A Techno-Economic Analysis of Active Optical Network Migration Towards the Next Generation Optical Access

K. Wang, C. Mas Machuca, L. Wosinska, P. J. Urban, A. Gavler, K. Brunnström and J. Chen

***Abstract*—Active Optical Network (AON) has been one of the most deployed fiber access solutions in Europe. However, with the increasing traffic demand, the capacity of the existing AONs is becoming insufficient. For the legacy AONs, there are two major variants of architectures, namely point-to-point and active star. Considering the different characteristics of these two AON architectures, this paper proposes and analyzes several migration paths towards Next Generation Optical Access (NGOA) networks offering a minimum 300Mbit/s sustainable bit rate and 1Gbit/s peak bit rate to every end-customer. Furthermore, this paper provides detailed descriptions of the network cost modeling and the processes for AON migration. The Total Cost of Ownership (TCO) for the proposed migration paths are evaluated taking into account different migration starting times, customer penetration, node consolidation and business roles in the fiber access networks. The migration from AON to NGOA can be economically feasible. The results indicate that a network provider plays a key business role and is responsible for the major part of TCO for AON migration. Moreover, performing node consolidation during AON migration can be beneficial from the cost point of view, especially in rural areas.**

***Index Terms*—Active Optical Network (AON), Next Generation Optical Access (NGOA), Migration, Capital Expenditures (CAPEX), Operational Expenditures (OPEX), Node consolidation.**

I. INTRODUCTION

Optical fibers offer ultra-high capacity transmission and are considered the future proof technology for Internet access. Active Optical Network (AON) [1] and Time Division Multiplexing (TDM) Passive Optical Network (PON) such as Gigabit-capable PON (GPON) [2] are currently the two most deployed fiber access solutions, i.e., Fiber To The X (known as FTTx, where x stands for the fiber termination point, e.g., home, building, curb, node, etc.). AON, also known as active Ethernet, has been standardized since 2004 [1]. According to [3], AON has been massively deployed in the past. Most of the deployed AONs are based on Fast Ethernet (FE), which is able to offer a sustainable bit rate up to 100 Mbit/s per customer. The capacity limitation is not due to the fiber infrastructure itself, but is mainly limited by the capacity of the network equipment. On the other hand, emerging services, such as Ulltra High Definition (UHD) video, cloud services, 4G/5G mobile backhaul/fronthaul (Xhaul) are driving the capacity demand beyond 100Mbit/s. Therefore, there is a need for proper migration strategies from the already deployed AONs towards solutions that can satisfy the new capacity-demanding services.

There are two variants of AONs: Point-to-Point (PtP) Ethernet and Active Star (AS). The PtP architecture is also referred to as 'homerun' (shown in Fig. 1(a)). In this architecture, each subscriber has a dedicated fiber connection between the home Residential Gateway (RG), which can be an Optical Network Terminal (ONT), and the Optical Line Terminal (OLT), such as an Ethernet switch, located in the traditional access node, also referred to as Central Office (CO). Unlike the PtP architecture, the AON AS has a point-to-multipoint fiber topology, employing active Remote Node (RN) connected to the CO and multiple households as illustrated in Fig. 1(b). The RN can be a cabinet, manhole or inside the building, e.g., a basement of a multi-dwelling unit. The Ethernet switch at the RN aggregates the traffic from a group of subscribers, and connects by a feeder fiber to another Ethernet switch at the CO. Two or more feeder fibers may be deployed to provide resiliency, but the amount of fibers used in the AON AS architecture is significantly reduced compared to the PtP case. Fig. 1(c) shows a FTTB/C/N (Fiber To The Building/Curb/Node) architecture based on AON AS. The optical signals terminate at the RN, which connects to the households via legacy copper cables. AON can support different types of users, i.e., broadband access for residential customers, business users, and backhaul/fronthaul (Xhaul) for mobile networks, as shown in Fig. 1(d). Mobile Xhaul

K. Wang is with the Optical Networks Lab (ONLab), KTH Royal Institute of Technology, and Acreo Swedish ICT AB, Stockholm, Sweden (kunw@kth.se).

Prof. L. Wosinska and Prof. J. Chen (J. Chen is corresponding author) are with the Optical Networks Lab (ONLab), KTH Royal Institute of Technology, Sweden.

Dr. C. Mas Machuca is with the Chair of Communication Networks (LKN), Technical University of Munich (TUM), Germany.

Mr. A. Gavler and Prof. K. Brunnström are with Acreo Swedish ICT AB, Stockholm, Sweden.

Dr. P. J. Urban is with Ericsson research, Stockholm, Sweden.

applications require higher bit rate AON systems, Gigabit or 10G bit rate.

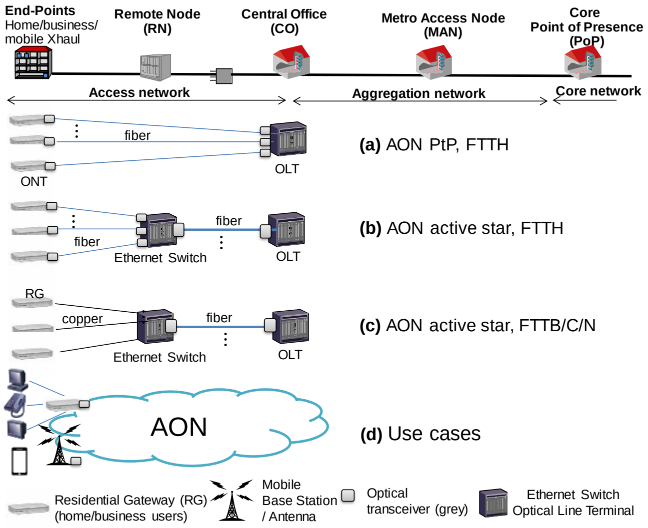

Fig. 1. Current AON based solutions for FTTx.

Different Next Generation Optical Access (NGOA) technologies have been considered as a target of the network migration. 10 Gigabit compatible PON (also known as XG-PON) was standardized in 2010 [4]. It can support asymmetric traffic at 10 Gbit/s downstream and 2.5 Gbit/s upstream. The symmetric version, 10 Gigabit compatible symmetric PON (XGS-PON), was also standardized recently in 2016 [5]. ITU-T approved the second Next Generation Passive Optical Network (NG-PON2) standard [6] where the primary technology is Time and Wavelength Division Multiplexing PON (TWDM-PON) [7]. ITU-T approved the second Next Generation Passive Optical Network (NG-PON2) standard [6] where the primary technology is Time and Wavelength Division Multiplexing PON (TWDM-PON) [7]. NG-PON2 supports at least 40 Gbit/s per feeder fiber in the downstream. It is achieved by multiplexing the traffic from several 10Gbit/s TDM PONs and multiple wavelength channels for transmission. Meanwhile, the Point-to-Point Wavelength Division Multiplexing PON (WDM-PON) is also included in the NG-PON2 standard as an option. Although NG-PON2 standard [6] specifies four and eight bi-directional wavelength channels for TWDM and PtP WDM, respectively. However, the specification anticipates a future increase in the number of wavelength channels for both technologies [8]. There are several works addressing a techno-economic analysis of NGOA architectures. Hülsermann et al. [9] presents both technical performance and cost assessment of several NGOA architectures, including WDM-PON and TWDM-PON. The cost study is too simple though. Operational aspects, such as service provisioning and fault management, are not considered. A complete cost evaluation of network migration from GPON to TWDM-PON is presented in paper [10], where it is shown that migrating to TWDM-PON is the best option thanks to the high sharing rate and high bit rate on a per-user basis. The work is limited to the migration starting from a PON architecture. A techno-economic analysis of migration path starting from AON AS has been conducted in [11]. The paper studies a NGOA architecture for legacy AON AS migration. It does not address, the proper migration paths for AON that covers both legacy PtP and AS. Meanwhile, Node Consolidation (NC) has been considered as an important trend for access network migration leading to a simplified access and metro network segment [12]. It is driven by the high potential for the Total Cost of Ownership (TCO) savings. Papers [9] and [10] demonstrate the cost benefits of network migration from GPON to consolidated NGOA architectures. Unfortunately, such results cannot be directly applied to AON, and therefore the impact of NC on AON migration still needs to be investigated.

In this paper, we focus on the TCO analysis of network migration from widely deployed AON towards NGOA concerning both infrastructure and technology upgrade. We propose five migration paths based on the characteristics of the deployed AON. Three of these consider NC, whereas the other two are not targeting NC. In the case of NC, part of the aggregation network is also included. Therefore, we bring the cost assessment of both access and aggregation network into TCO analysis enabling us to perform a fair comparison of NC and Non-NC scenarios. Furthermore, the different types of business roles on the broadband market have been taken into account when evaluating the cost and identifying who is charged for which type of the cost.

The remainder of the paper is organized as follows. Section II describes the methodology and assumptions for the total migration cost evaluation. Section III provides a detailed description of migration paths. Section IV depicts the cost modeling. The TCO results have been presented in Section V, and the analysis of node consolidation is included in Section VI. Finally, Section VII provides the conclusions.

II. Methodology and Assumptions for TCO Assessment

The TCO modeling in this paper focuses on the migration starting from a Fast Ethernet (FE) based AON PtP and AS towards NGOA architectures. Proper network planning and dimensioning have to consider many aspects that may affect a techno-economic analysis, such as traffic evolution, changing of subscribers, time frame, etc. A general methodology covering all the aforementioned aspects for evaluating TCO are given in paper [13]. In order to facilitate the techno-economic analysis of AON migration, in this work we further extend the models from paper [13] to adapt to AON characteristics. There are six important aspects for AON migration, namely migration time frame, business roles, sustainable bandwidths, customer penetration, geographical and network model, are elaborated in this section. The assumptions used for the TCO assessment, made in later sections, are also presented.

A. *Migration time frame*

The migration time frame plays an important role in the access network TCO study. Its impact on the cost depends on the penetration curve, which gives the total number of connected users every year. Typically, the more users are connected to the legacy network at the migration starting time, the higher the migration cost will be. On the other hand, the earlier migration will enable network operators to provide higher bit rates and better quality of service. As a result, not only the existing subscribers are satisfied and would stay in the migrated networks, but also more new customers may be attracted from the other network operators. Therefore, even if the subscribers would not pay more for higher bandwidth, higher incomes can be expected by the operators.

Our TCO analysis considers a time frame of 20 years. The migration process towards NGOA begins in the 10th year (referred to as the migration year), and it is assumed to take one year to complete the migration, which is realistic in certain areas [14]. For a large-scale deployment, the migration may be performed area by area at different years. The one-year migration time considered here is for the tasks such as installations of new fiber infrastructure, filters, splitters, and patch panels that are needed for migration. It also includes testing the new network, and decommissioning of legacy network. The actual transition of end-users from the legacy network to the targeted architecture can be considered as an unplug and plug action which just takes a few seconds (max. a few minutes). If it is done in the middle of the night so that the interruption is rarely noticed by the users. Furthermore, the service disruption experienced by a big amount of customers can be also minimized by performing the migration in limited areas. The deployment in a country may be performed area by area at different years. In order to find out the impact of a different starting year on the migration costs, we have also investigated a network migration starting at the 15th year, where the capacity demand per customer is close to the limit of existing AON. During the migration, the legacy network and partly migrated NGOA are running simultaneously. When the migration process finishes, the legacy network can be fully dismantled since all customers of the legacy network are then connected to the new network. We assume that the network migration is driven by a strong need for the capacity upgrade by majority of the customers. Therefore, when NGOA is ready, most of the customers are willing to subscribe the services offered by the new network. Less demanding customers will be also migrated to the new platform while keeping their subscribed service unchanged.

This study focuses on the TCO evaluation of network migration towards NGOA. Therefore, the initial investment of the legacy network, especially the infrastructure investment, is excluded from this study, although it is substantial. However, reusing the existing infrastructure as much as possible is one of the important criteria used for the selection of NGOA architectures, so that the migration costs can be minimized.

B. *Business roles*

Because of different business roles on the broadband market, in many cases the TCO of a network is not associated to a single actor [14]. Responsibilities can be split into several entities playing different business roles [15]. The Physical Infrastructure Provider (PIP) owns and maintains the passive infrastructures such as ducts, fiber cables, passive filters and optical distribution frames, etc. The Network Provider (NP) is responsible for the active network equipment, such as OLTs, RGs, amplifiers and cooling equipment. The service provider delivers the digital services (e.g., Internet, video streaming, e-health, cloud services, etc.). The role of the service provider is out of scope for this study as we focus on the TCO of network migration, where the service layer is not included. Furthermore, there are some costs which are directly associated with the end users or third parties (e.g., housing management company, real estate company), such as energy bills for RGs, in-house cabling, or sockets.

The division of business roles is also valid in different network segments. For example, there can be NPs in the aggregation network who are independent from the NPs in access network. Therefore, in this paper, the access network and aggregation network are modeled separately, as described in Section II (F). The aggregation network cost is modeled as leased lines.

C. *Sustainable bit rate*

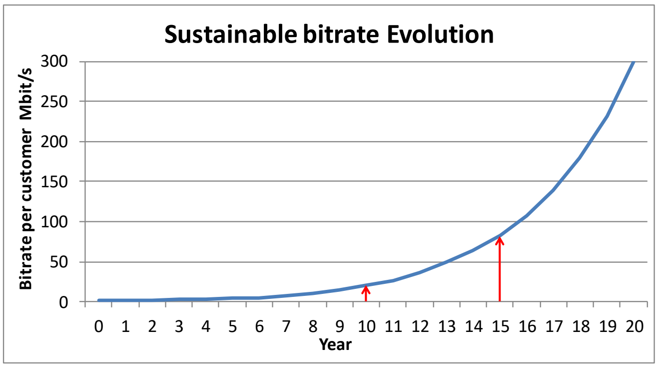

Fig. 2. Evolution of sustainable capacity over 20 years.

One of the major goals of the network migration is to offer higher capacity. There are two measures for capacity, namely sustainable bit rate and peak bit rate. The sustainable bit rate is the guaranteed bit rate that is always available whenever a customer connects to the network. The peak bit rate means the maximum rate a customer may get from the network (e.g., during off-peak time when other customers rarely use the network), which is not necessarily guaranteed. We consider the sustainable bit rate as common baselines for assessing all the NGOA architectures and migration paths. It is especially relevant for the network planning and dimensioning to define the number and type of OLTs, switches and aggregation network equipment. In this paper, a traffic evolution curve shown in Fig. 2 is assumed for the TCO modeling [16], where in the final year the network should be able to offer every customer a sustainable bit rate of 300 Mbit/s. Furthermore, a peak bit rate not less than 1Gbit/s is taken into account.

The arrows in Fig. 2 indicate the sustainable bit rate in the 10th year (20Mbit/s) and in the 15th year (83Mbit/s). Those two years are specifically studied in this paper as the migration starting years.

D. *Customer penetration*

In the cost assessment, it is important to define customer penetration rate reflecting the percentage of the network/infrastructure that is utilized. According to the business roles (PIP or NP), two customer penetration curves need to be considered. One is for the PIP and the other is for the NP. Fig. 3 shows an example of the penetration curves [17][18]. In order to concentrate on the network migration study, we assume that the entire PIP infrastructure of AON PtP or AS is already available from the Year 0, taking into account 100% coverage of all potential connected FTTH customers in the area. There is no other investment on the PIP infrastructures in the following years, until the network migration towards NGOA happens. Migration towards NGOA deployment may involve additional investment on the infrastructures, which is required to support NGOA architecture but not for increasing the penetration of the end users. We also assume that the infrastructure of NGOA is rolled out with 100% coverage at the year of network migration.

The NP penetration curve indicates the percentage of users in an area who subscribe for network access. In the example shown in Fig. 3 [17][18], the final penetration rate reaches 74% in the 20th year. There are two migration starting years investigated in this paper. One is the 10th year when customer penetration is 10%, and the other is 15th year when the penetration is about 40%. The curve is used to dimension the network equipment, RGs, etc.

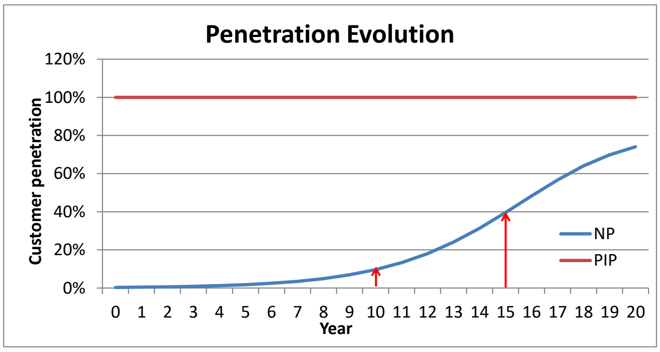

Fig. 3. Evolution of customer penetration curve over 20 years

E. Geographical model

In this paper, the geographical model is based on the network topology of Germany [19]. We consider 3 types of areas according to the population density, i.e., Dense Urban (DU), Urban (U) and Rural (R). The reference areas are characterized by the number of households and area size, as shown in TABLE I.

In order to study the impact of Node Consolidation (NC) on the TCO, the scenarios with and without NC (Non-NC) are considered. Non-NC includes 7500 network nodes, which reflects the current situation of the legacy telecommunication network. These 7500 nodes are serving all network connected households. According to the population density, they are divided into 3 classes: DU, U and R areas. The nodes in the Non-NC case are equivalent to the traditional access nodes, i.e., COs and Metro Access Nodes (MANs)), whereas in the NC case, all COs are removed and only MANs remain. Therefore, the number of nodes in the NC case is reduced from 7500 (in Non-NC case) to 1000. The parameters for these two scenarios are shown in TABLE I.

TABLE I: PARAMETERS FOR THE AREA TYPES

Node Consolidation Type	Area Type	Number of users per node	Area size (km^2) per node	Density (users per km^2)
Non-NC	DU	15600	5.00	3120
Non-NC	U	8640	24.00	360
Non-NC	R	3060	56.67	54
NC	DU	44500	14.26	3120
NC	U	51000	141.67	360
NC	R	33000	611.11	54

F. Network Modeling

The network model consists of two segments: access and aggregation. The demarcation points between access and aggregation network are different in NC and Non-NC scenarios (see Fig. 4).

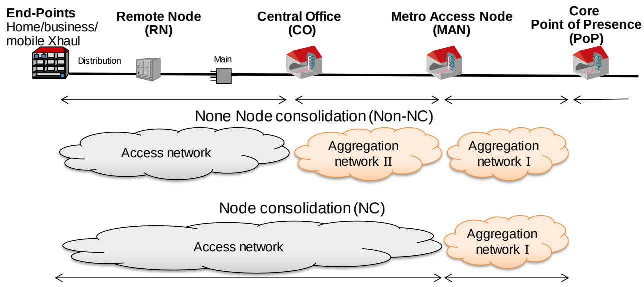

Fig. 4. Network model: access and aggregation

The access network in a Non-NC scenario is defined from end-point to the CO, but in a NC scenario, the access segment is extended until the MAN. In order to have a fair comparison between NC and Non-NC scenarios, a techno-economic study should take into account the network infrastructure and equipment cost between the end-points and the core Point of Presence (PoP), as it shows in Fig. 4. Therefore, we split the conventional aggregation network into two parts [13], i.e., aggregation network I and II. Aggregation network I, which connects the MAN with the core network, is always present in both NC and Non-NC cases. Aggregation network II only appears in the Non-NC case, while in the NC scenario, aggregation network II is merged with the access network, and hence does not exist anymore. In Sections III, IV and V, the analysis of migration paths, cost modeling, etc. focuses on the access network segment. The aggregation segment is included in Section VI when comparing NC and non-NC solutions.

III. Migration Paths

In this section, we present detailed migration paths from traditional AON to NGOA, taking into account the characteristics of existing AON deployments. TABLE II summarizes the proposed migration paths.

TABLE II: STUDIED MIGRATION PATHS (MG)

	Starting Architecture	Target Architecture
MG#1	AON PtP (FE), Non-NC	WDM-PON (80ch), NC
MG#2	AON AS (FE) , Non-NC	TWDM-PON (1:32, 40ch), NC
MG#3	AON AS (FE) , Non-NC	WDM-backhaul (40ch.), NC
MG#4	AON PtP (FE), Non-NC	AON PtP (GE), Non-NC
MG#5	AON AS (FE), Non-NC	AON AS (GE), Non-NC

**FE (Fast Ethernet), GE (Gigabit Ethernet)*

A. Starting architectures

The two architectures considered are AON PtP and AS, as illustrated in Fig. 1(a) and (b). Both are in Non-NC scenario and equipped with Fast Ethernet (FE) in the first mile, giving a maximal bit rate of 100Mbit/s.

B. Target architectures

One of the main drivers for network migration is to increase the capacity per user (e.g., corresponding to the bit rates ≥1Gbit/s peak, 300Mbit/s sustainable). The motivation for node consolidation is to reduce the number of COs saving the cost associated with these nodes, e.g., housing, energy and maintenance costs. The network equipment in the COs is therefore moved to the MAN allowing for support of much more customers and for serving larger areas. In order to study the NC impact on AON migration, in this paper we investigate 5 target architectures (3 in NC scenario and 2 in Non-NC scenario) referred to as Point-to-Point WDM-PON, TWDM-PON, WDM-backhaul, and two GE network upgrade scenarios.

1) Point-to-Point WDM-PON (NC scenario, MG#1)

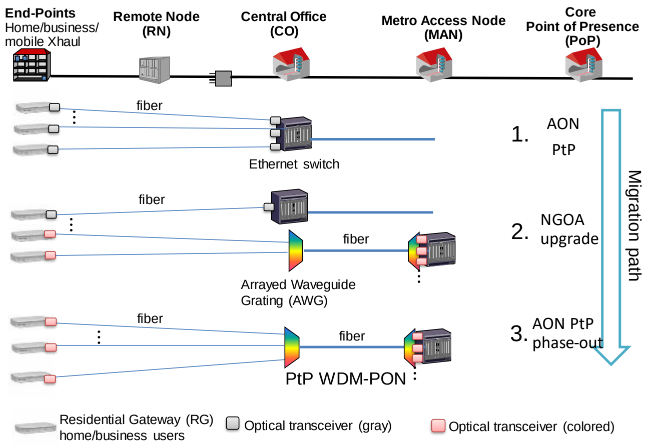

Fig. 5. Migration path (MG#1) from AON PtP to WDM-PON

PtP WDM-PON is one of the selected NGOA architectures for NG-PON2 [6], which provides a dedicated wavelength to each end user, corresponding to a point-to-point connection in the logical layer. Figure 5 shows a proposed migration path from the current AON PtP to WDM-PON. The considered WDM-PON implementation [9][20] has 80 wavelength channels with space of 50 GHz, which is beyond the standardized WDM-PON option in NG-PON2 [8]. Cyclic Arrayed Waveguide Gratings (AWGs) are used at the CO to aggregate 80 distribution fibers into one feeder fiber which uplinks to the OLT at the MAN. The cyclic AWG allows using multiple wavelength bands, e.g. C, L and S band. RGs with tunable lasers and avalanche photodiode (APD) receivers are used at the end-points. The existing AON PtP fiber infrastructure between the CO and the end-points can be re-used. Therefore this WDM-PON implementation offers an opportunity for AON PtP migrating from a Non-NC to a NC scenario without additional investment on the fiber infrastructure between end-points and COs. The number of available feeder fibers (CO to MAN) for the legacy network is not sufficient, and therefore more feeder fibers have to be installed. For 80-channel WDM-PON, we consider that every 80 customers share a single feeder fiber. The additional feeder fibers required for WDM-PON will be newly installed for the network migration. During the migration phase, both the legacy network and NGOA are running in the operator's networks, because some of the users are migrated to the new technology earlier, and some remain in the legacy network, as shown in Phase 2, Figure 5. The newly deployed AWG and the legacy switch are co-located and the fibers between end points and CO are the same from Phase 1 to Phase 3. A summary of the major changes is presented in TABLE III.

TABLE III: MAJOR CHANGES FOR MG#1

Major changes	Location	Business role	TCO category
Residential gateway	End-points	NP	Home equip.
AWG	CO	PIP	Infrastructure
Fiber management	CO	PIP	Infrastructure
Feeder fiber & installation	CO -MAN	PIP	Infrastructure
Fiber management	MAN	PIP	Infrastructure
OLT	MAN	NP	Network equip.
Service adding/cancelling	MAN	NP	SP

*fiber management includes costs of splicing, fusion, patching, optical distribution frames (ODF).

2) TWDM-PON (NC scenario, MG#2)

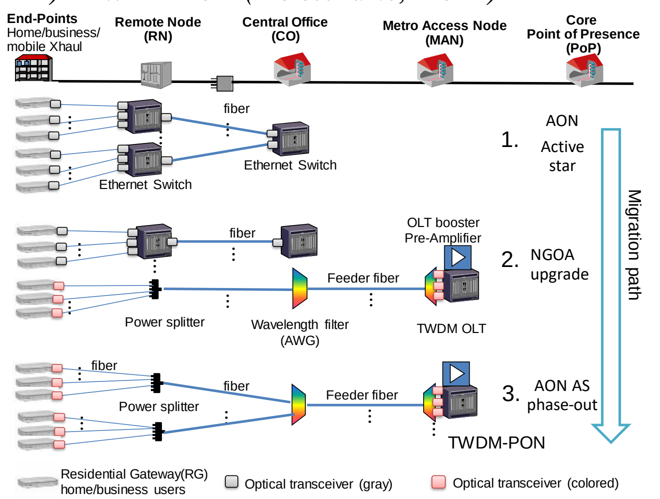

Fig. 6. Migration path from AON AS to TWDM-PON

TABLE IV. MAJOR CHANGES FOR MG#2

Major changes	Location	Business role	TCO category
Residential gateway	End-points	NP	Home equip.
Power splitter	RN	PIP	Infrastructure
Fiber management	RN	PIP	Infrastructure
AWG	CO	PIP	Infrastructure
Fiber management	CO	PIP	Infrastructure
Feeder fiber & installation	CO - MAN	PIP	Infrastructure
Fiber management	MAN	PIP	Infrastructure
OLT	MAN	NP	Network equip.
Service adding/cancelling	MAN	NP	SP

For the existing AON AS, the migration towards a fully passive solution, e.g., TWDM- PON may be a proper option. TWDM is a hybrid technology of WDM and TDM, which is also used by ITU-T [6] as a primary technology for NG-PON2. In this paper, the considered TWDM-PON implementation [9][20] has 40 wavelength channels, which is beyond the 4 or 8 wavelength channels defined in the current NG-PON2 standard [8]. In the considered migration case, the active RNs are replaced by passive power splitters (1:32), while the Ethernet switches at the old COs are replaced by 40-channel AWGs (see Fig. 6, phase 3). It leads to the situation where 1280 subscribers share one feeder fiber from CO to MAN. Since the power splitters and AWGs are passive, it is possible to bury them underground in the enclosures so that both RNs and COs can be closed down. Optical amplifiers (i.e., boosters and pre-amplifiers) are attached to the OLTs at the MAN to increase the reach. 10Gbit/s burst-mode transceivers are used at the ONT with the tunability of 40 wavelengths. The considered TWDM-PON is able to offer symmetric 10 Gbit/s peak bit rate and 300 Mbit/s average bit rate to every subscriber. An unplug and plug action can be considered for switching users from legacy platform to the new network. There are multiple switches co-located in one RN. During the migration phase (see Fig. 6, Phase 3), users connected to one legacy switch can be fully migrated to a power splitter at one time, while users from other switch can stay in the legacy switch and be migrated later. A summary of the major changes needed for the upgrade is shown in TABLE IV.

3) *WDM-backhaul (NC scenario, MG#3)*

Another alternative migration path for the AON AS is towards the WDM-backhaul solution shown in Fig. 7. The active equipment in the CO is replaced by 40 channel AWGs. Each of the WDM channels has a capacity of 10 Gbit/s and is used to backhaul a 32-port Ethernet switch at the RN. The number of required feeder fibers in WDM-backhaul solution is the same as in the 40-channel TWDM-PON, because the amount of users that share one feeder fiber is the same in both cases. Although the Ethernet switches are still in use at the RN, the equipment needs to be replaced in order to cope with the WDM technology and a higher bit rate. 1 Gbit/s grey transceivers are applied in the RG, which can support a peak bit rate of 1 Gbit/s. A summary of the major changes needed for the upgrade is shown in TABLE V.

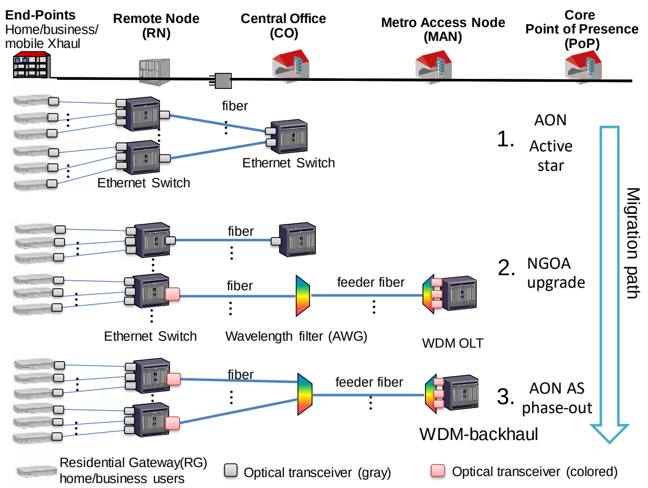

Fig. 7. Migration path from AON AS to WDM-backhaul

TABLE V. MAJOR CHANGES FOR MG#3

Major changes	Location	Business role	TCO category
Residential gateway	End-points	NP	Home equip.
Fiber management	RN	PIP	Infrastructures
Ethernet Switch	RN	NP	Network equip.
AWG	CO	PIP	Infrastructure
Fiber management	CO	PIP	Infrastructure
Feeder fiber & installation	CO -MAN	PIP	Infrastructure
Fiber management	MAN	PIP	Infrastructure
OLT	MAN	NP	Network equip.
Service adding/cancelling	MAN	NP	SP

4) *Gigabit Ethernet network upgrade (Non-NC scenario, MG#4, MG#5)*

TABLE VI. MAJOR CHANGES FOR MG#4 and MG#5

Major changes	Location	Business role	TCO category	MG#4 (PtP FE →GE)	MG#5 (AS FE → GE)
Residential gateway	End- points	NP	Home equip.	x	x
Fiber management	RN	PIP	Infrastructure		x
Ethernet Switch	RN	NP	Network equip.		x
fiber management	CO	PIP	Infrastructure	x	x
Ethernet switch	CO	NP	Network equip.	x	x
Service adding/cancelling	CO/RN	NP	SP	x	x
Feeder fiber& installation	CO - MAN	PIP	Aggregation II	x	x
Fiber management	MAN	PIP	Aggregation II	x	x

In contrast to the NC approach, a network upgrading from Fast Ethernet to Gigabit Ethernet would increase the bit rate in order to meet the high capacity demand in the future. The GE based AON is able to offer a symmetric 1Gbit/s peak bit rate to every customer. Here, we denote the migration path from PtP FE to GE based AON as MG#4 and the migration path from AS FE to GE based AON as MG#5. Such an upgrade (i.e., Non-NC) does not change the network topology and PIP infrastructure. It only upgrades/replaces the old network equipment and optical interfaces. The major changes are related to the NP costs, e.g., replacement of OLTs and RGs. A summary of the major changes is shown in TABLE VI.

IV. Cost Modeling

The cost assessment of the network is based on the TCO that consists of both Capital Expenditures (CAPEX) and Operational Expenditures (OPEX) [21]. In this section, firstly we divide the CAPEX and OPEX into six categories as shown in Fig. 8, and then those categories are reorganized according to different business roles: PIP, NP and User as shown in Fig.9. The cost values presented in this paper are normalized to the cost of a standard GPON ONT (i.e., a single unit includes optical transceiver, four Gigabit Ethernet interfaces, one plain old telephone service interface and one radio frequency interface), referred to as one Cost Unit (CU).

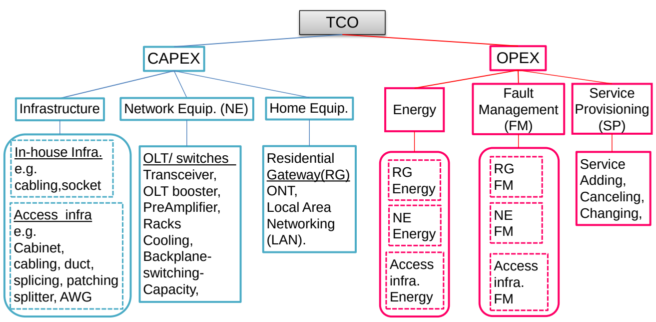

Fig. 8. TCO breakdown, cost category view

CAPEX can be categorized into three major parts as described below:

- ***Infrastructure*** is divided in access infrastructure, and in-house infrastructure. The access infrastructure cost includes fiber cables, ducts, trenching, fiber splicing and fusion, optical distribution frames (ODF), and passive components in the access network Passive components covers optical branching boxes, cabinets, power splitter, AWG and related installations for all those components. The in-house infrastructure cost consists of in-house cabling, optical sockets and installation required at the customer premises or buildings.

$$I\ (Y) = \sum_{i=1}^{N_T} (V_i(Y) \times \Pr_i(Y)) \tag{1}$$

The cost model of yearly investment can be generalized as Eq. (1), where *I(Y)* denotes the investment in the Y^{th} year, $V_i(Y)$ is the volume of a certain type of component *(i)* at the Y^{th} year, N_T is the number of component types, and $Pr_i(Y)$ is the unit price of component *(i)* in the Y^{th} year.

Depending on different infrastructure types, the $V_i\,(Y)$ is further modeled as shown in Eq. (2) for access infrastructure and in Eq. (3) for in-house infrastructure.

$$V_i(Y) = \frac{PC_{PIP}(Y) \times N_{user}}{S_i} \tag{2}$$

$PC_{PIP}(Y)$ is the penetration curve for PIP infrastructure in the Y^{th} year (as shown in Fig. 3), N_{user} is the total number of users in the area, and S_i is the sharing ratio of component *(i)*. The initial investment in the fiber access network infrastructure (assuming 100% coverage) is made at the beginning when the legacy FE based AON PtP or AS is rolled out. Although most of the legacy access network infrastructure can be re-used when a network migrates towards NGOA, the investment in the new components and related installation work will be needed. The volume of those components is modeled according to the Eq. (2), with the variable *Y* equal to the migration year (i.e., Y_{mig}).

$$V_i(Y\ ) = \frac{[PC_{NP}(Y) - PC_{NP}(Y-1)] \times N_{user}}{S_i} \tag{3}$$

The cost modeling of in-house infrastructure is dependent on the NP penetration curve as shown in Eq. (3). We assume that the investment of in-house infrastructure happens only in the year when the customers are joining the network. Once the in-house infrastructure has been invested, it can be fully re-used for any type of NGOA architecture, and therefore the dimensioning of in-house infrastructure is dependent on the number of new users joining the network each year. The investment in a particular migration year is also following Eq. (3) with the input year denoted by Y_{mig}.

- ***Network Equipment (NE)*** refers to the active equipment located in the access network segment, e.g. from RN to MAN in the NC scenario, and from RN to CO in the Non-NC scenario. It includes the Ethernet switches, OLTs, optical transceivers, backplane switch fabric, cooling equipment, OLT boosters and pre-amplifiers, if needed.

The cost modeling of Network Equipment is divided into two classes, active or passive, according to the selected type of NGOA architecture. For architectures that have active NE in RN and/or CO, e.g., Gigabit Ethernet (GE) based AON PtP/AS or WDM-backhaul, the NE costs are modeled as incremental investment. The number of NE invested in a year is proportional to the number of new subscribers. The number of new NE required yearly can be modeled according to Eq. (3).

In the migration year, the new NGOA equipment is required for both new and existing customers from the legacy network. Therefore, the NE cost in the migration year Y_{mig} can be calculated according to Eq. (4), where *i* refers to the component that is replaced at the year Y_{mig}.

$$V_i(Y_{mig}) = \frac{PC_{NP}(Y_{mig}) \times N_{user}}{S_i} \tag{4}$$

For passive architectures (e.g. WDM-PON, TWDM-PON), the deployment of NE is planned to cover 100% of users in the migration year. Due to the passive Optical Distribution Network (ODN), the investment of NE follows Eq. (1). Furthermore, we assumed that all passive components and infrastructure are deployed underground, so that the cost of floor space for PON can be minimized. However, it is more difficult to physically access the underground infrastructure than cabinets and premises that are located above the ground. All potential customers in the area are passed by the PON. Such a configuration does not prohibit the possibilities for introducing other competitors. Different network providers can access customers on the same fiber infrastructure via isolated bit stream, wavelength, or fiber [22]. Note that a fiber level open access will require reconnecting customers in RNs and COs. WDM-PON and TWDM-PON are highly consolidated. One PON OLT port covers many users that are on the same PON tree (e.g., 1280 users in the TWDM-PON case). On the other hand, such a powerful OLT needs to be installed even if only a few users on the tree subscribe to the services. Users who join/terminate every year are randomly distributed, and for that reason, it is difficult to optimize the number of OLTs according to the yearly NP penetration curve. Therefore, the volume of required NEs in the migration year is modeled according to Eq. (2) for PON based architectures.

- ***Home Equipment*** refers to the cost of RG that includes the ONT and Local Area Network (LAN) function. The yearly investment in RG follows the NP penetration curve. The number of RGs is modeled according to Eq. (3). In the migration year (Y_{mig}), the total number of RGs is modeled according to Eq. (4), since all the RGs in the legacy AON have to be changed.

OPEX assessment considers several cost driving processes such as Service Provisioning (SP), Fault Management (FM), maintenance, energy consumption, and floor space. As shown in Fig. 8, three major categories are covered and described below:

- ***Energy*** refers to the cost of the energy consumed by any equipment in the network including the cooling devices and RG. Some items that belong to the infrastructure can also have energy costs, e.g. an active outdoor cabinet (energy for cooling, etc.). The energy cost differs depending on the equipment location (CO or cabinet), business roles, and year.

$$I_{engery}(Y) = \sum_{j=1}^{N_L} \sum_{i=1}^{N_T} (V_{ij} \times E_{ij} \times \Pr_{ij}(Y)) \quad (5)$$

The yearly energy cost can be modeled according to Eq. (5), where $I_{energy}(Y)$ is the cost of energy consumption in the Y^{th} year, i denotes a certain equipment type, and j denotes a specific location (e.g., CO, cabinet). V_{ij} is the volume of equipment i at location j. N_T and N_L denote the total number of equipment and location types, respectively. E_{ij} represents the energy consumption of component i at location j during one year (considering running time per year 24hours*365days). $Pr_{ij}(Y)$ is the unit price of energy (CU per kWyear) which differs from year to year and is dependent on the location. Some of the $Pr_{ij}(Y)$ values used in this study are shown in TABLE VII [26].

TABLE VII PRICE OF ENERGY OVER 10 YEARS FOR DIFFERENT LOCATIONS

Location type	Y10	Y11	Y12	Y13	Y14	Y15	Y16	Y17	Y18	Y19	Y20
Indoor	73	75	77	79	82	84	87	89	92	95	98
Outdoor	86	89	91	94	97	100	103	106	109	112	116
Residential	52	53	55	57	58	60	62	64	66	68	70

**unit [CU(cost unit) per kWyear],*

- ***Service Provisioning (SP)*** is the cost associated with any activities related to adding, changing and cancelling the customer services. It is related to many factors such as fiber management (e.g. patching, splicing), remote configuration, human resources, travelling, etc. The model of SP considered in this paper is based on the process model described in [23].

- ***Fault management (FM)*** is the cost associated with the failure monitoring, detection, component replacement and reparation. The cost depends on the type and location of the network equipment or infrastructure that has failed. Each network element/device is characterized by a set of parameters related to the fault management, such as, Mean Time To Repair (MTTR), travelling time to the failure location and the number of technicians needed to perform the reparation. It is assumed that in the case of the RG failure a new RG is shipped to the user. FM calculations are also according to the process model proposed in [23].

The aforementioned TCO categories can be grouped according to different business roles: PIP, NP and User. Figure 9 shows the CAPEX and OPEX items (the same items as listed in Fig. 8) from multi-actors' perspective.

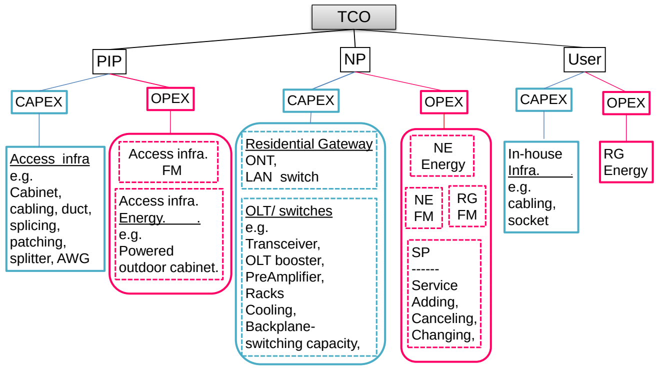

Fig. 9. TCO breakdown, multi-actor view

- ***PIP CAPEX*** refers to the deployment cost associated to access infrastructure that belongs to PIP.
- ***NP CAPEX*** includes costs of both network equipment and RGs owned by NP.
- ***User CAPEX*** refers to the In-house Infrastructure and RG. The In-house Infrastructure is usually paid by users, construction companies, real estate companies or house/building management companies.
- ***PIP OPEX*** comprises FM and energy consumption of PIP owned infrastructure. PIP FM involves events such as reparation of a fiber cut or AWG or power splitter failures. Energy cost of PIP is associated with the energy bills related to the infrastructure. For example, in some access network architectures, the outdoor cabinets (remote node) require a power supply for accommodating the active equipment. Although the energy of the active equipment is part of the NP OPEX, there is still energy cost paid by PIP for cooling and maintenance of the cabinet.
- ***NP OPEX*** consists of the expenses for FM of network equipment and RG, energy consumption of network equipment, and SP.
- ***User OPEX*** refers to the energy bill related to RG, which is normally paid by the customer.

V. TOTAL COST OF OWNERSHIP ANALYSIS

In this section, the TCO for five different AON migration paths towards NGOA (described in Section III) are compared and analyzed.

A full list of components that are used for the TCO calculation are included in APPENDIX I. The TCO results of Non-NC scenarios have been normalized to the same service area as NC cases. In this section we focus on the dense urban area, while the other deployment areas show a similar trend for the TCO.

A. Migration in the 10^th year

1) Yearly TCO over 20 years

The migration towards different NGOA architectures being compared is based on the yearly TCO as shown in Fig. 10. The TCO per year shows the investment evolution over the entire lifetime of 20 years, where migration is assumed to start in the 10th year. This takes into account the users that are connected in each year based on the penetration curve. The TCO calculation is based on one NC node (MAN) service area. For the Non-NC architectures, the results have been mapped to the service area corresponding to NC node coverage. The initial investment of the legacy network infrastructure is excluded from the analysis, as it is considered to be available at Year 0 already. From Year 1 to the migration year, the TCO results not only include OPEX of the legacy network but also some CAPEX related to the new subscribers (e.g. OLT, ONT costs) added every year.

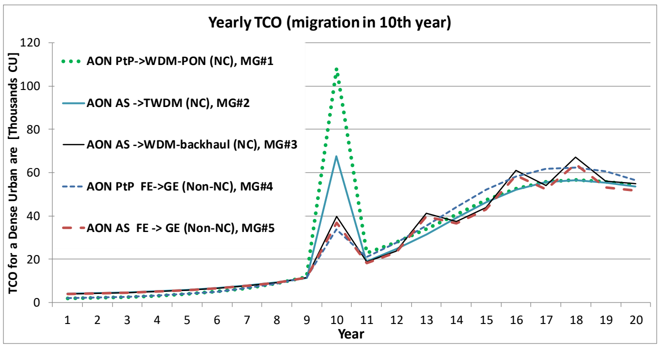

Fig. 10. Yearly TCO for a dense urban area in access network, when the migration starts in the 10th year. *TCO results of Non-NC scenarios have been normalized to the service area corresponding to the NC node coverage.

It can be observed that when the migration starts with a very low customer penetration rate (10%) for the NGOA, the costs of the migration path from AON PtP to WDM-PON and from AON AS to TWDM-PON are significantly higher than the others. They are both in the NC scenario and involve introducing the new WDM/TWDM technology during the migration. The remaining migration paths are at the similar cost level of about 40 thousand CU. The migration paths from FE to GE in the Non-NC scenario have lower cost because there is no new technology introduced during the migration, and the network topology remains the same as the legacy AON. The investment in the migration year (the 10th year) only involves upgrading the network equipment. However, both GE PtP and GE AS have obviously higher costs after the migration year, i.e., between the 11th and the 20th year. This will gradually reduce their investment savings gained in the beginning of the migration. On the contrary, the passive technologies, i.e., TWDM-PON and WDM-PON, exhibit the lower costs after the migration year.

It should be pointed out that in the Non-NC scenario the feeder fiber (from CO to MAN) and the related installation cost is excluded because it is modeled as part of the aggregation network, which is addressed in Section VI.

2) *Cost breakdown*

We now zoom in for a close-up of the peak in yearly TCO results occurred in the migration year as shown in Fig. 11. The TCO in the 10th year is divided into six categories according to Fig. 8. Different shades of blue in Fig. 11 represent the CAPEX items, and the red shows the cost components belonging to the OPEX. The WDM-PON has the highest migration costs mainly due to the investment on new network equipment (55% of TCO). The WDM-PON with 80 wavelength channels can only support up to 80 users while the TWDM-PON can increase this number to 1280 (32 TDM slots * 40 wavelength channels). Therefore, while the WDM-PON OLT is less complex and costly than the TWDM-PON OLT, the amount of required WDM-PON OLTs is much larger than the TWDM-PON OLTs, which leads to the highest network equipment cost and energy consumption among all migration paths. For the same reason, the infrastructure cost of WDM-PON is also high (17% of TCO). The lower number of users supported by a single WDM-PON results in higher cost of feeder fiber and related installation. The migration path from AON AS to TWDM-PON is characterized by the highest cost of infrastructure (38% of TCO). It is due to the expenses related to changing from active RN to passive RN, where new passive equipment (e.g. power splitters) and massive installations are required. Migration from FE AON to Gigabit Ethernet AON has the lowest cost of infrastructure because the infrastructure in the access network does not change at all. Only the cost of new in-house infrastructure is included, which is proportional to the number of new customers joining the network every year.

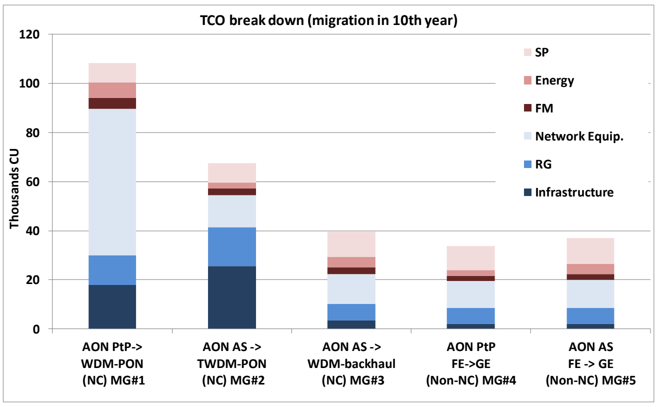

Fig. 11. TCO breakdown for a dense urban area when the migration starts in 10th year. *TCO results of Non-NC scenarios have been normalized to the service area corresponding to the NC node coverage.

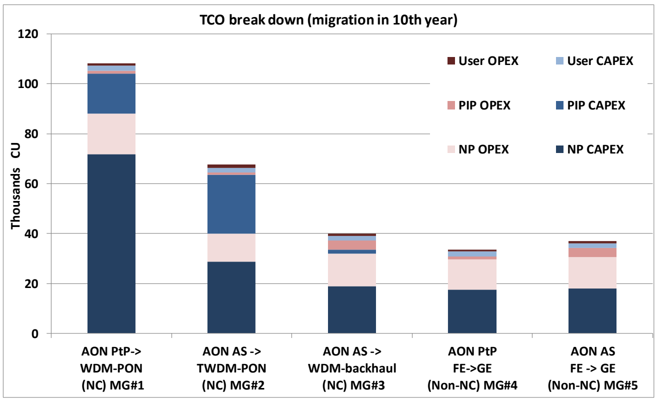

Fig. 12. TCO breakdown for a dense urban area when the migration starts in the 10th year with a multi-actor view.

When the TCO is divided according to the different business roles, as shown in Fig. 12, it can be observed that the NP is a major player in the network migration because the NP part of TCO is dominating. Although PIP investment is the largest part of the TCO in the initial deployment (i.e., at Year 0) [24][25], the network migration with efficient migration paths can maximize the re-use of legacy access network infrastructure and minimize the extra investment on PIP infrastructure in the NGOA. For all of the investigated migration paths for AON, the NP cost attributes to more than 80% of the overall TCO in the migration year for most of the migration paths. The exception is for the migration path from AON AS to TWDM-PON where the NP cost is representing 60%.

B. Migration in the 15th year

1) Yearly TCO over 20 years

Figure 13 illustrates a yearly TCO during network migration when the migration starts in year 15. The total investment in year 15 (peaks in Fig. 13) is higher than in year 10 for the migration staring in the 10th year. It is mainly because of the much higher penetration rate when the migration starts. Although the migration paths from AON PtP to WDM-PON and from AON AS to TWDM-PON represent the highest and second highest migration cost, respectively, the difference between migration paths becomes less distinct comparing to the case where the network migration starts in the 10th year. The migration cost for AON PtP from FE to GE is not the lowest any more (different from Fig. 10), it is comparable to the one from AON AS to TWDM-PON, and becomes third highest investment.

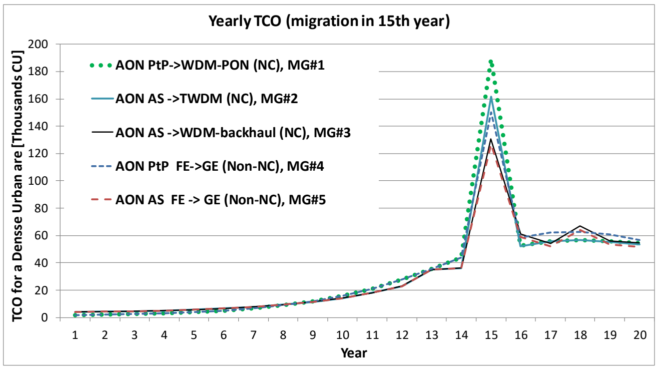

Fig. 13. Yearly TCO for a dense urban area when the migration starts in the 15th year

2) Cost breakdown

Figure 14 shows the TCO details for a network migration conducted in the 15th year. Notable differences can be observed between migration in the 15th and the 10th years. We can find that the cost of RG and SP play more important roles in the TCO when migration starts in the 15th year. In the 10th year, the customer penetration of legacy networks is only 10%, but it increases to 40% in the 15th year, and therefore the number of users that have to be migrated to a new NGOA is significantly higher in the beginning. It leads to much larger number of replacements of network equipment, RGs and SP. For the TWDM-PON, the cost of RGs accounts for more than 40% of TCO. The reason is that the RG of TWDM-PON is more expensive than of the other NGOA architectures due to the higher complexity (it involves both TDM and WDM technologies, while WDM-PON RG is based only on the WDM technology).

Two architectures that have the highest SP costs (accounting for 40% of their TCO) are GE AON AS and WDM-backhaul. Both architectures have active equipment in RNs, which require much more SP effort (e.g., travelling to many RN locations, human resources, manual disconnecting/connecting fibers) than PON based NGOA. For TWDM-PON and WDM-PON there is no active equipment in RNs and COs, and hence the SP events only happen in MAN, leading to lower SP costs.

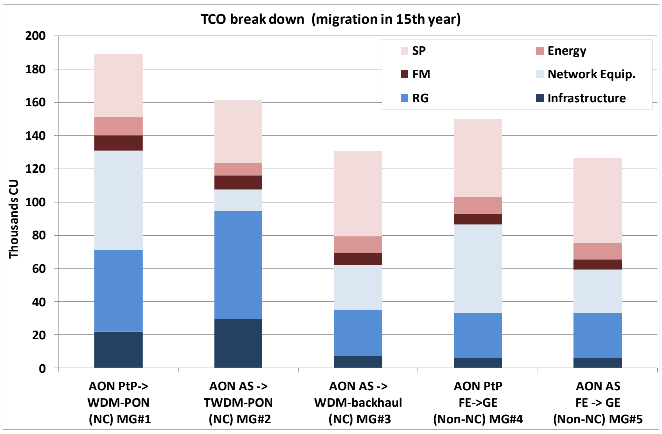

Fig. 14. TCO breakdown for a dense urban area when the migration starts in the 15th year

Different migration starting years have little impact on the migration cost of infrastructure. The major part of the infrastructure cost (i.e., access infrastructure) is modeled according to Eq. (2). Therefore, no matter which year the network migration starts, new investment on the access infrastructure is the same and considers the 100% PIP penetration when the migration starts (as shown in Fig. 3). Only the cost of in-house infrastructure differs from year to year.

For the same reason, the migration starting year doesn't have any impact on the network equipment cost of TWDM-PON and WDM-PON, which is modeled according to Eq.(2). In contrast, the network equipment cost of the GE AON and WDM-backhaul is modeled according to Eq.(4) which follows the NP penetration (as shown in Fig. 3), and therefore the network equipment cost in the year 15th is higher than in the case when migration starts in the 10th year.

VI. Node Consolidation Analysis

In Section V we have analyzed the TCO results in the access network segment. In this section we investigate if NPs can benefit from NC. Therefore, both access and aggregation segments are taken into account for a fair comparison of the TCO results for NC and Non-NC scenarios.

The aggregation network cost was provided by Deutsche Telekom within EU FP7 OASE project [16]. It is based on the model shown in Fig. 4. A detailed description can be found in [9][13]. The aggregation network cost is modeled as leased lines whose costs are counted on a per 10G-WDM-channel basis. The aggregation network cost of the NC and Non-NC scenarios are different. However, within the same scenario, the cost values do not depend on the access network architectures.

The TCO of a network provider is given in terms of cost per user ($I_{peruser}$), which is modeled according to Eq.(6)

$$I_{peruser} = \frac{\sum_{Ymig}^{Y_{20}} I\ (Y)}{N_{user} \times PC_{NP}(Y_{20})} \qquad (6)$$

where $I(Y)$ is the sum of TCO from the migration year (the 10th year) to the 20th year, $PC_{NP}(Y_{20})$ is the penetration rate at the 20th year, and N_{user} is the total number of users in the area.

The cost difference per user (I_{diff}) between NC scenario and Non-NC scenario is calculated according to Eq.(7). When I_{diff} is a positive value it indicates that NC approach leads to cost savings after Y_{mig}.

$$I_{diff} = I_{Non-NC} - I_{NC} \qquad (7)$$

Three NGOA architectures (i.e., WDM-PON, TWDM-PON and WDM-backhaul) in NC scenario are compared to the GE AON PtP and GE AS in Non-NC scenario as shown in TABLE VIII.

TABLE VIII. COST DIFFERENCE BETWEEN NON-NC AND NC SCENARIOS

Non-NC	NC	Cost diff. according to Eq.(7)	Cost diff. in [CU]/ user
AON PtP FE →PtP GE (MG#4)	AON PtP FE → WDM-PON (80ch) (MG#1)	I(MG#4) - I(MG#1)	*0.4(DU)* *0.5(U)* *1.6 (R)*
AON AS FE → AS GE (MG#5)	AON AS FE → TWDM-PON (1:32, 40ch) (MG#2)	I(MG#5) - I(MG#2)	*0.4(DU)* *0.7(U)* *1.3 (R)*
AON AS FE → AS GE (MG#5)	AON AS FE → WDM backhaul (40ch.) (MG#3)	I(MG#5) - I(MG#3)	*0.2(DU)* *0.5(U)* *1.8 (R)*

Figure 15 depicts the cost difference (I_{diff}) between the NC and Non-NC scenario in three different types of the deployment area, namely DU, U and R. The red bar presents the I_{diff} in the aggregation network segment, and the blue bar indicates the I_{diff} in the access network segment. It can be observed that in the aggregation network all NC related NGOA architectures bring the obvious cost savings in all types of areas, mainly because the NC scenarios only involve Aggregation I cost, while Non-NC scenarios include both Aggregation I and II cost. The cost saving in the aggregation network is significantly higher in rural area due to the low sharing factor. When it comes to the access network part (blue bars in Fig. 15), we can find that the values are negative. This means that network migration with the NC approach does not bring cost benefits due to the new investment on network equipment. However, the cost saving in the aggregation network is higher than the loss in the access network. Therefore, it is worth applying NC approach to the AON network migration, especially in the rural areas. In the case that the aggregation NP is different from the access NP, although the access NP needs investment for the node-consolidation, who may still gain, due to a lower cost to lease less lines from the aggregation NP.

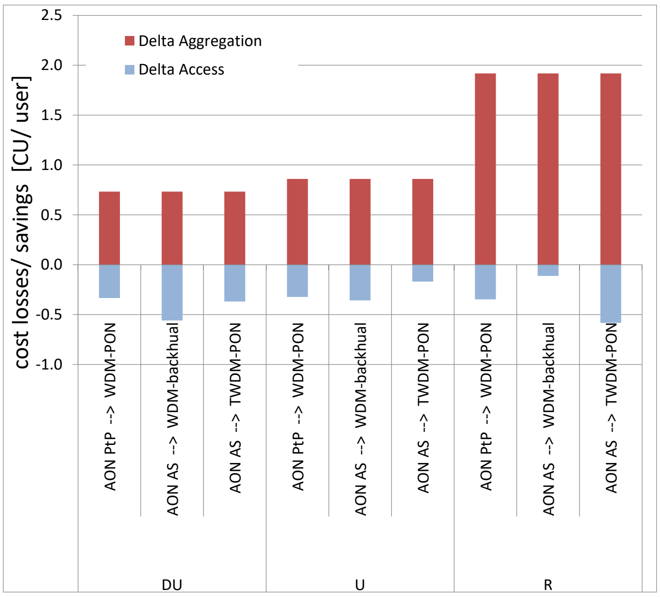

Fig. 15. Cost difference between NC and Non-NC in access and aggregation network

VII. Conclusions

This paper proposes and evaluates several migration paths from FE based AON to NGOA. The key elements of both CAPEX and OPEX are assessed and compared. The results show that the cost of migration to TWDM-PON and WDM-PON is higher than towards the other considered NGOA architectures. However, when migration is finished, the expenditures per year in TWDM-PON and WDM-PON are lower than in WDM backhaul. Moreover, if the longer operation period after migration is considered, the higher economic benefits of the AON migration to TWDM-PON and WDM-PON can be achieved. Different starting years for AON migration have a significant impact on the service provisioning and residential gateway. The AON migration costs are also analyzed with respect to different business roles, such as PIP, NP and users. The results show that NP is the dominant player in the AON migration, who is responsible for more than 60% of the total migration costs.

Furthermore, this paper analyzed the impact of node consolidation on the TCO with the consideration of both access and aggregation network costs. It was shown that the cost savings in the aggregation network is large enough to cover the increased migration costs in the access network. In particular, the benefit of performing NC during AON migration becomes significant in the rural areas.

The paper has compared different technological solutions for AON migration. In our future work, the other important parameters that are not highly technology-dependent, such as different business strategies, migration timing and duration of the migration, will be evaluated.

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APPENIX I INPUT DATA FOR TCO CALCULATION

This section provides three set of input data used for the TCO calculation in a dense urban area. TABLE IX is for WDM-PON, TABLE X is for TWDM-PON, TABLE XI is for WDM-backhaul. The cost values presented in this paper are normalized to the cost of a GPON ONT and referred to as one Cost Unit (CU). More details about cost input data can be found in [20][26].

TABLE IX INPUT DATA FOR WDM-PON TCO CALCULATION

Component	Location	Power [watt]	Price [CU]
DWDM OLT linecard (80 channels, incl.TRx,Diplexer, 2 slot shelf space)	MAN	98	72.1
WDM PON OLT shelf (18 tributary slots+2 uplink slots)	MAN	100	111
Infra - Floor Space Dense Urban [per year in m²]	MAN	0	4.4
Infra - ODF (fiber termination side) - terminated fiber	MAN	0	0.4
Infra - ODF (system side, CO/MAN) - connected fiber	MAN	0	0.8
L2 Switching capacity (Granularity 100Gbps)	MAN	100	10
OLT PreAmplifier EDFA (1 slot sfelf space)	MAN	12	15
Infra - Fiber for aggregation [per fiber and km]	MAN-CO	0	2.4
Infra - ODF (fiber termination side) - terminated fiber	CO	0	0.4
Infra - ODF (system side,CO/CAN) - connected fiber	CO	0	0.8
Infra - Optical Splitter - 1:80	CO	0	24
Infra - Duct Multitube - 4 [km]	CO-MDP	0	74
Infra - Fiber Cable 72f [km]	CO-MDP	0	20
Infra - Fiber Cable 96f [km]	CO-MDP	0	24
Infra - Fiber Cable Installation [km]	CO-MDP	0	10
Infra - Microduct-10-7mm incl. Installation [km]	CO-MDP	0	111
Infra - Microduct-6-7mm incl. Installation [km]	CO-MDP	0	78
Infra - Digging Dense Urban [per Route_km]	MDP-RN	0	1000
Infra - Duct 100 mm diameter incl. Installation [km]	MDP-RN	0	120
Infra - Duct Multitube - 4 [km]	MDP-RN	0	74
Infra - Fiber Cable 72f [km]	MDP-RN	0	20
Infra - Fiber Cable 96f [km]	MDP-RN	0	24
Infra - Fiber Cable Installation [km]	MDP-RN	0	10
Infra - Microduct-6-7mm incl. Installation [km]	MDP-RN	0	78
Infra - Branching Box - Large & Installation (192 fiber)	RN	0	16
Infra - Fiber Splicing Preparation [per cable]	RN	0	0.12
Infra - Fiber Splicing (Fusion)	RN	0	0.12
Infra - Digging Dense Urban [per Route_km]	RN--building	0	1000
Infra - Fiber Cable 12f [km]	RN—building	0	8
Infra - Fiber Cable Installation [km]	RN—building	0	10
Infra - Microduct-1-7mm incl. Installation [km]	RN—building	0	14
Infra - Microduct-20-7mm incl. Installation [km]	RN—building	0	140
Infra - Fiber Splicing Preparation [per cable]	Building/ site	0	0.12
Infra - Fibre Splicing (Fusion)	Building/ site	0	0.12
Infra - In house Fiber Cable Connector	Building/ site	0	0.063
Infra - In house fiber Termination M & I Dense_Urban	Building/ site	0	3.3
Infra - In house Fiber Cable Tube Cost incl. Installation[km]	Building-EndPoint	0	160
Infra - In-house fiber Cable (SMF) incl. Installation [km]	Building-EndPoint	0	15
Infra - In house optical socket (incl.Installation)	EndPoints	0	1.6
ONT related costs for installation	EndPoints	0	0.6
WDM ONT (incl.TRx. SFP/APD tunable)	EndPoints	4.7	2.2

**the price in the table is at reference year of 2020. MDP denotes cable Main Distribution Point.*

TABLE X. INPUT DATA FOR TWDM-PON TCO CALCULATION

Component	Location	Power [watt]	Price [CU]
TWDM-PON 8xDiplexer /Mux /DeMux (2 slots shelf space)	MAN	0	2.4
TWDM-PON OLT Line card (incl.TRx,MAC,10x10Gchannels,2 slot shelf space)	MAN	98	57.5
TWDM-PON OLT shelf (18 tributary slots+2 uplink slots)	MAN	100	111
Infra - Floor Space Dense Urban [per year in m²]	MAN	0	4.4
Infra - ODF (PIP side) – per terminated fiber	MAN	0	0.4
Infra - ODF (NP side) – per connected fiber	MAN	0	0.8
L2 Switching capacity (Granularity 100Gbps)	MAN	100	10
OLT Booster (1slot shelf space)	MAN	12	15
OLT PreAmplifier EDFA (1 slot shelf space)	MAN	12	15
Infra - Fiber for aggregation [per fiber and km]	MAN -CO	0	2.4
Infra - Floor Space Dense Urban [per year in m²]	CO	0	4.4
Infra - ODF (fiber termination side) – per terminated fiber	CO	0	0.4
Infra - ODF (system side) – per connected fiber	CO	0	0.2
Infra - AWG - 1:40	CO	0	12
Infra - Duct Multi-tube - 4 [km]	CO-MDP	0	74
Infra - Fiber Cable 12f [km]	CO-MDP	0	8
Infra - Fiber Cable Installation [km]	CO-MDP	0	10
Infra - Microduct-10-7mm incl. Installation [km]	CO-MDP	0	111
Infra - Microduct-6-7mm incl. Installation [km]	CO-MDP	0	78
Infra - Digging Dense Urban [per Route_km]	MDP-RN	0	1000
Infra - Duct 100 mm diameter incl. Installation [km]	MDP-RN	0	120
Infra - Duct Multi-tube - 4 [km]	MDP-RN	0	74
Infra - Fiber Cable 12f [km]	MDP-RN	0	8
Infra - Fiber Cable Installation [km]	MDP-RN	0	10

Infra - Microduct-6-7mm incl. Installation [km]	MDP-RN	0	78
Infra - Branching Box - Large & Installation (192 fiber)	RN	0	16
Infra - Fiber Splicing Preparation [per cable]	RN	0	0.12
Infra - Fiber Splicing (Fusion)	RN	0	0.12
Infra - Optical Splitter - 1:32	RN	0	6.6
Infra - Digging Dense Urban [per Route_km]	RN-Building	0	1000
Infra - Fiber Cable 12f [km]	RN-Building	0	8
Infra - Fiber Cable Installation [km]	RN-Building	0	10
Infra - Microduct-1-7mm incl. Installation [km]	RN-Building	0	14
Infra - Microduct-20-7mm incl. Installation [km]	RN-Building	0	140
Infra - Fiber Splicing Preparation [per cable]	Building/site	0	0.12
Infra - Fiber Splicing (Fusion), per fiber	Building/site	0	0.12
Infra - In house Fiber Cable Connector	Building/site	0	0.063
Infra - In house Fiber Termination Material & Installation, Dense Urban	Building/site	0	3.3
Infra - In house Fiber Cable Tube Cost incl. Installation[km]	Building-EndPoint	0	160
Infra - In-house Fiber Cable (SMF) incl. Installation [km]	Building-EndPoint	0	15
TWDM-PON ONT (incl. TRx /APD)	EndPoints	5.5	3.1
Infra - In house optical socket (incl. Installation)	EndPoints	0	1.6
ONT related costs for installation	EndPoints	0	0.6

**the price in the table is at reference year of 2020. MDP denotes cable Main Distribution Point.*

TABLE XI. INPUT DATA FOR WDM-backhaul TCO CALCULATION

Component	Location	Power [watt]	Price [CU]
WDM PON OLT shelf (18 tributary slots+2 uplink slots)	MAN	100	111
WDM OLT line card (8port x 10Gbps,incl.TRx,2 slot shelf space)	MAN	43	72
Infra - Floor Space Dense Urban [per year in m²]	MAN	0	4.4
Infra - ODF (fiber termination side) - terminated fiber	MAN	0	0.4
Infra - ODF (system side,CO/CAN) - connected fiber	MAN	0	0.8
Infra - Optical Splitter - 1:40	MAN	0	12
L2 Switching capacity (Granularity 100Gbps)	MAN	100	10
Infra - Fiber for aggregation [per fiber and km]	MAN-CO	0	2.4
Infra - Floor Space Dense Urban [per year in m²]	CO	0	4.4
Infra - ODF (fiber termination side) - terminated fiber	CO	0	0.4
Infra - ODF (system side, RN - Cabinet 1.7sqm) - connected fiber	CO	0	0.2
Infra - Optical Splitter - 1:40	CO	0	12
Infra - Duct Multitube - 4 [km]	CO-MDP	0	74
Infra - Fiber Cable 12f [km]	CO-MDP	0	8
Infra - Fiber Cable Installation [km]	CO-MDP	0	10
Infra - Microduct-10-7mm incl. Installation [km]	CO-MDP	0	111
Infra - Microduct-6-7mm incl. Installation [km]	CO-MDP	0	78
Infra - Digging Dense Urban [per Route_km]	MDP-RN	0	1000
Infra - Duct 100 mm diameter incl. Installation [km]	MDP-RN	0	120
Infra - Duct Multitube - 4 [km]	MDP-RN	0	74
Infra - Fiber Cable 12f [km]	MDP-RN	0	8
Infra - Fiber Cable Installation [km]	MDP-RN	0	10
Infra - Microduct-6-7mm incl. Installation [km]	MDP-RN	0	78
AON ETH monolithic shelf (32x1Gbps + 1x10Gbps uplink) pluggable not includ	RN	20	10.55
Infra - Cabinet Outdoor (generic active)	RN	100	150
Infra - ODF (fiber termination side) - terminated fiber	RN	0	0.4
Infra - ODF (system side, RN - Cabinet 1.7sqm) - connected fiber	RN	0	0.2
SFP BiDi 1.25G LC 3.3V SM 1550R/1310T LX 20KM	RN	1	0.36
TRx 10Gbps (XFP)	RN	3.5	8
Infra - Digging Dense Urban [per Route_km]	RN—building	0	1000
Infra - Fiber Cable 12f [km]	RN—building	0	8
Infra - Fiber Cable Installation [km]	RN—building	0	10
Infra - Microduct-1-7mm incl. Installation [km]	RN—building	0	14
Infra - Microduct-20-7mm incl. Installation [km]	RN—building	0	140
Infra - Fiber Splicing Preparation [per cable]	Building/site	0	0.12
Infra - fiber Splicing (Fusion)	Building/site	0	0.12
Infra - In house Fiber Cable Connector	Building/site	0	0.063
Infra - In house fiber Termination Material & Installation Dense_Urban	Building/site	0	3.3
Infra - In house Fiber Cable Tube Cost incl. Installation[km]	Building-EndPoint	0	160
Infra - In-house fiber Cable (SMF) incl. Installation [km]	Building-EndPoint	0	15
AON ONT Gigabit (incl. TRx)	EndPoints	3.5	0.96
Infra - In house optical socket (incl. Installation)	EndPoints	0	1.6
ONT related costs for installation	EndPoints	0	0.6

**the price in the table is at reference year of 2020. MDP denotes cable Main Distribution Point.*

APPENIX II LIST OF ABREACTIONS

AS	Active Star
CO	Central Office
CU	Cost Unit (normalized to GPON ONT cost)
DU	Dense Urban
FE	Fast Ethernet
FM	Fault Management
GE	Gigabit Ethernet
GPON	Gigabit compatible Passive Optical Network

MAN	Metro Access Node
MDP	Main Distribution Points (cabling)
NC	Node Consolidation
NE	Network Equipment
NGOA	Next Generation Optical Access
NP	Network Provider
OLT	Optical Line Terminal
ONT	Optical Network Terminal
PIP	Physical Infrastructure Provider
PtP	Point-to-Point
RG	Residential Gateway
RN	Remote Node
SP	Service Provisioning
TCO	Total Cost of Ownership
TDM	Time Division Multiplexing
TRx	Transceiver
TWDM	Time and Wavelength Division Multiplexing
WDM	Wavelength Division Multiplexing