO 160G Ind. Temp.	40	216,831	24,8	4,612	65,33
Fans	40	1.527,74	174,4	655	17,97
TA48GE	40	241,761	27,6	4,136	72,7
TU40G	40	486,874	55,6	2,054	

Table 18 – C.O. MTBF

Central Office (OLT1T3)	Temperature (ºC)	MTBF (hours)	MTBF (Years)	Failure Rate (FIT)
CXO 640G	40	186,491	21,3	5,362
OLT1T3 Chassis	40	300,937	34,4	3,323
Fans	40	644,637	73,6	1,551
TU40G	40	486,874	55,6	2,054

4   Field Trial Feedback

4.1   Customer characterization

During the course of the field trial, the users of the DELTA demonstrator were characterized in terms of network usage. These users have mostly a "residential profile". The bandwidth usage was assessed and a daily average was calculated for the duration of the day. For this daily profile, the types of traffic that were measured were the pure Internet Access and the IPTV unicast service. Next figures show that, the average peak bandwidth per customer is below 300 kbps for each of these services, and that these peaks occur near 10 PM. These values are important to dimension the ARN uplinks and show that the bandwidths provided by SODALES are, by far, above the current needs.

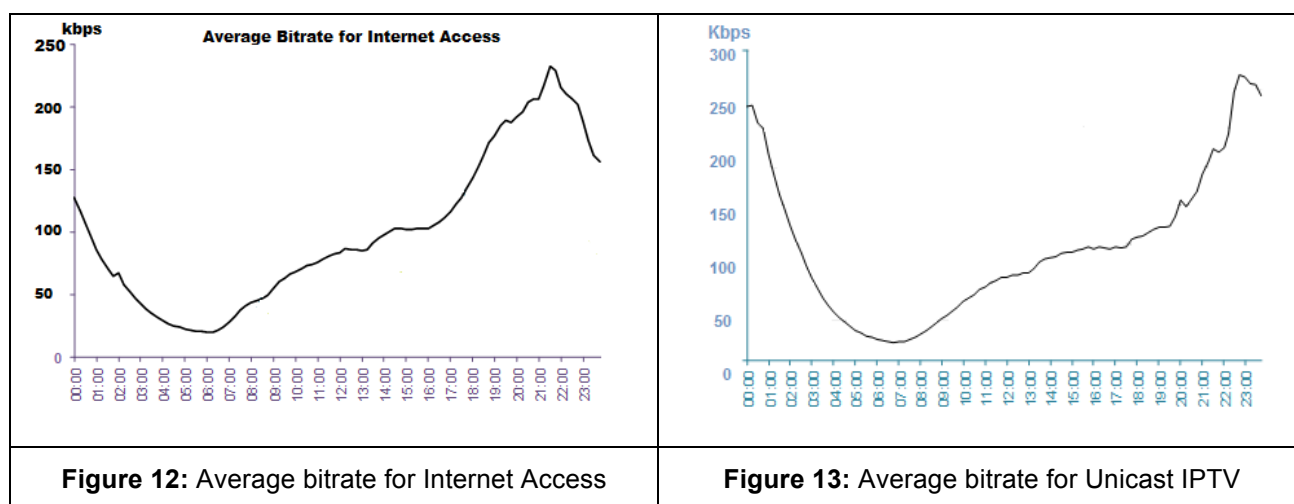|	
Figure 12: Average bitrate for Internet Access	**Figure 13:** Average bitrate for Unicast IPTV

Figure 14 presents the evolution and distribution of the type of traffic. The correlation between the data shown on Figure 12, Figure 13 and Figure 14 allows us to conclude that, on average, each customer (present days) demands a little more than 1 Mbps (sustained) at peak (prime time). This information is very important and justifies that it is technically viable and justifiable that each SODALES ARN port may be shared among several users, as we pointed on section 2.2.4.
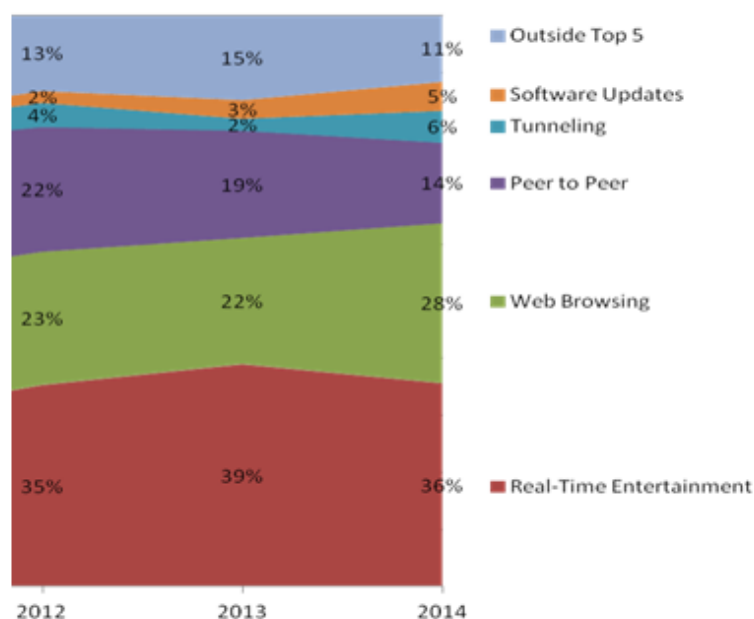
Figure 14: Customer traffic type distribution and evolution

If we further add the data provided from Figure 15 and Table 19 (Fixed Access) we can conclude that the bandwidth demand increased about 100% in 2 years. Part of this growth is, naturally, from new users. But, even considering that this growth rate was only due to existent customers increase on demand, and taking the same growth rate for the upcoming years, it is possible to conclude that the SODALES architecture, with 16 customers per CPE (resulting on 16 customers per ARN port), will still be able to provide sufficient bandwidth for the upcoming 12 years. In the event that the bandwidth would become scarce, it is possible to increase it by introducing more CPEs and migrating some of the 16 customers to these new CPEs, resulting on a flexible and smooth approach to network (customer) and traffic growth.
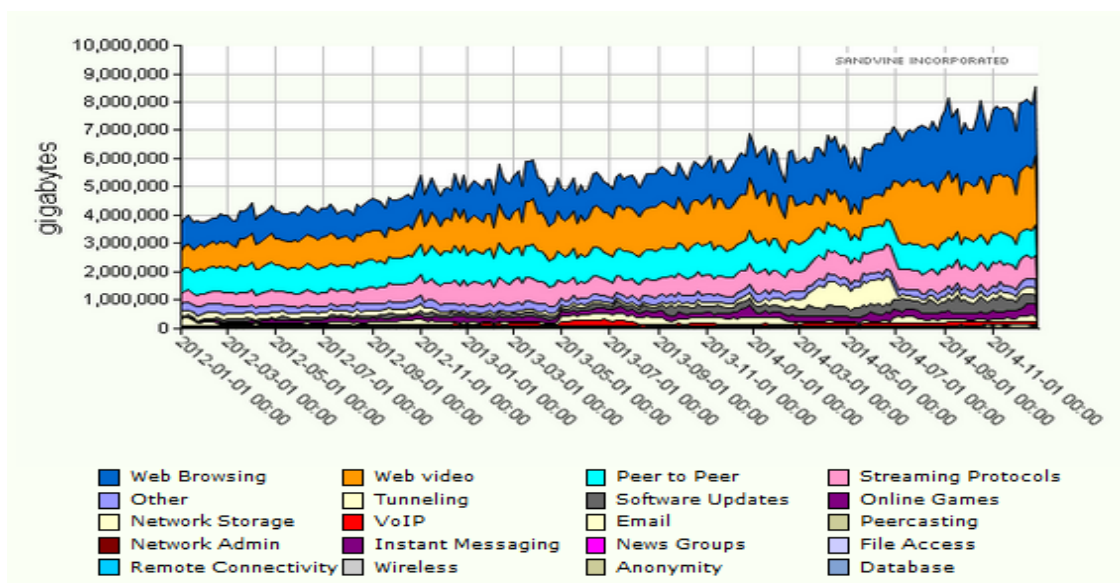

Figure 15: Evolution of the total Internet traffic by traffic type

Table 19 – Growth rate per type of Internet access

Growth rate 2012-2014			
Protocol Category	**Fixed Access**	**WiFi (hotspot)**	**Celular**
Web Browsing	143%	812%	87%
Web video	172%	902%	20%
Streaming Protocols	99%	854%	18%
Peer to Peer	17%	235%	-65%
Software Updates	545%	489%	314%
Others	58%	437%	6%

4.2 Usage and user feedback

The SODALES field trial allowed us to verify that this architecture provides network resources that enable a very high quality of service and of experience. During the all field trial time period (and it is still running), the users with SODALES accesses never had any constraint related to this part of the network. As shown on SODALES deliverable D4.4, the Internet access bottleneck is outside the SODALES part of the network. Additionally, the resources available allowed a very high quality IPTV service, allowing each user to have as many HDTV channels as they could consume. Other less demanding services ran smoothly, without any complaints or even observations from the end-customers.

The provision of a new customer and its services is done by the Open Access management platform on a very clear, smooth and expedite way, as also shown on D4.4.

The overall user feedback was extremely positive, without any negative comment or even new requirement.

## 5   Cost comparison between SODALES and GPON deployments

SODALES presents itself as flexible future-proofed access technology with support for both residential users as well as SMEs and BTSs. GPON in other way is residential user intended, but lately support for both SMEs and also so LTE and UMTS offload capabilities are being developed. GPON architecture was taken in mind to lower the CapEx and OpEx cost of access networks and at the same time offer high bandwidth to end-users.

CapEx reduction is achieved by sharing the same fibre span from the OLT to the splitter which is passive, using a splitting ratio of 64 users per PON port and aggregating many PON ports per OLT line card. The final result is a really low cost for OLT cost for each end-user served. The most important GPON cost comes from the FTTH ONU cost, even when mass production is assumed.

For our brief comparison we used the same chassis for both the SODALES ARN and also GPON OLT. GPON OLT was equipped with 2 line cards with 16 PON ports each serving a total of 1024 (1:64) users with 40 Mbps for each user. Using this assumptions the total cost per PON end user is less than 50 €, Figure 16.

For the SODALES networks the bulk cost comes also from the CPE which is almost 150 € (including SFP), almost 3 times the PON cost. The cost of each user per ARN is also higher at around 55 €. The total cost of the SOLADES network per user is therefore estimated to be a little more than 200 €, which is about 4 times the cost of the GPON (about 50 €), just for CAPEX; but the total bandwidth available is more than 25x the one offered by the GPON, which results on a reduced cost per Mbps (see Figure 18).

Also it must be taken in mind that the interfaces offered at the CPE and described at D1.1, such as the internal 10G switching, are superior as compared to the GPON ONUs.

Cost per Home passed GPON/SODALES

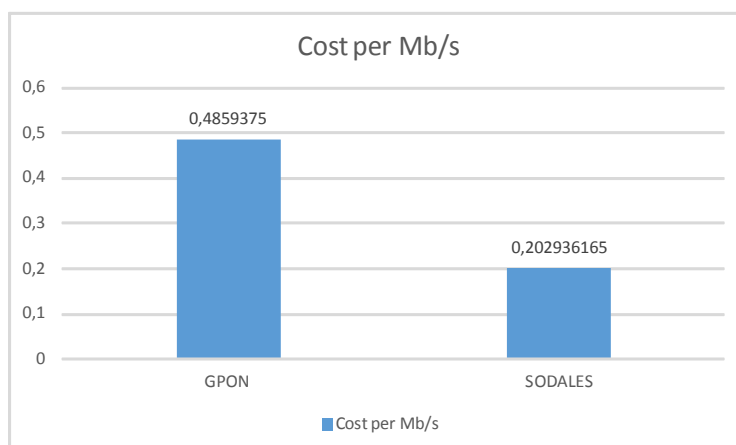|	GPON	SODALES
ARN/OLT	8,59375	55,53
CPE/ONT	40	147,408
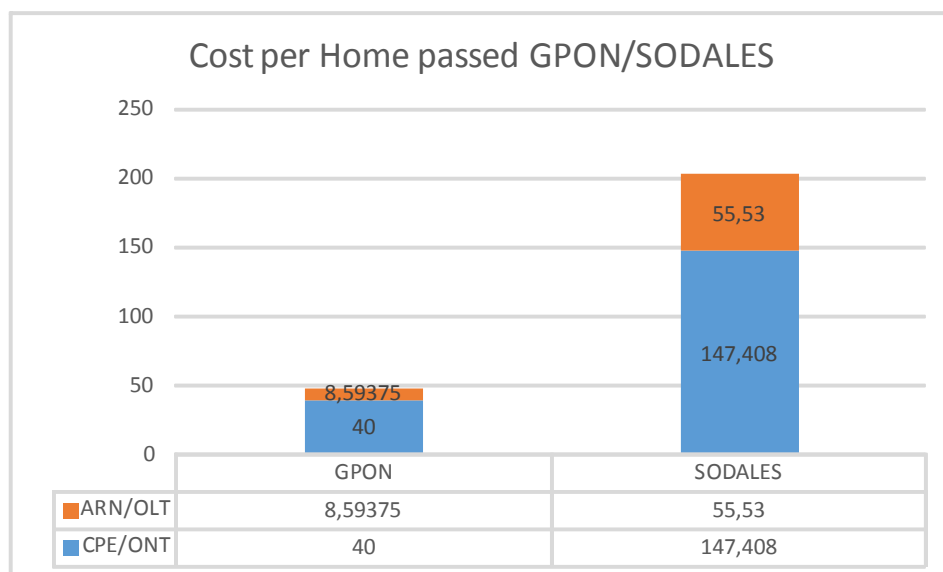
Figure 16: Cost per home passed using GPON and SODALES

As presented on section 4.1, the data rates demanded today and the expected growth rate, allow us to adopt a different approach, serving 16 customers per CPE (instead of only 1), further reducing the cost per customer by that factor of 16. With this approach we are able to decrease the SODALES cost per user to less than 13 €, more than 4 times less than GPON, and even so, providing more than 50% more bandwidth per customer (more than 60 Mbps, constant, without considering any statistical multiplexing).
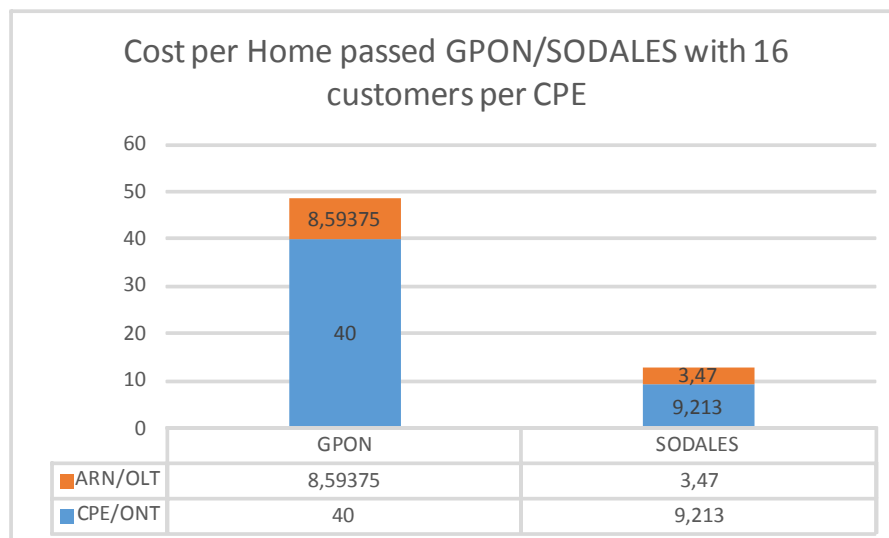
Figure 17: Cost per home passed using GPON and SODALES, with 16 customers per CPE

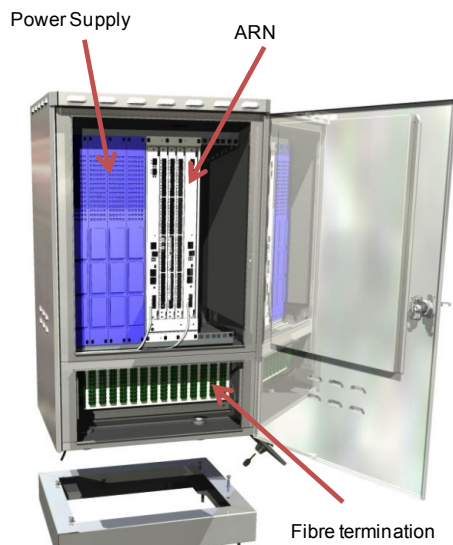**Figure 18:** Cost per Mbps offered to residential users

As cost per Mbps is much lower in SODALES, we foresee the platform to become an optimal option to offer ultra-broadband services for radio and fixed access, especially when user demands require Gigabit data rates. On the next section we already describe a real scenario where a variation of this network architecture was commercially deployed.

Also, SODALES constitutes a viable option for traffic offload of 4G/5G radio networks, as it provides high transmission capabilities and advanced OAM features and does not require additional switching equipment, as per existing Fibre-to-the-Antenna (FTTA) approaches, which require expensive MEF switches with price levels similar to our proposed ARN.

5.1 Commercial deployments

The SODALES ARN and concept was deployed commercially. Due to legal agreements the Operator where it was deployed cannot be disclosed.

The network that was built was based on the SODALES CO and ARN equipments, providing active Ethernet connections for residential users. Each 1Gbps connection was then shared among several houses by means of an Ethernet Switch (up to 48 customers per ARN port), acting like SODALES CPEs. The ARN was installed on remote outdoor cabinets, mounted on poles. On this solution, each ARN is equipped with 3x48GE client side interfaces, making it a total of 144 GE access ports, each shared among several users (up to 48). At this point, this provider is not using this infrastructure to connect base stations. For the customer side no 10GE interfaces are being used (up to 4x10GE are used as uplinks).

Power Supply
ARN
Fibre termination

Figure 19: ARN on an outdoor cabinet

Outdoor cabinet
Heat Exchange climate control, aided by convection system
Hard body double walls
Modular design
Weight < 40 Kgs
IP55 protection level; IP2X protection level w/ door open
288 optical fibre terminations and patching; LC/APC to pre-connected cables
Incorporated cabling management;
Pole, wall or floor installation
Environment temperature range: 5ºC to 50ºC
Compliance with requirements: IEC61439-0-1-2 ; IEC60950 ; IEC60529
Dry contacts cabinet Alarm: Doors open; Ac fail; Surge protection fail
Max external dimensions 800x500x400mm (H x W x D)
Door with lockers prepared to receive the special operator key lockers
Easy instalation
Shelf for optical fibre patch cord accommodation

Table 20 – Outdoor cabinet specifications
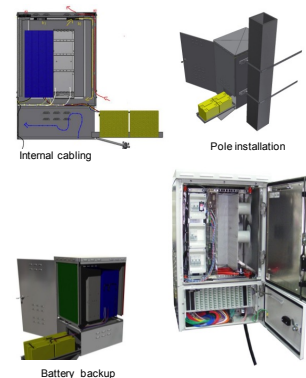
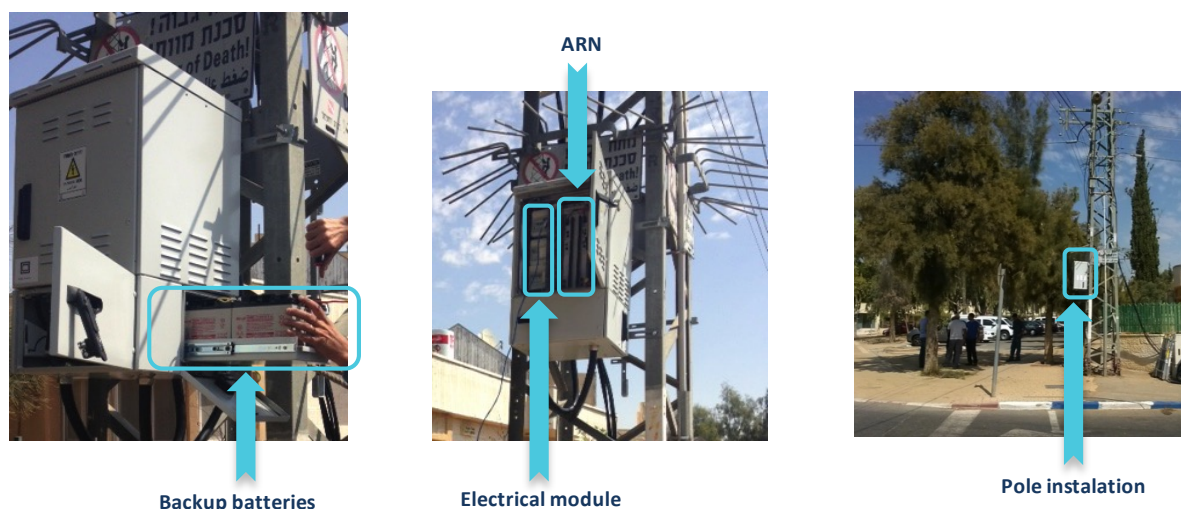| Electrical |
|---|
| No grounding connection - Class 2 |
| AC/DC Converter with capacity up to 900W and equipped with 3 modules of 300W each for redundancy (full power 96% - hot swap) |
| Battery charge management |
| LVD system |
| Plastic protection to the power system AC/DC block |
| Plastic supports to the AC/DC converter unit |
| Electrical circuit protections: AC: Mains circuit breaker 2poles 6A 25KA |
| High voltage surge protection breaker 40KA; DC: Battery circuit breaker |
| 2poles 16A 6KA; Fans circuit breaker 2A 6KA; |
| Equipment A circuit breaker 10A 6KA ; Equipment B circuit breaker 10A 6KA |

Table 21 – Electrical specifications

Internal cabling
Pole installation
Battery backup

Figure 20: ARN outdoor cabinet details

Figure 21: Field installation of an ARN supporting up to +65ºC

6   Conclusions

As the project progressed into its 2nd and 3rd years, we refined the techno-economic study, taking into account changes in the pricings of the components, revising some of the assumptions we have made, and also calculating expected pricings for some of the more innovative final-drop technologies (e.g. optical wireless final-drops) that we developed. We observed a significant price reduction, especially at the CPE level, which can be further reduced by connecting 16 customers to each CPE, which will still allow enough bandwidth per user, as we shown on this report.

As in D5.2, we have studied the costs associated with the CO, ARN, and CPE components of the SODALES network, using the Olsen learning curve model to estimate the component costs in volume production, from 1 through to 100,000 units.

It is interesting to observe that the prices of the several components/elements were reduced in these 2 years that passed from D5.2 to D5.6, as expected.

We also provided indication of the estimation of each SODALES customer over the next 15 years, using the Olsen model to do the prediction of the price evolution.

With respect to SODALES OpEx, we presented the main theoretical considerations behind the OpEx of such infrastructures. On the same section we presented some currently available values of MTBF and power consumption for the ARN that, applied to a specific implementation scenario, on a specific region, allows the calculation of the several OpEx costs, such as penalties for downtime, energy costs and repair costs.

On section 4 we presented the customers characterization that allowed us to conclude that the initial SODALES network dimensioning is still largely over the necessary resources of present users. We also observed that SODALES will be able to cope with the growth rates of traffic for the next decade, even sharing each access between 16 end-customers. Of course that there are "heavy users" that demand more bandwidth, and for those particular cases, it is necessary to make adjustments (on the limit, one user per SODALES access, as specified on the SODALES architecture).

Finally, on section 5 we presented a commercial solution, already implemented on the field, for a network operator that is using the electricity poles as the location for the ARNs. In this particular scenario, the ARNs are equipped with 3x48GE interfaces (total of 144 GE per ARN), each being shared by several customers (through the use of an Ethernet switch connected to each GE port of the ARN). This solution as proved to be cost efficient and as also proved to provide enough bandwidth to high bit rate Internet access and, HD- and Ultra HD-TV.

7 References

[1] http://www.ict-oase.eu/

[2] EU FP7 OASE Project deliverable D8.5 "Integrated OASE results overview", 2013

[3] EU FP7 OASE Project deliverable D3.2 "Description and Assessment of the Architecture Options", 2011

[4] http://www.ict-fiver.eu/

[5] Bart Lannoo, Gent University, "Techno-economics of Optical Access Networks", Brussels, 18 Of October 2010

[6] S. Verbrugge, K.Casier, J. V. Ooteghem, B. Lannoo, "Practical steps in techno-economic evaluation of network deployment planning," White paper April 2009.

[7] B. T. Olsen and K. Stordahl, "Models for forecasting cost evolution of components and Techno-logies", Telektronikk 4.04, pp. 138-148, 2004.

[8] Wright, T P.Factors affecting the cost of aeroplanes. Journal of Aeronautic Sciences,3 (4), 122-128, 1936

[9] Crawford, J R. Learning curve, ship curve, ratios, related data. Lockheed Aircraft Corporation , 144.