A comprehensive model for techno-economic studies of next generation central offices for Metro Networks

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This article introduces a novel and simplified cost model for designing and evaluating Central Offices Rearchitected as Datacenters (CORD). The model includes equipment and elements for the realization of optical, packet switching and data center parts with a special focus not only on relative costs but also on power consumption figures. The cost model is then applied to the design and comparison of a Metropolitan Area Network (MAN) including both Aggregation and Metro-Core nodes following several MAN node architectures based on CORD-like leaf-and-spine fabric. In particular, equipment disaggregation at the Central Offices, both on the packet switching and optical components, can provide important cost savings to telco operators. On the other hand, incorporating computing/storage capabilities in the MAN for the realization of Multi-access Edge Computing (MEC) has a significant impact on the total network cost but especially on power consumption. © 2020 Optical Society of America

1. INTRODUCTION

Metropolitan Area Networks (MAN) are at a turning point as they are subjected to the incessant growth of traffic with annual increase rates between 25% and 40%, the technological changes driven by fiber access networks and 5G systems, and factors such as Hardware/Software (HW/SW) disaggregation, cloudification and automation. The need to rethink the network architecture and most importantly the new internal architecture of the Central Office (CO) node, now including new elements (e.g., Data Centers moved to the edge), requires the assessment of not only its technical feasibility but also of its economic sustainability.

The Next Generation MAN architecture analysed in this work features distributed data-center equipment in the different nodes with compute and storage resources used to host network and service application virtual functionality, focused on the support of emerging 5G services. This equipment results in much increased cost and power consumption compared to traditional MAN architectures. However, it is essential if network service providers want to offer support to many of the future services like Industry 4.0 or verticals, so as not to incur a loss of op-

portunity. Another benefit of this architecture is the reduced requirements for transmission capacity in the metro segment, which also leads to savings. These capacity benefits are not quantified in this study.

EU H2020 project METRO-HAUL [1] aims at designing next generation MANs featuring higher performance and cost efficiency than existing MAN architectures, but, more importantly, embedding edge computing capabilities and support for 5G services, namely URLLC, mMTC and eMBB, along with emerging 5G related verticals (Industry 4.0, etc) [2]. To this end, the project, supported by the experience of three major European telecommunications operators (Telefonica, Telecom Italia and British Telecom) has defined a new MAN architecture with a number of key required innovations in the architecture of the MAN nodes, which include:

- Incorporating computing and storage capabilities realized as micro Data-Centers (uDC), following the CORD reference design [3].

- Disaggregated systems leveraging SDN and open-source

Table 1. Acronyms

AMEN	Access-Metro Edge Node
AI	Artificial Intelligence
CAPEX	Capital Expenditures
CO	Central Office
CORD	Central Office Rearchitected as Datacenter
C-RAN	Cloud/Centralized Radio Access Network
CU	Cost Unit
DC	Data Center
DCM	Dispersion Compensation Module
DSLAM	Digital Subscriber Line Access Multiplexer
DU/CU	Distributed Unit / Centralized Unit
eMBB	enhanced Mobile Broadband
HH	Household
HW	Hardware
IM/DD	Intensity Modulation / Direct Detection
KPI	Key Performance Indicators
LOC	Lines Of Code
MAN	Metropolitan Area Network
MCEN	Metro-Core Edge Node
MEC	Multi-access Edge Computing
ML	Machine Learning
mMTC	massive Machine-Type Communications
NAS	Network-Attached Storage
OLA	Optical Line Amplification
OLT	Optical Line Terminal
ONOS	Open Network Operating System
OPEX	Operational Expenditures
PON	Passive Optical Network
ROADM	Reconfigurable Optical Add/Drop Multiplexer
S-BVT	Sliceable Bandwidth Variable Transponder
SDN	Software Defined Networking
SSD	Solid State Drive
SW	Software
TOR	Top-of-the-Rack
uDC	micro Datacenters
UPF	User Plane Function
URLLC	Ultra-Reliable Low Latency Communications
vBNG	virtual Border Network Gateway
VNF	Virtual Network Functions
WDM	Wavelength Division Multiplexing
WSS	Wavelength Selective Switch

software like ONOS [4], seeking faster agility and flexibility regarding service provisioning, while reducing vendor lock-in leading to important cost savings [5–8].

- Both filtered and filterless optical WDM technology enabling S-BVTs, with reduced line system deployment cost but retaining bandwidth allocation flexibility [9, 10].

- Intelligent SDN-based control plane that allows the orchestration of both the computing and communication infrastructure resources, leveraging network telemetry and performance monitoring along with ML/AI algorithms for fast network reconfiguration and automation [11, 12].

These novel technologies, that will transform MAN architectures, need to be evaluated not only from a performance point of view, but also from an economic perspective. Indeed, techno-economic studies have become a major goal in many research projects as the proposed hardware and network architectures need to be compared with existing conventional designs to justify any possible system and architecture shift.

Essentially, the target of meeting Key Performance Indicators (KPIs), where a number of quantitative objectives are measured for a successful evaluation of a given research solution/architecture, has triggered the need to demonstrate that novel research proposals are more cost-effective (better performance with reduced cost) than existing ones. In other words, newly adopted technologies need not only be of higher performance, but also cost and energy efficient.

Several research projects and studies have provided in the past cost models regarding the metro network segment. Some of them make available cost values to some of (but not all) the building blocks. Thus, there is a need for a complete, yet simplified, cost model for next-generation MAN architectures with updated cost and power consumption figures for existing and emerging relevant technologies.

Furthermore, the proliferation of edge computing platforms, often co-located with traditional aggregation and transport sites, has made joint dimensioning of both the compute and communications infrastructure essential to fully optimize deployment and operation costs [13]. Given that cost models for optical transport and data-center/packet components are typically siloed, optimization frameworks find it difficult to accurately assess the trade-offs between components in different layers, being forced to either use parametric approaches or prioritize one component over the other (e.g., minimizing the nodes with DC capabilities). As such, an integrated cost model for MAN node/network design can be highly valuable for the practical implementation of advanced optimization algorithms.

Having this target in mind, the first part of this article focuses on providing an up-to-date cost model with a detailed description of the required elements to build the next-generation MAN nodes. Such elements are categorized into: optical components, packet-switching hardware and data-center equipment, with enough variety to build a large number of MAN node architectures. The second part uses the cost model to compare different MAN node architectures following the Trellis [14] guidelines, a recent project under the CORD umbrella, defined as "Production-ready multi-purpose leaf-spine fabric designed for NFV". Trellis describes the physical and functional configuration of a multi-site switching infrastructure that combines transport, switching fabrics and computing/storage servers using white-boxes organized in a Leaf-and-Spine topology to optimize East-West traffic in MAN scenarios. Specialized hardware would be available

only for access interfaces to (residential, mobile, business) customers and for optical transport components. Using the cost model for optical, packet and data-center elements, we show that incorporating computing and storage capabilities into the MAN nodes has a moderate impact in terms of CAPEX, but on the contrary the power consumption of the Central Offices massively increases to feed the servers in the data-center.

Thus, the remainder of this work is organized as follows: Section 2 reviews previous techno-economic studies conducted on optical WDM and data-center architectures. Section 3 overviews the cost model along with the three main building blocks to realize Central Offices with Data Center capabilities, namely optical components, packet switching and computing/storage elements. Section 4 shows a techno-economic use-case where the cost model is applied to the design of next-generation Metro networks. Finally, section 5 completes this work with its main findings and conclusions.

2. PREVIOUS WORK

Techno-economic studies have been traditionally a must for telecom operators before adopting any new technology. Essentially, the operator needs to evaluate not only the performance metrics of emerging technologies (throughput, latency, etc.), but also adoption costs, which include both CAPEX and OPEX-related metrics like power consumption, integration, and its operation and management. As a rule of thumb, a new solution is considered for potential deployment when it shows a significant performance improvement with at least 30% cost-savings with respect to existing solutions [15].

In the past, several research projects have provided cost models regarding the metro network segment addressed here, which join the efforts and expertise of a large number of researchers and technology specialists from both operators, system providers and academia. In particular, the first set of projects in addressing the cost modeling issues were STRONGEST [16] and IDEAL-IST [17] which focused on the evaluation of elastic/gridless optical technologies and their adoption in longhaul wide-area networks, and further provided a first set of tables with techno-economic data [18]. A summary of the STRONGEST cost model was published in [19] and attracted much attention from the research community, who used this article as a starting point in subsequent cost model analyses [20–22]; this is the case of projects like FOX-C [23], ACINO [24], ORCHESTRA [25] and 5G-CROSSHAUL [26].

Some newer 5G-related EU projects provide cost models in other network segments, namely the radio access segment, like 5G-NORMA [27], iCIRRUS [28] and METIS [29] or in the optical access part of the network, namely PONs and its flavors, like COMBO [30], thus having limited applicability in the techno-economic analysis of MAN architectures [31–34].

There is also a broad number of earlier techno-economic studies published in journals and conferences, however, most of them rely on the original equipment data provided by the seminal paper [19] from the STRONGEST project. Remarkable examples of application include the joint optimization of multi-layer network design with and without protection [35–38], the feasibility and cost-saving opportunities of elastic/gridless optical networks [39–41] and cloud/grid design over optical WDM networks [42, 43]. Other interesting techno-economic studies on optical access technologies and C-RAN may also be found in [20, 44–49].

On the other hand, cost models for packet switching devices and computing/storage servers are relatively easy to find in public websites, but not many regarding specialized optical equipment. For instance, the authors in [50] study the feasibility of incorporating optical circuit switching in data-center networks, and [51, 52] give an overview of the cost of deploying different data-center architectures, namely BCube, FatTree and deBuiyin and Leaf-and-Spine.

In the next section, a simplified yet-updated cost model for the design of next-generation MAN nodes featuring MEC is presented; this includes both optical transmission systems, packet-switching devices and datacenter hardware. The model is then applied to an example use case where MAN nodes with both aggregated and disaggregated packet switches are compared against a solution with legacy routers.

3. COST MODEL FOR MAN ARCHITECTURES

This section overviews the cost model focusing on the three main building blocks for constructing the next-generation MAN nodes, namely optical components accessing the metro networks, packet-switching equipment both interfacing the optical infrastructure and composing the Data-center architecture (Leaf-and-Spine based) and computing/storage nodes enabling caching, virtualization and processing. This model has been developed inspired from the references above, and the publicly available datasets, albeit updated with the expertise and internal datasets of major telecommunication operators and the network system providers that participate in the METRO-HAUL Project.

The number and heterogeneity of equipment is very large, so an effort to simplify the model was conducted by reducing the amount of hardware options. As it is typical in techno-economic studies, the cost values of hardware components have been normalized to Cost Units (CU), where the value of 1 CU is equal to the cost of a 10G transponder (see Table 2).

Fig. 1 gives a simplified overview of next-generation MAN nodes inspired by the Trellis architecture, showing their main representative blocks and connectivity. Equipment and connections shown in the figure do not reflect a real implementation of a MAN node, but they are only a high-level visualisation of the model.

The optical layer is represented in the figure with a Mux/Demux (in case that a simple optical line terminal is used to interconnect the node with the other ones) or, alternatively, with a ROADM which includes both WSSs and add/drop (A/D) block units. Depending on the node architecture, A/D blocks can be realised with a combination of WSSs, Splitter/Combiner modules and Amplifiers. Transponders and flexible transponders connected with the packet switching equipment complete the optical systems, while other components like DCMs, wavelength blockers, that form part of the model as well, are not shown for the sake of brevity but can be used for implementing other node architectures (e.g., Fixed OADM or filterless optical nodes) and in the case of compensated links.

The packet switching equipment shown in Fig. 1 is a single piece of equipment, a router or a carrier-grade switch, but in general the structure within a metro node may include more than one switch, possibly connected in a hierarchical manner (for instance Leaf-and-Spine). The model adopts a compact equipment block characterised by a maximum capacity that can host grey pluggable transceivers, added to the switch until maximum capacity is reached.

A modular structure (i.e., equipment made of shelf hosting line cards) has been avoided for two reasons. First, different
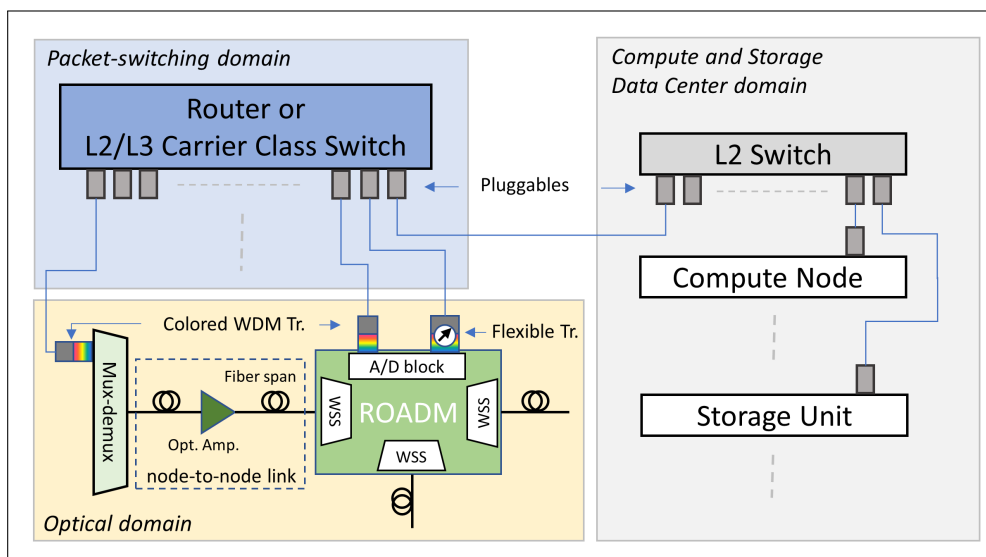
Fig. 1. Diagram showing blocks used in the cost model and their potential interconnections.

vendors have different equipment modules and as a result it is difficult to define a unifying model. Secondly, the trend for carrier-class switches, at least those with up to tens of Tb/s of capacity suitable for metro nodes, seems in the direction of adopting a compact structure, e.g., a single block of a maximum capacity requiring a number of slots in a rack. This makes L2/L3 carrier-grade switches similar to L2 DC-like switches but with higher capacity and additional features.

The data center part of the model has three main block components: compute server nodes, storage server units and L2 switches. Compute and storage servers are connected to the switch (usually within the same rack, i.e., Top-of-Rack switch) by means of cables and pluggable transceivers.

In the next sections, different components for these three parts of a MAN node (optical, packet switch and data center) are presented.

A. Optical WDM equipment

Table 2 shows the main building blocks for the optical layer of a generic metro node. The first set of elements include generic optical WDM equipment necessary to build the Analog WDM network elements, namely ROADMs and OLA systems. The second and third parts of the table include classical state-of-the-art transponders for metro scenarios featuring multiple bitrates along with a set of BVTs. The cost/power figures do not include the chassis housing the optical components, since these can vary significantly depending on adopted configurations.

It is worth noticing from the table that both fixed/flex-grid WSS have the same cost value, since according to equipment manufacturers there is no real difference in terms of hardware elements. In addition, the transponder values provided in the table span several standard and emerging technologies ranging from IM/DD, coherent, PAM4 IM/DD modulation and BVTs with various configurations, such as the one presented in [10].

B. Packet-switching equipment

Regarding the packet-switching components, the cost model defines four different sets of hardware equipment: Layer-2/Layer 3 telco-like carrier-class switches with high-performance chipsets (e.g., Broadcom Qumran or Jericho+), that can in turn be dis-

tinguished between Aggregated and Disaggregated switches, Layer-2 data-center-like switches with lower-performance chipsets (e.g., Broadcom Tomahawk2 or Trident), intended for inter/intra data-center traffic mainly, and classical Layer-3 IP routers, to provide the case where a telco operator already has expensive IP equipment that can be reused in its solutions. These are listed in Table 3.

Concerning the L2/L3 telco-like carrier-class switches, the Aggregated switches consist of HW and SW provided by the same equipment vendor, whereas in Disaggregated cases implementing the CORD concept, these are composed of white-box HW while SW can be developed by the telco itself (in house) or provided by a third party. Next, a set of conventional IP routers are shown for completeness, where a fixed configuration is assumed for simplicity, even if the router can be also modular with a chassis and lines cards. Finally, several pluggable transceivers are provided, although their relative cost compared with the previous hardware sets are almost negligible.

The large availability and variety of switch and router configurations regarding port speeds and fanout have been segmented into seven capacity sizes, namely XXSmall (400G), XSmall (800G), Small (1.6T), Medium (3.2T), Large (6.4T), XLarge (12.8T) and XXLarge (25.6T).

These capacity values are intended as the maximum sum of rates of interfaces that can be connected to the router or the switch. This is what is called bidirectional capacity in [53] (e.g., 400 Gb/s can host up to 4 interfaces at 100G, or 2 at 100G plus 20 at 10G. However, datasheets usually provide the maximum unidirectional capacity value for their switches or routers which is twice this value (i.e., 800G in the previous example), since the equipment must be able to process the bitstream in the two transmission directions.

The cost values of routers and switches in Table 3 are assumed to increase linearly with capacity, although some studies suggest that the cost of packet equipment increases less than linearly (the linear assumption is slightly pessimistic). Concerning power consumption values, the values represent a less-than-linear increase with capacity as observed from vendor datasheets and previously analysed in [53–55]. Thus, such typical/average consumption values should be considered indicative since different

Table 2. Optical components

Optical components		
Name	Cost (normalized)	Power consumption
Generic optical components		
DCM for 20 km spans	0.2	0 (power associated to shelf/controller)
Optical splitter 1x2 for wavelength blocker	0.004	0 (power associated to shelf/controller)
Optical splitter 1x4	0.01	0 (power associated to shelf/controller)
Optical splitter 1x8	0.02	0 (power associated to shelf/controller)
EDFA dual-stage var. gain (booster+preamp)	0.6	27 W (typ), 33 W (max)
Wavelength blocker, only blocker, one direction	0.8	7.2 W (typ.), 12 W (max)
WSS 1x4 fix/flex-grid (one direction), B&S confs + power eqz	1.1	30 W (typ), 50 W (max)
WSS 1x9 fix/flex-grid (one direction), B&S confs + power eqz	2.2	40 W (typ), 75 W (max)
WSS 1x20 fix/flex-grid (one direction), B&S confs + power eqz	3	75 W (typ), 100 W (max)
Fixed-grid Mux/Demux (80 ch.)	0.8	0 (power associated to shelf/controller)
Colored WDM transponders (fixgrid)		
10G (includes client+line pluggables)	1	58 W (typ); 77 W (max)
25/50G PAM4 (includes client+line pluggables)	3.5	58 W (typ), 77 W (max)
100G coherent (includes client+line pluggables)	5	95 W (typ), 120 W (max)
400G coherent, (includes client+line pluggables)	12	160 W (typ), 200 W (max)
Flexible transponders		
200G BVT (QPSK/8-QAM/16-QAM), 4x QSFP28 at client side	8	125 (typ), 145 W (max) including pluggables
S-BVT Transceiver 2X50G (MCM/ DD), lab prototype (50 km reach)	2.7	58 W (typ), 77 W (max) (per carrier pair)
BVT Transponder 100-600G, variable baud-rate/mod-format	17	140-220W (typ), 220 W (max)

vendor equipment with similar capacity and features may report different power consumption values in their datasheets.

C. Computing and Storage equipment

Finally, Table 4 shows the computing and storage equipment elements for data-center design along with other specialized hardware that may be required in certain scenarios. Again, the table is reduced to show only four relevant sizes concerning computing nodes, namely Small, Medium, Large and XLarge sizes, and 2-4 sizes regarding storage hardware.

4. TECHNO-ECONOMIC USE CASE: DESIGN OF A NEXT-GENERATION MAN NODES

A. Reference topology and node architecture

The application scenario used for evaluations is a reference generic metro network topology composed of 60 nodes, as shown in Fig. 2, which is considered to span a large metropolitan area providing network services to two million people, including residential, 4G/5G mobile and business traffic.

On average, each node serves about 15,000 households and 15 mobile stations for 4G/5G (first stage of deployment of 5G is considered), i.e., 33,000 residents (2.2 resident per household) and about 55,000 mobile lines (1.66 mobile lines per person). These numbers are inline with many Western European Countries, see for instance Italy where its population is approximately 60 million people. In Italy, there are 27 million houses (i.e., 2.2 persons per households) and about 100 million mobile lines are active (i.e., 1.66 lines per person).
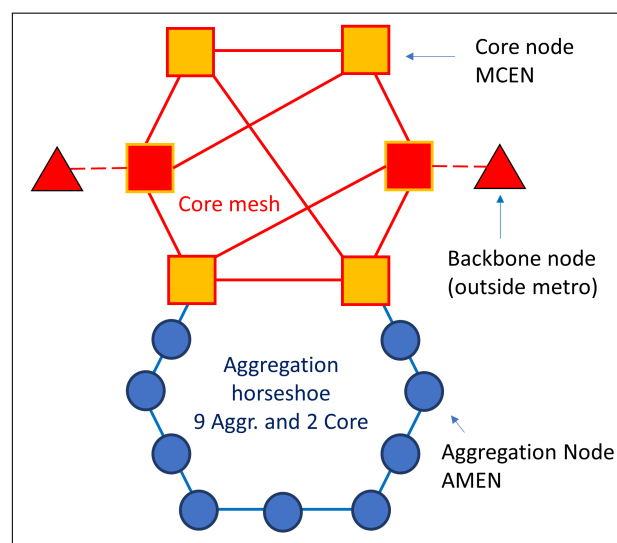

Fig. 2. Ring-meshed metro network topology and architecture assumptions for the techno-economic evaluation.

Table 3. Packet-switching components

Packet components		
Name	Cost (normalized)	Power consumption
Carrier-class switches (chipset Jericho+)		
XXSmall (up to 400G)	4	300 W
XSmall (up to 800G)	8	450 W
Small (up to 1.6T)	16	670 W
Medium (up to 3.2T)	32	1,000 W
Large (up to 6.4T)	64	1,500 W
XLarge (up to 12.8T)	128	2,200 W
XXLarge (up to 25.6T)	256	3,250 W
DC-like switches (chipset Tomahawk2)		
XXSmall (up to 400G)	2	200 W
XSmall (up to 800G)	4	300 W
Small (up to 1.6T)	8	450 W
Medium (up to 3.2T)	16	700 W
Large (up to 6.4T)	32	1,100 W
XLarge (up to 12.8T)	64	1,600 W
XXLarge (up to 25.6T)	128	2,500 W
IP Routers (Fixed configuration, including chassis and LineCards)		
XXSmall (up to 400G)	12	2,000 W
XSmall (up to 800G)	24	2,500 W
Small (up to 1.6T)	48	3,100 W
Medium (up to 3.2T)	96	3,900 W
Large (up to 6.4T)	192	4,900 W
XLarge (up to 12.8T)	384	6,100 W
XXLarge (up to 25.6T)	768	7,600 W
Pluggables		
10G SFP+ copper	0.01	1.2 W
40G QSFP copper	0.02	1.5 W
100G QSFP copper	0.04	5 W
10G SFP+ Short Range	0.016	1.5 W
40G QSFP Short Range	0.05	5 W
100G QSFP28 Short Range	0.1	5 W
400G CFP Short Range	0.6	15 W

Table 4. Data-center components

Data-center components		
Name	Cost (normalized)	Power consumption
Compute nodes		
Small (Intel Xeon Gold 8 cores, 64GB RAM, 600GB HDD)	0.7	1,100 W
Medium (Intel Xeon Gold 16 cores, 128GB RAM, 1.2TB HDD)	1.7	1,600 W
Large (Intel Xeon Platinum 2 CPU X 24 cores, 128 RAM, 3.6TB HDD)	2.6	2,000 W
XLarge (Intel Xeon Platinum 4 CPU X 24 cores, 192 RAM, 3.6TB HDD)	3.9	2,400 W
Storage		
SSD Small 4 TB	0.2	-
SSD Large 8 TB	0.4	-
NAS Small 20 TB	2.1	140 W
NAS Medium 60 TB	3.1	140 W
NAS Large 120 TB	4.6	200 W
NAS XLarge 400 TB	6.3	200 W
Other specialized hardware		
HW Firewall	7	310 W
Load Balancer Small	1.1	150 W
Load Balancer Medium	2.8	150 W
Load Balancer Large	5	150 W

The network topology comprises six fully meshed Metro-Core Edge Nodes (MCEN), each adjacent couple connected to a horseshoe formed by two MCENs and nine Access-Metro Edge Nodes (AMEN), for a total of 60 COs (6 MCENs + 6x9=54 AMENs) serving a total of 900,000 households (about 15,000 households per node). This MAN serves approximately 2 million resident people and 900 mobile stations collecting traffic from about 3.3 million mobile lines.

For simplicity only one horseshoe is shown in Fig. 2 (the one connected to the lower MCENs) while the other five identical horseshoes around the central mesh are not shown. According to such composed topology, it results in the MCEN having a topological degree of five (not including the connection to the Backbone node, which is left out of the evaluation) while the AMEN nodes have degree-2, thus resulting in an average node degree of 2.1 for the whole network topology under evaluation.

Regarding traffic and equipment requirements, both intra- and inter-CO links do not come from a dimensioning study based on traffic and routing rules, but simply assigned. Concerning offered traffic per node, a total traffic on the order of 100 Gb/s for AMENs and 1 Tb/s for MCENs is assumed to be exchanged respectively. All the interfaces connecting AMENs to the access networks (fixed residential OLTs/DSLAMs, mobile antennas, equipment of business customers) and to datacenter servers are at 10G. Networking at metro level relies on 100G interfaces on horseshoes and on 400G in the central mesh.

Concerning computing and storage capabilities at the nodes, servers are assigned considering a limited local processing requirement in the AMENs, and a significantly higher processing requirement in shared datacenter resources in the core nodes.

Four DC profiles have been defined following the experience of the METROHAUL project participants, as shown in Table 5. Without an exact definition of edge VNFs in the nodes (e.g.,

Table 5. Number of CPU cores in DC profiles considered

DC profile	AMEN	MCEN	Total in MAN
Basic	240	2,400	27,369
High C	240	6,000	48,960
High B	480	4,800	54,720
High D	720	3,600	60,480

vOLT for fixed access, DU/CU/UPF for mobile, vBNG for IP traffic, etc.) and their compute and storage requirements, which is out of scope of this work, the assignments of CPU cores for different DC profiles have been based on numbers discussed within the project that seemed reasonable for a first phase of deployment of a CORD-like metro network. In this sense, in the aggregation segment the number of required cores should be on the order of tens or few tens of server), while in the metro segment the required CPU cores should be on the order of a tens or hundreds of servers.

Therefore, as summarized in Table 5, a basic DC resource profile (identified as Basic) requires 240 CPU cores per AMEN and 2,400 cores per MCEN. Three more DC profiles are then introduced to evaluate the impact of the DC component on cost and power consumption. These three profiles are assumed to require more processing capacity than the Basic one, in particular twice for the High Balanced (High B) profile (480 cores per AMEN and 4,800 cores per MCEN). The High Concentrated profile (High C) considers 240 cores on AMEN and 6,000 cores on MCEN, and the High Distributed profile (High D) comprises 720 cores on AMEN and 3,600 cores on MCEN.

Essentially, the Basic profile comprises a starting minimal

one, while the other three consider some variants where more computing resources are necessary (2-3 times), with a different balance between centralized and distributed workloads. It can be expected that a massive deployment of VNF at the network edge will require significantly higher compute and storage resources than those listed in Table 5 and these scenarios are left for further analysis.

All High profiles are assumed to support the same processing load at network level. Compared with the High B profile, the High C needs less compute capacity at the AMENs since these can benefit from pooling servers at MCENs; on the other side, the High D profile gets penalized due to compute resources being distributed, which results in less server sharing at MCENs. As far as conversion of cores into number of servers in the nodes, Large and XLarge type servers are assumed to be installed in AMEN and MCEN respectively. RAM memory and storage resources follow considering the configuration of each server type.

Concerning optical WDM networking, this can be either aggregated or disaggregated equipment (ROADM, transponders, OLA, etc.). Disaggregated equipment is assumed to have similar functionality than the aggregated equipment, but at reduced HW cost. In the optical WDM layer two A/D units and one A/D unit are assumed in MCEN and AMEN respectively, giving an average number of 1.1 A/D units per node. WDM systems of 40 fixgrid channels with 100 GHz spacing is enough for AMENs while 80 fixgrid channels with 50 GHz spacing are used for the links in the core mesh.

Concerning packet switching, three architectural options are considered in the analysis:

- Option 1, named Legacy Router, that uses traditional carrier class IP routers for networking and a separate DC communication infrastructure. Aggregated Optical WDM equipment is considered in this case.

- Option 2, named Aggregated L2/L3 Switch (Aggr. L2/L3 Switch), that uses L2/L3 switch-routers for both inter- and intra-node networking and assumes that networking SW on switch-routers is supplied as integrated SW by the same vendor that provides the HW. No assumptions are made about the SW used by the switches: it can be distributed like in legacy routers or centralized (using an SDN controller). Optical WDM equipment is provided as aggregated.

- Option 3, named Disaggregated L2/L3 Switch (Disaggr. L2/L3 Switch), that uses L2/L3 switch-routers for both inter- and intra-node networking. In this option HW is made of white-boxes while networking SW is developed in-house or by a third party. The reference model for the CO architecture is CORD and the paradigm of networking control plane is SDN, with the Trellis extension. Disaggregateed optical WDM equipment is also considered.

Fig. 3 shows the AMEN and MCEN equipment for the Legacy architecture, where standard L3 routers are used. The Aggregation node has a simple structure, including only one Router and an Micro-DC with two servers, one storage unit and a L2 switch. The Metro node has two Routers and a Mini-DC with equipment redundancy composed of eight servers, four storage units and two L2 switches.

Fig. 4 shows the AMEN and MCEN equipment for the architecture based on L2/L3 switches, that can be either L2/L3 Aggregated or Disaggregated equipment. The Aggregation node

has a simple structure, including two L2/L3 switches with no redundant HW parts, and a Micro-DC as described above. The Metro node follows a Leaf-and-Spine architecture (two Spine and three Leaves) and a Mini-DC.

B. Evaluation

The cost of the three CO architectural options described above is evaluated applying the cost tables shown in Section 3. The cost of the CO is split into three main parts: packet layer, optical layer and DC costs.

For the packet layer in Option 1 (Legacy Router), one traditional XSmall-size (800G) router and two Medium-size (3.2T) routers are assumed for AMENs and MCENs respectively. The choice of having only one piece of equipment in the AMEN is motivated by the fact that routers are assumed to be "carrier class" (i.e., full equipment redundancy) and only the data rate requirement is considered. The cost of all SW required for packet networking is included in the equipment cost. The DCs are connected to the routers using 100G links coming from TOR switches, which are connected to the servers using 10G links.

For Option 2 (Aggr. L2/L3 Switch), the packet layer has two XSmall-size (800G) switches for COs in the aggregation sites and a fabric of five switches, namely three Small-size (1.6T) leaves and two Medium-size (3.2T) spines for the MCENs. The adoption of two pieces of equipment in AMENs is because L2/L3 switches are only partially redundant and a couple of switches are necessary to ensure an adequate level of reliability. The DC is directly connected to leaf switches with 10G interfaces, avoiding the use of TOR switches.

Concerning Option 3 (Disaggregated), plain whiteboxes without SW are considered in the analysis. Such HW are assumed a -50% discount with respect to its legacy counterpart, as it follows from [5, 56, 57]. Essentially, such a discount is justified by the fact that both equipment SW and its integration is provided separately. In particular, the SW cost in Option 3 is evaluated by assuming a SW development of 100,000 Lines Of Code (LOC) for the whole customized carrier class SDN controller environment based on ONOS plus the Network Edge Mediator (NEM) for the CO [58]. The SW cost results in 500 CU, under the assumption of a SW productivity of 4 LOC per hour and the cost of a SW engineer is 0.02 CU per hour, as it follows from the studies of [5, 56, 57].

The 4 LOC per hour productivity number comes from [59] where the authors conducted an extensive study on SW projects employing different programming methodologies and languages, finding an estimated range between 325 and 750 LOC per month (i.e., 2 to 4.3 LOC/h) and including all the software life cycle, namely requirements, design, coding, documentation, validation, operation, and support. Such SW development cost is shared among all L2/L3 equipment owned by the operator and, assuming that 250 switches share the SW, thus resulting in a SW cost of 2 CU per switch, which totals 276 CU for the entire MAN of 60 nodes and 138 switches.

Concerning the DC equipment, the cost is basically the same for all architectures. From the number of cores reported in Table 5 it follows that the Basic profile requires 5 Large-size servers per AMEN and 25 XLarge-size servers per MCEN. For the other DC profiles, the results show that 5, 10 and 15 Large-size additional servers are required per AMEN, while 63, 50 and 68 XLarge additional servers are required per MCEN, for High C, High B and High D DC profiles respectively. A Medium/Small size NAS storage unit is added to AMENs and 2 Medium size
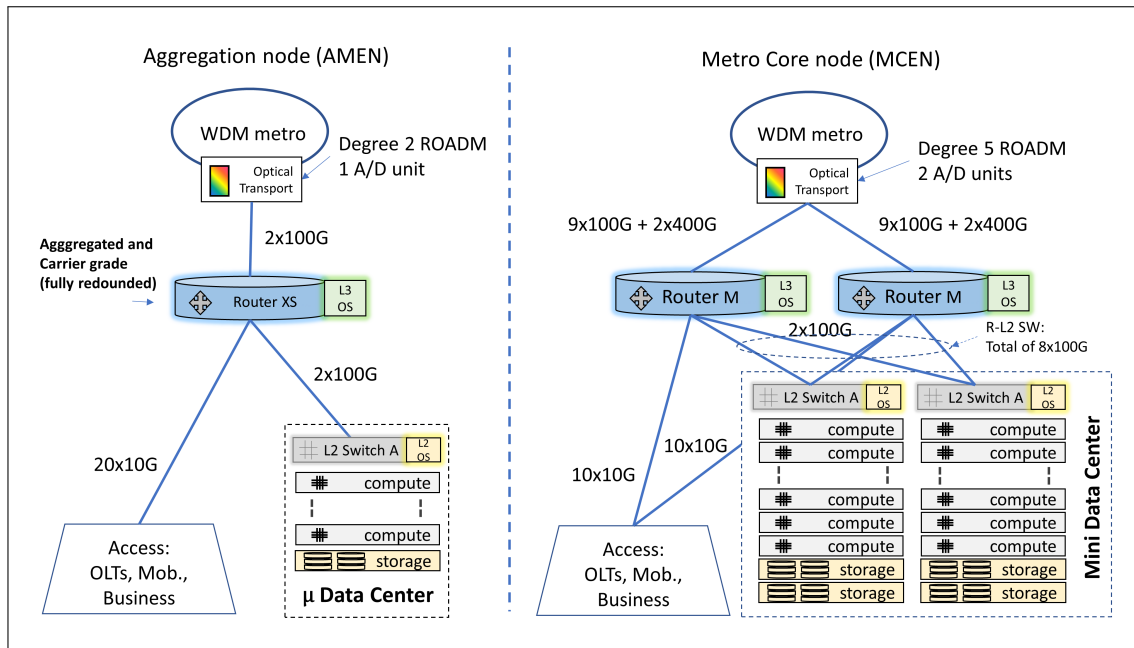
Fig. 3. Router based legacy architecture (Option 1 - Legacy Router) in aggregation (AMEN) and core (MCEN).
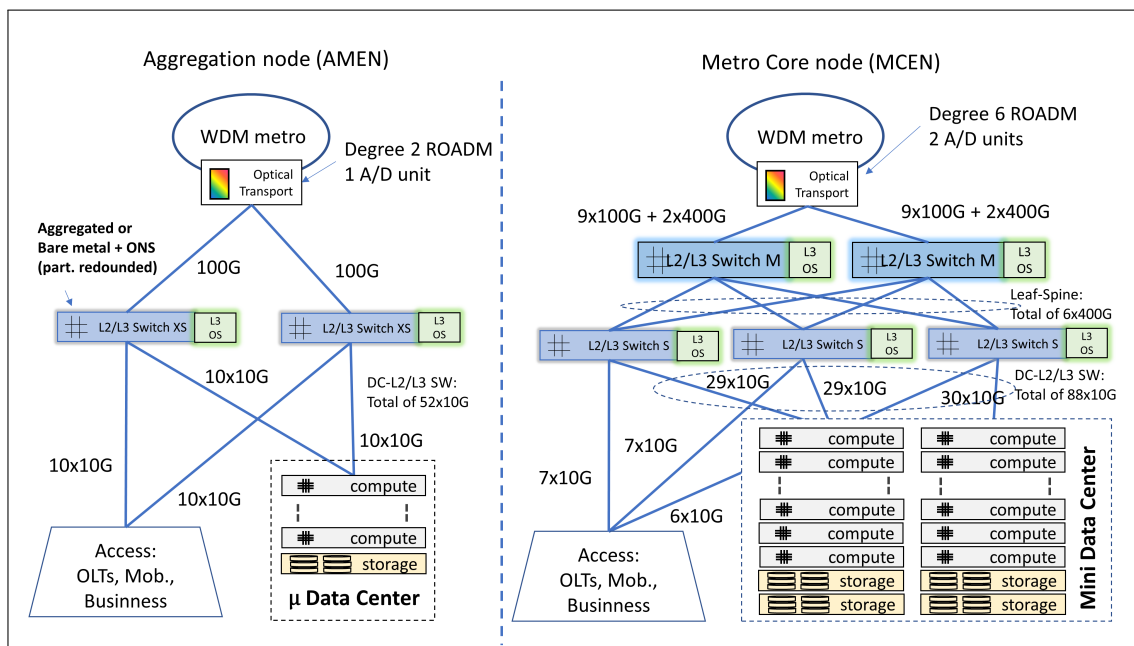

Fig. 4. L2/L3 Switch based architecture. Equipment and SW can be either aggregated or disaggregated. (i.e., the architecture adapts to both Option 2- Aggr. L2/L3 Switch - and Option 3 - Disaggr. L2/L3 Switch).

NAS storage units are added to MCENs, for every single DC profile.

For the optical layer, in aggregation network segments (horseshoe in Fig. 2) each AMEN is equipped with two 1:4 WSS modules for interconnection to the other nodes plus an A/D block based on one 1:4 WSS module and a Mux/Demux with two Amplifiers. In the core mesh segment each MCEN is equipped with six 1:9 WSS modules for mesh interconnection with the other MCEN nodes (four links) and to aggregation horseshoes (two links), plus two more 1:4 WSS modules, two Mux/Demux with four Amplifiers to build the two A/D blocks. The HW has the same characteristics for the three options, but in Option 3 the optical layer is assumed disaggregated. A discount of 20% in the disaggregated WDM HW with respect to the prices of the aggregate devices has been applied, as shown in [56, 57]. However, an additional investment in SW is necessary for the disaggregated case, but medium or large size operators can share this cost among a large number of equipment. For the disaggregated WDM layer, the SW cost is calculated following the same assumptions used for disaggregated switches, i.e., 2 CU per ROADM and O.5 CU per transponder (100,000 LOC SW is assumed shared by 250 ROADMs and again 100,000 LOC SW shared by 1,000 transponders).

The cost and power analysis results are depicted in the following charts. In Fig. 5, the cost of a single node is shown for the three options and for the two types of metro nodes (i.e., AMEN and MCEN) in case of Basic DC profile. The total cost is broken down into the data center, packet switch, optical and disaggregated SW components. The Disaggregated SW includes the SW for both optical and packet disaggregated equipment. The cost of an AMEN represents about 12% of the cost of an MCEN. As the cost of DC component does not change significantly for different node architectures (the small difference is due to the presence of additional L2 switches in the Legacy router architecture), the difference of cost between node architectures comes from the cost of the packet and optical parts.

For both AMEN and MCEN, the Aggregated L2/L3 switch architecture shows nearly equally balanced costs between packet, optical and datacenter components. Compared to Aggregated L2/L3 switch architecture, in the Legacy router case the cost of packet layer is remarkably higher, while for Disaggregated L2/L3 switch case both the cost of packet and optical parts are lower than the other two cases and the additional cost of the Disaggregated SW does not offset the reductions in equipment costs, which makes these solutions the cheapest option.

The percentages of cost reduction of the two cases adopting L2/L3 switches having as a reference the Router Legacy case are highlighted in the diagram. The percentage decrease obtained with Aggregated L2/L3 architecture are -21.6% and -15.4% for MCEN and AMEN respectively, and become noticeable for the Disaggregated architecture that, compared to the Router Legacy, reaches -33.2% and -21.7% reduction for MCEN and AMEN respectively.

Fig. 6 shows the total equipment cost of the MAN, obtained summing up 6 identical contributions from each MCEN and 54 from each AMEN. Results for the three node architectures are shown as an absolute cost component breakdown (bar diagram with scale of values on secondary y-axis) and as a value normalized to the households (HH) covered by the entire MAN on the primary y-axis (i.e., total cost divided by 900,000 HH). In the cost breakdown part of the diagram the cost components are differentiated not only in terms of infrastructure component (DC, optical or packet), but also between aggregated and dis-

aggregated. Moreover, the contribution of the Disaggregated SW (including SW for both packet and optical equipment) is explicitly shown for the L2/L3 Disaggregated node architecture. The DC cost component is less than half of the total cost, ranging from 33% (Legacy router) to 43% (L2/L3 Disaggregated Switch), as shown from the ratio between the yellow bar over the total in Fig. 6. Overall, the cost reduction obtained with L2/L3 switches, if used instead of routers, is of -18.4%, while the disaggregation of both packet and optical layer increases the cost reduction to about -27.3%. The cost of the disaggregated SW is about 10% of the total cost. Results for the HH normalized cost range from 0.0075 CU per HH for Legacy router, to 0.0061 of L2/L3 Agrregated Switch, to 0.0054 CU per HH for the L2/L3 Disaggregated Switch (the percentages of reduction with respect to Legacy Router are the same as reported before for the absolute total cost).

Fig. 7 shows the power consumption of a single AMEN and MCEN for the Basic DC profile. The values for L2/L3 switches architectures, aggregated and disaggregated, are the same and so only one category which applies to both is reported in the diagrams (HW of switches is the same in the two cases, the difference only being in the way SW is provided). Noteworthy is the large percentage of power required by the DC, even in the presence of a Basic DC profile for which the number of computation cores deployed is not large. The percentage of total power consumed in a node ranges between 74% (for AMEN in Legacy Router) to 91% (for both AMEN and MCEN in L2/L3 switch). The power reduction achievable thanks to L2/L3 switches (all other parts consume the same) is about -5.9% in MCEN and about -18.0% in MCEN.

Fig. 8 reports the total power consumption of the entire MAN (broken in subparts with reference for values on secondary y-axis scale) and the resulting power consumption per HH (scale on primary y-axis) for the Basic DC profile. The high impact of power consumption of the DC component is evident. The absolute consumption of the entire MAN for the reference case (Legacy Router) reaches about 1,200 kW, with a DC component of about 80% of the total, while for L2/L3 switch the power consumption results in just under 1,000 kW with the DC component increased to 90% of the total, and a reduction of -13.6% of the power consumption cost compared to the Legacy router case. The large reduction of power consumption achievable in the packet layer with the adoption of switches, instead of the high energy consuming routers, is offset by the high power consumption of the DC components which remains approximately the same (as mentioned in the cost analysis it differs only by the presence of additional top-of-rack switches and pluggables in the Legacy router architecture). The total normalized power consumption of the MAN gives 1.31 W per household in case of Legacy Router and 1.15 W per household in case of L2/L3 Switch architecture.

Fig. 9 reports the cost and power per household for the Disaggregated L2/L3 Switch architecture for the four specified DC profiles. As expected from the results already presented, it emerges that compared to the cost, the power consumption has a slightly higher sensitivity to the DC component. Going from 27,360 computation cores of the Basic DC profile to 60,480 cores of the High-D profile (+220%), the cost increases by +53% while the power consumption increases by +125% reaching 2.5 W per household. The percentage of power due to the DC component is not shown in the figure, but it grows from 84% of the total (Basic DC profile) to a value close to 94% (High-D DC profile).

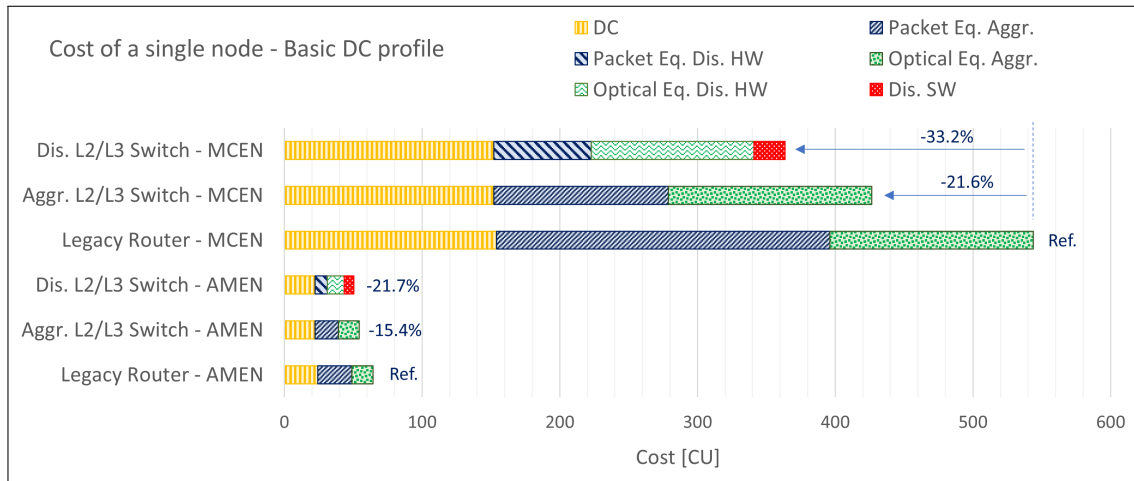Fig. 10 shows the partitioning between the sum of equip-

Fig. 5. Cost of a single node (AMEN or MCEN) for the three different node architectures and Basic DC configuration profile.
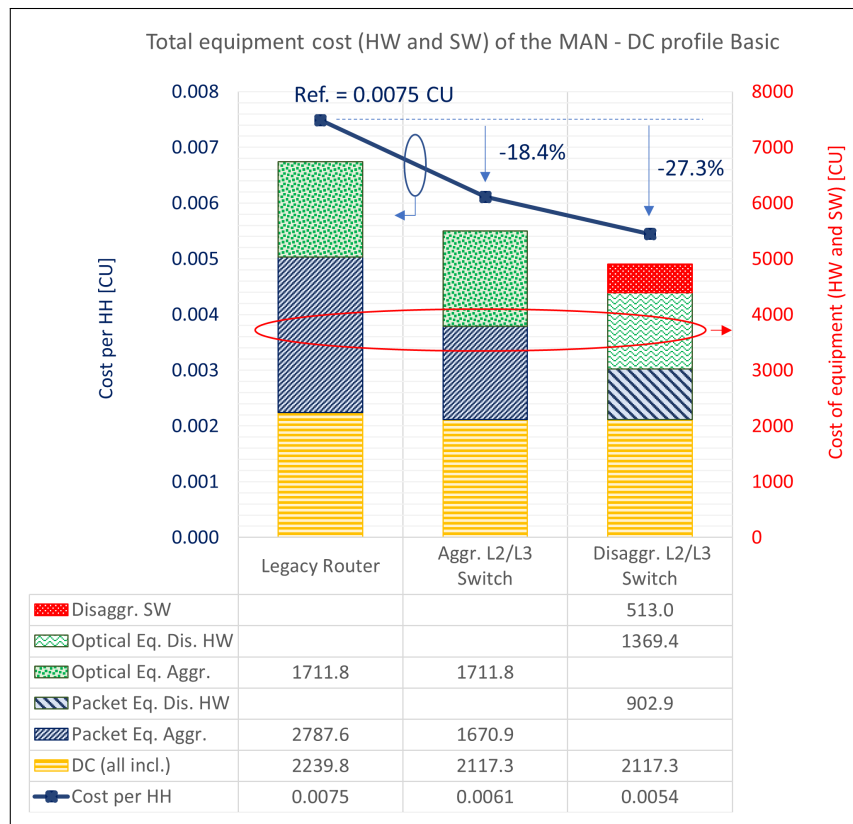

Fig. 6. Cost per Household (primary y-axis, markers) and total cost of the MAN (secondary y-axis, bars) for the three node architectures and Basic DC configuration profile.
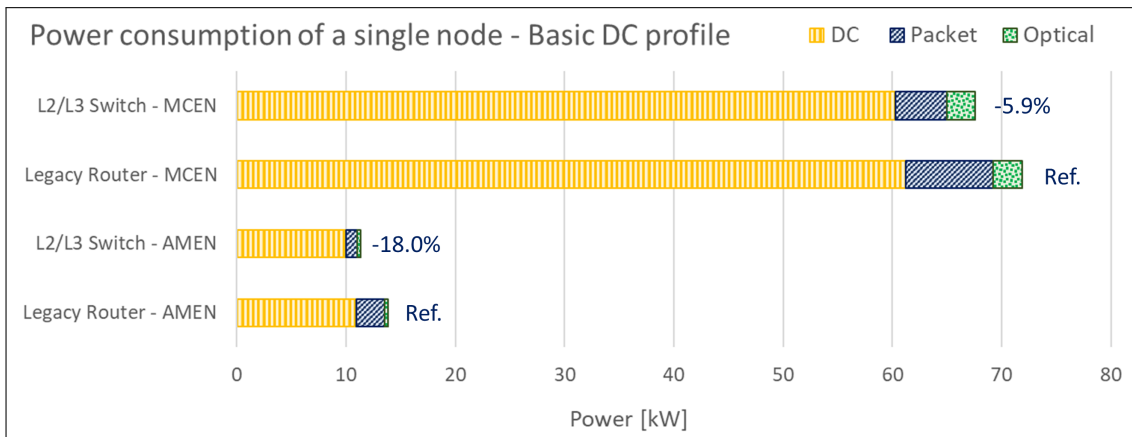
Fig. 7. Power consumption of a single node (AMEN or MCEN) for the router legacy and L2/L3 switch cases for Basic DC configuration.
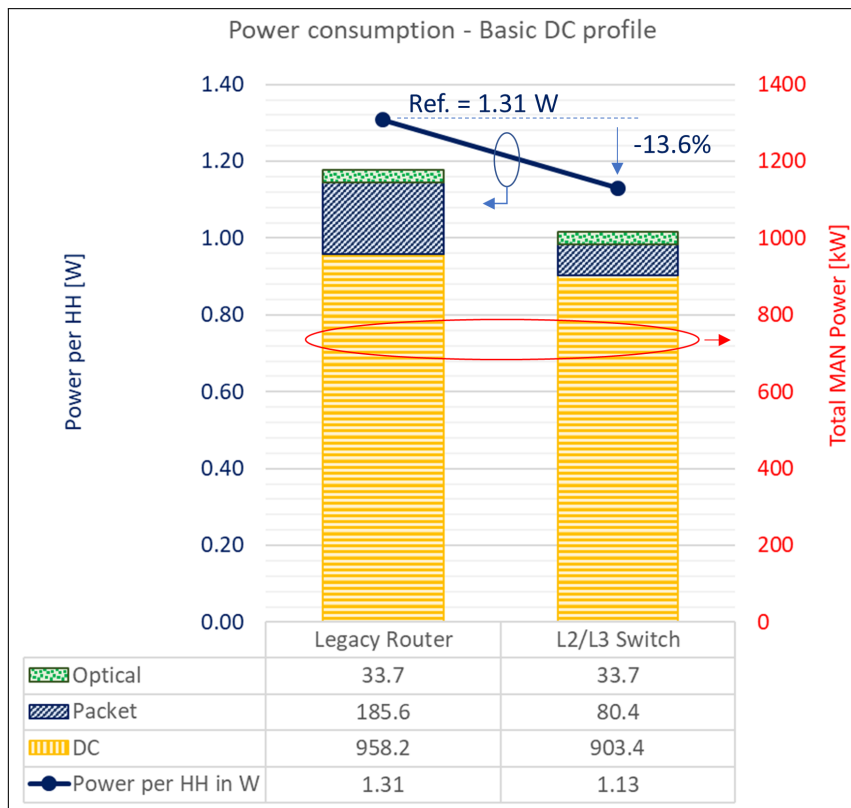

Fig. 8. Consumption per Household and Total MAN Power consumption for the Router Legacy and L2/L3 switch cases for Basic DC configuration.
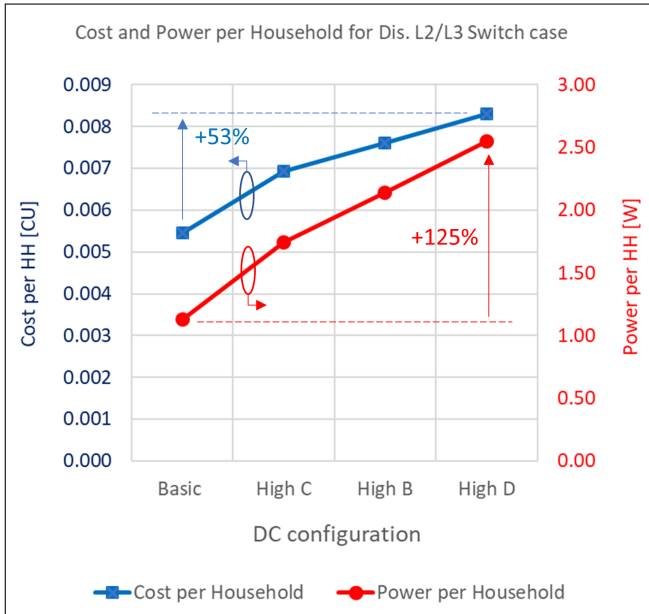
Fig. 9. Cost and Power per Household for the Disaggregated L2/L3 Switch case and the four DC configuration profiles considered. (Power values hold also for the Aggregated L2/L3 Switch case).
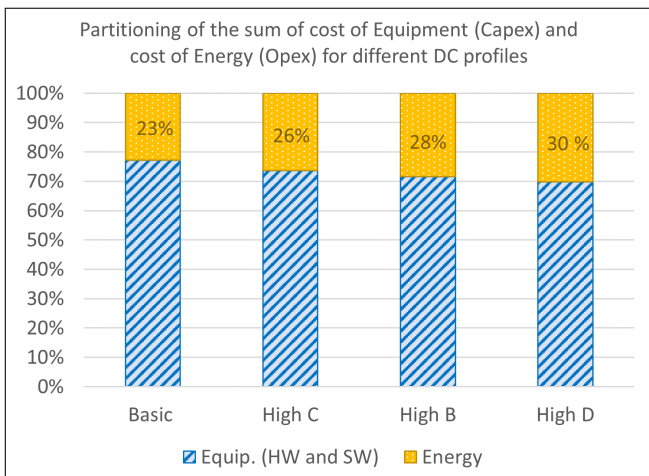

Fig. 10. Percentage of cost partitioning between CAPEX due to Equipment and OPEX due to Energy for different DC profiles (the cost is calculated on an annual basis and CAPEX for equipment investment is equally partitioned in 8 years).

ment cost and energy cost. To make comparable the CAPEX due to equipment purchase and OPEX due to energy cost, the two costs are referred to a period of one year. In this CAPEX-OPEX analysis, only power consumption and equipment cost is considered while other important cost sources like installation, maintenance or housing and floor rental are out of the scope of the article. Yearly cost of equipment is evaluated distributing the total equipment cost (as shown in Fig. 8 left y-axis) in 8 years (i.e., the amortisation period). The yearly energy cost is calculated using the power consumption values shown in Fig. 9 (right y-axis) and assuming a cost of 0.00002 CU per kWh (which is approximately the average energy cost for industrial customers in Europe and the USA). The diagram shows that the energy cost approximately amounts to one fourth of the total, reaching 30% of the total for the High D profile, which is the one that employs the largest volume of compute resources. The share of energy cost is significant with a remarkable sensitivity to the amount of compute resources.

5. SUMMARY AND DISCUSSION

This work presents both a cost model with the necessary building blocks to realise COs with computing/storage capabilities and, as an example of application, a techno-economic evaluation and comparison of different MAN node architectures based on the CORD model. The building blocks of the next-generation MAN architectures, featuring Multi-access Edge Computing (MEC) and 5G support, have been described with updated cost and power consumption values, for the optical layer components, packet switching and the storage/computing elements.

A techno-economic cost comparison of different CO architecture options is then presented. The analysis shows that moving toward disaggregated CO architectures can reach important cost savings in the range between 15 to 30% approximately, thanks to cost savings in the optical and packet switching components of the MAN nodes. On the other hand, introducing DC capabilities at the MAN nodes rises the total cost by approximately one third extra in CAPEX, but has a tremendous impact in OPEX, in particular, regarding the power consumption of the data-center part at the CO, which increases between 3x to 5x with respect to legacy CO without data-center capabilities. In this sense, future research efforts are necessary on investigating different ways to reduce power consumption of mini-DCs, for instance dynamic on/off strategies during low periods of activity. Also, operators need to investigate where it makes sense and profit the deployment COs with datacenters within the MAN.

In conclusion, the large investment required to transform legacy Central Offices into COs with data-center capabilities, both in terms of CAPEX, but especially in terms of power consumption, will require a sound business case planning the offered services for return of investment. However, in an increasingly digitised world, the loss of opportunity (not addressed in this study) must also be included in the investment decision making.

It is worth adding that such an architecture can also bring, in general, a reduction of the transmission capacity needed in the metro network. This benefit has not been quantified in this study because the traffic assumptions and the granularity chosen for the connections (i.e., 100G) preclude further reduction of the aggregation part, resulting in a minimum of 100G between any pair of connected nodes. To achieve such savings opportunities, a wider choice of connection rates (e.g., 25G and 50G), or scenarios with higher traffic volumes, should be considered. In this

respect the cost and power model presented in this article paves the way to further techno-economic evaluations of forthcoming MANs.

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