Disaggregated OTN-over-WDM vs. Private Line Emulation based IP-over-WDM Core Networks: A Techno-Economic Comparison

Arantxa Villavicencio Paz[1,2*], Ronald Romero Reyes[2], Thomas Bauschert[2], Achim Autenrieth[1], Jörg-Peter Elbers[1]
[1]*Department of Advanced Technology, Adtran Networks SE, Munich, Germany*
[2]*Chair of Communication Networks, Technische Universität Chemnitz, Chemnitz, Germany*
[*]arantxa.villavicenciopaz@adtran.com

***Abstract*—Over the last two decades, Optical Transport Network (OTN) technology has been a crucial enabler of the core network by efficiently switching and multiplexing traffic with quality-of-service guarantees. Despite their high costs, core network architectures based on traditional monolithic OTN solutions still dominate due to their robustness and performance. Nevertheless, with the increase in high-speed services and the adoption of 400 Gb/s interfaces, novel architectures are needed to fully exploit the transmission capacity of the underlying wavelength division multiplexed (WDM) optical system. In this regard, this paper conducts a techno-economic study that investigates two emerging architectures: disaggregated OTN-over-WDM and Private Line Emulation (PLE)-based IP-over-WDM. They differ in the mechanisms applied to serve packet and circuit-switched services over a common WDM network. Disaggregated OTN-over-WDM replaces monolithic OTN fabrics with white-box Ethernet devices that interwork with IP routers and WDM optical switches. In contrast, PLE-based IP-over-WDM emulates private lines to enable circuit-switched services over IP infrastructures. Both architectures are compared against the standard monolithic OTN-over-WDM solution. Compared to this baseline solution, the results show that disaggregated OTN-over-WDM can achieve cost savings of up to 39%, while the PLE-based architecture can incur cost increments of up to 113%.**

***Index Terms*—Optical transport networks, strategic network planning, techno-economic evaluation, network optimization.**

I. Introduction

OTN was introduced by the International Telecommunication Union in the report ITU-T Rec. G.709. This technology enables OTN-over-WDM core networks in which OTN switches - that operate in the electrical domain - groom client signals into optical connections, thereby addressing the speed mismatch between client signals and the WDM line port speeds. While these networks have been massively deployed in the market and cope well with client signals up to 100 Gb/s, evolving traffic demands now favor higher-speed services and the adoption of coherent pluggable optics. OTN not only lacks support for high-speed interfaces (beyond 100 Gb/s), but it also deploys switching architectures that entail high support fees, high power consumption and costly product discontinuation cycles. Despite this, many providers continue to invest in OTN. This investment is driven by the high reliability and low latency guarantees that OTN provides, as well as the ongoing growth in demand for OTN services among some users [1].

In our previous work [2], we conducted a techno-economic analysis of two OTN-over-WDM architectures: one based on monolithic optical transport switches (MOTS) and the other on disaggregated optical transport switches (DOTS). A MOTS switch consists of a chassis with an integrated backplane that interconnects components from a single vendor. The chassis integrates line cards (LCs) for client interfaces and inter-node communications, switch fabrics for traffic management, power and fan modules for energy supply and cooling, and controllers with protocol software. In contrast, a DOTS switch comprises a cluster of interconnected Ethernet white-boxes. White-boxes are modular switches/routers with decoupled software and hardware, allowing components from multiple vendors to be combined and customized. The study demonstrated that DOTS-based architectures reduce the total cost of ownership by 39.7% compared to their monolithic counterparts.

Building on this foundation, this paper expands the scope of the techno-economic analysis. First, a new architecture, PLE-based IP-over-WDM, is introduced for techno-economic comparisons against DOTS-based OTN-over-WDM. In addition, operating costs due to maintenance and reparation are now considered in the analysis, providing a more comprehensive evaluation. Furthermore, this work extends the study to three distinct network topologies to broaden the scope of the findings. Finally, a cost model with updated unit cost values is provided together with a sensitivity analysis in order to ensure that the results reflect current technology and market trends.

This paper is structured as follows. Section II outlines the concepts and differences between the proposed network architectures. Section III presents a comprehensive framework for the techno-economic analysis of multilayer core networks. Section IV discusses the results of a case study. Finally, Section V concludes the paper, summarizing key findings.

II. Multi-layer Core Network Architectures

A. DOTS-based OTN-over-WDM Architecture

1) Encapsulation Method: This architecture employs OTN, which efficiently maps and grooms services onto WDM line

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ports without requiring synchronization, encapsulating the services into containers that maintain their native protocol structure, timing and management information. OTN implements a frame structure consisting of three overheads: the Optical Payload Unit (OPU), the Optical Data Unit (ODU) and the Optical Transport Unit (OTU) overheads. The OPU overhead indicates the client signal type, while the ODU overhead provides optical path-level monitoring and communication channels. The OTU overhead includes performance monitoring features. Additionally, OTN frames incorporate forward error correction bytes, enhancing the optical signal-to-noise ratio by 4 to 6 dB.

2) Node Configuration: A DOTS node is a cluster made up of Ethernet white-boxes interconnected in a leaf-spine topology (which is commonly used in inter-data centre networks). These white-boxes decouple the software of the network operating system (NOS) from the hardware, taking away vendor lock-in restrictions and enabling compatibility with any NOS software, which simplifies management and control [3]. Specifically, the leafs white-boxes implement the LCs that provide interface ports to connect to client interfaces, to reconfigurable optical add/drop multiplexers (ROADMs) in the WDM layer and to spine white-boxes. The interconnections between leafs and spines are carried out through active optical cables (AOCs), which replace the chassis backplane. The spines are Ethernet switches that perform the functions of an OTN fabric. For that, the leafs implement OTN-over-packet-fabric protocols to emulate the switching of ODUs over the spine Ethernet fabrics. These protocols include a Constant Bit Rate Interface (CBRI) that uses the Interlaken protocol to switch ODUs through the fabrics. The timing of the ODUs is transferred by OTN phase signaling algorithms (OPSA) implemented on the leaf devices. Information about existing CBRI and OPSA implementations can be found in [4]. With the adoption of a leaf-spine topology, the disaggregated OTN switch may increase its capacity just by the addition of LCs and spines as needed, thereby enabling a pay-as-you-grow model. Furthermore, the absence of a monolithic backplane increases reliability as it removes single points of failure.

B. PLE-based IP-over-WDM Architecture

1) Encapsulation Method: This architecture employs PLE to converge packet- and circuit-switched services. PLE operates at the bit-stream level within packet networks, enabling circuit-switched service support. Ingress PLE-IP routers encapsulate incoming bit-streams into Virtual Private Wire Service (VPWS) packets, which are routed through the IP network. Upon reaching the egress routers, packets are stored in de-jitter buffers for de-packetization, utilizing differential clock recovery to reassemble the bit-stream based on packet timestamps. The PLE encapsulation method involves demultiplexing (demux) headers, PLE headers and VPWS payloads. The demux header conveys information regarding the network demultiplexing mechanisms, while the PLE header facilitates fault detection and stores packet timestamps. Regarding Service Level Agreements (SLAs), OTN overheads allow for comprehensive end-to-end signal quality monitoring, while PLE uses Circuit-Style Segment Routing (CS-SR) for traffic engineering, enabling path computation and bandwidth management. The transport functions of OTN switches introduce signal delays ranging from 10 to 100 microseconds, while advancements in IP router technologies target PLE transport delays below 10 microseconds.

2) Node Configuration: PLE-enabled IP routers are installed using a monolithic implementation. IP nodes consist of LCs that connect - via a chassis backplane - to IP fabrics. These LCs provide interface ports to connect to client interfaces and to ROADMs in the WDM layer. The chassis provides power, fan and controller modules. Thus, besides performing packet transport functions (through the forwarding of IP packets), PLE-enabled IP routers facilitate the transport of private line services over the IP infrastructure, catering for non-packet type services such as SONET/SDH, OTN and fiber channels. This is accomplished by the above-mentioned encapsulation method and the deployment of CS-SR functions for routing and traffic engineering.

III. Techno-Economic Evaluation Methodology

The techno-economic framework in Fig.1 is used to compare the cost efficiencies of the core network architectures. The methodology consists of three steps, starting with the collection of input information, which is used to perform strategic network planning with the subsequent assessment of the total cost of network ownership (TCO). The TCO comprises the capital (CapEx) and operational (OpEx) expenditures incurred throughout the network life-cycle.

A. Collection and Processing of Input Information

The techno-economic evaluation is carried out over a planning period that spans multiple years. The evaluation is performed at the beginning of the period. For that, the following information is collected and processed. First, the topologies of the network layers are defined (i.e. IP, OTN and

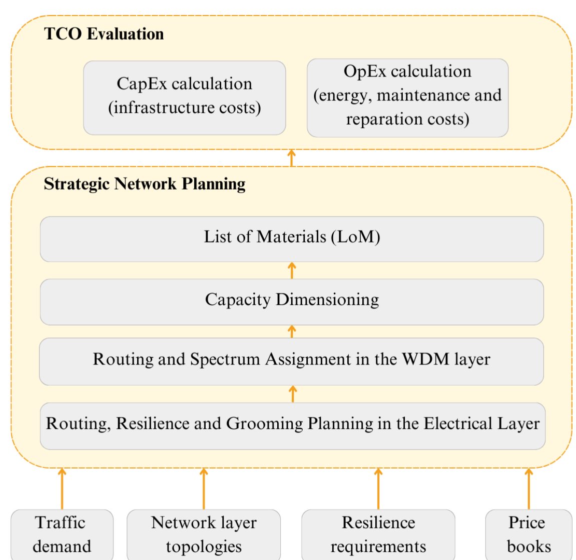

Fig. 1: Techno-economic evaluation framework.

WDM). A traffic matrix of service demands is then defined and forecast on an annual basis over the planning period. The matrix provides the size (in Gb/s) of the traffic flows to be served between each network node-pair. Besides, the resilience requirements of the service demands are specified. Some services may not need protection, while others may require shared or dedicated protection. This step also considers the definition of price books with information about the network components. For each component, such information includes its capacity (in Gb/s), unit acquisition costs, power consumption (in Watts), mean time between failures (MTBF), mean time to repair (MTTR), energy unit costs (e.g. in kWh), wages of personnel, etc. Forecasting models are applied to estimate - across the planning period - the annual depreciation of the unit acquisition costs, as well as the annual increment of factors such as wages and energy unit costs.

B. Strategic Network Planning

This step involves the use of network optimization algorithms across three design phases, which are applied for each year within the planning period. In the first phase, a routing algorithm is applied in the electrical layer (i.e. IP or OTN) to determine optimum working and protection paths for each service demand in the traffic matrix. (In the case of OTN, the algorithm performs grooming as well.) With the resulting distribution of traffic flows in the electrical layer, in the second phase, an algorithm for routing and spectrum assignment is applied in the WDM layer. The goal is to optimize the number and configuration (i.e. the routing and spectrum) of the optical connections that provide the transmission capacity of the electrical layer links. The third phase takes as input the size (e.g. in Gb/s) and routing of both service demands and optical connections optimized in the previous two phases. With this information, an algorithm for capacity dimensioning is applied to determine the optimum number and configuration (e.g. port speeds) of LCs, fabric modules, transponders, ROADMs, etc. The result is a list of materials (LoM) that specifies the network deployment plan for each year within the planning period. It is worth noting that the planning process implicitly assumes that protection is implemented in the electrical layer (as described in the first phase). Nonetheless, protection could also be implemented in the WDM layer, if deemed necessary. This approach is however seldom used in practice owing to the slow reconfiguration response times of optical components.

C. TCO Evaluation

The LoM obtained in the network planning step is used to calculate the cumulative TCO over the planning period. The TCO is a cash flow made up of CapEx and OpEx contributors. The former consists of costs associated with the acquisition of infrastructure, such as LCs, transponders, fabric modules, AOCs, ROADMs, etc. OpEx are costs incurred to keep the network operational throughout its life cycle. Relevant OpEx contributors that stem from the network infrastructure are energy consumption (EC) and maintenance and reparation (MR). The former depends on the power requirements of the network components, whereas the latter on factors such as the component acquisition costs, their associated MTBF and MTTR values, as well as the wages of the personnel involved in the MR process. Note that the MTBF provides an estimate of the expected number of component failures per year. With this estimate, it is then possible to calculate the cost incurred to replace a faulty component, which is the acquisition cost of the new component added to the labour costs of the personnel that detects and fixes the failure. The cost evaluation step provides a TCO cash flow stream spread over the planning period.

IV. Case Study

The techno-economic framework was applied for a 10-year planning period - starting in 2024 - in order to evaluate three distinct core networks: Coronet30, Cost266, and Germany50. Coronet30 is an American network with 30 nodes and 36 links that is designed to serve 91 demands, which offer an aggregate traffic of 6.6 Tb/s in 2024. Cost266 is a European network consisting of 28 nodes and 41 links, serving 2 Tb/s of aggregate traffic in 2024 from 378 demands. The Germany50 network has 50 nodes and 88 links, with an aggregate traffic of 7.2 Tb/s in 2024 distributed over 1072 demands. A compound annual growth rate of 30% was applied to each demand to forecast its annual traffic growth over the planning period. Each network is designed for three architectures, i.e. MOTS-based OTN-over-WDM, DOTS-based OTN-over-WDM and PLE-based IP-over-WDM. For each architecture, three separate network designs are optimized. The first design assumes a No Protection (NP) scheme, meaning unprotected demands (i.e. capacity for protection is not calculated). The second design considers a Shared Protection (SP) scheme (i.e. each demand has a protection path assigned, which can be shared among different demands). The third design regards a 1+1 Protection scheme (1+1P), which assumes that demands require 1+1 protection (i.e. each demand has a dedicated protection path).

For each network design, network planning is carried out by solving first the routing, resilience and grooming problems in the electrical layer (i.e. IP and OTN). For routing, a shortest path algorithm is applied for each demand w.r.t the total distance. Depending on the resilience requirements (i.e. shared or 1+1 protection), additional disjoint protection paths are computed. For grooming (in the case of OTN), an adapted version of the algorithm in [5] was applied. The resulting traffic routing determines the capacities of the links in the OTN and IP layers. These links are realized by optical connections in the WDM layer, which are routed through their minimum length paths. Their spectrum is assigned with a first-fit policy.

Capacity dimensioning is carried out with the components in Table I. These components perform switching, grooming and transport in the electrical and optical layers. The capacity is calculated by determining the number of components that minimize the TCO. For all architectures, the WDM layer is designed as a flex-grid system operating in the C-Band. This system consists of 100 Gb/s flex-grid transponders installed with colorless, directionless and contentionless ROADMs. These ROADMs are built by wavelength selective switches (WSSs) that implement both the ROADM add/drop sections as well as the optical switch fabrics. Optical amplifiers (OAs)

TABLE I: Component specifications in the reference year 2024.

Node Type	Component	Cost [CU]			Power [W]	MTBF [Kh]	MTTR [h]
		1 CU = 5000 USD	1 CU = 7450 USD	1 CU = 9900 USD			
MOTS-based OTN Switch	Transceiver 10 Gb/s	0.01	0.01	0.01	1.5	238	4
	Transceiver 40 Gbs/s	0.02	0.02	0.02	5	238	4
	Transceiver 100 Gb/s	0.06	0.06	0.06	5	238	4
	Line Card 48x10 Gb/s	0.23	0.23	0.23	1523	250	4
	Line Card 25x40 Gb/s	0.64	0.64	0.64	3891	250	4
	Line Card 10x100 Gb/s	1.11	1.11	1.11	3491	250	4
	Basic node with 8 LC slots	0.32	0.32	0.32	870	585	4
	Basic node with 16 LC slots	0.47	0.47	0.47	1800	585	4
	Basic node with 32 LC slots	0.77	0.77	0.77	4800	585	4
DOTS-based OTN Switch	DOTS Line card 1.2 Tb/s	1.81	1.22	0.92	260	668	4
	Leaf switch with 10 service and 13 fabric ports	3.40	2.28	1.72	501	292	4
	Leaf switch with 36 service and 40 fabric ports	8.05	5.40	4.06	1502	290	4
	Spine switch	3.44	2.31	1.74	985	257	4
	AOC QSFP-DD to QSFP-DD	0.18	0.12	0.09	20	468	2
	AOC QSFP28 to QSFP28	0.07	0.05	0.04	5	468	2
	AOC QSFP28 to Dual-QSFP28	0.05	0.03	0.03	5.7	187	2
	AOC SFP+ to SFP+	0.01	0.006	0.005	1	468	2
PLE-enabled IP Router	Line card 36x100 Gb/s	41.52	27.87	20.97	1050	118	4
	Basic node with 4 LC slots	27.14	18.21	13.70	1504	205	4
	Basic node with 8 LC slots	35.54	23.85	17.95	2600	205	4
	Basic node with 16 LC slots	86.08	57.77	43.47	6620	205	4
	AOC 4x10 Gb/s to QSFP	0.02	0.01	0.01	4.7	187	2
	AOC 40 Gb/s to QSFP+	0.01	0.01	0.01	3	468	2
	AOC 100 Gb/s to QSFP28	0.03	0.02	0.01	5	468	2
WDM Components	WSS(1x9)	0.24	0.24	0.24	75	250	4
	WSS(9x9)	2.82	2.82	2.82	135	250	4
	WSS(1x20)	0.35	0.35	0.35	120	250	4
	Optical Amplifier (OA)	0.05	0.05	0.05	33	250	6
	Transponder 100 Gb/s	1.00	1.00	1.00	100	128	6

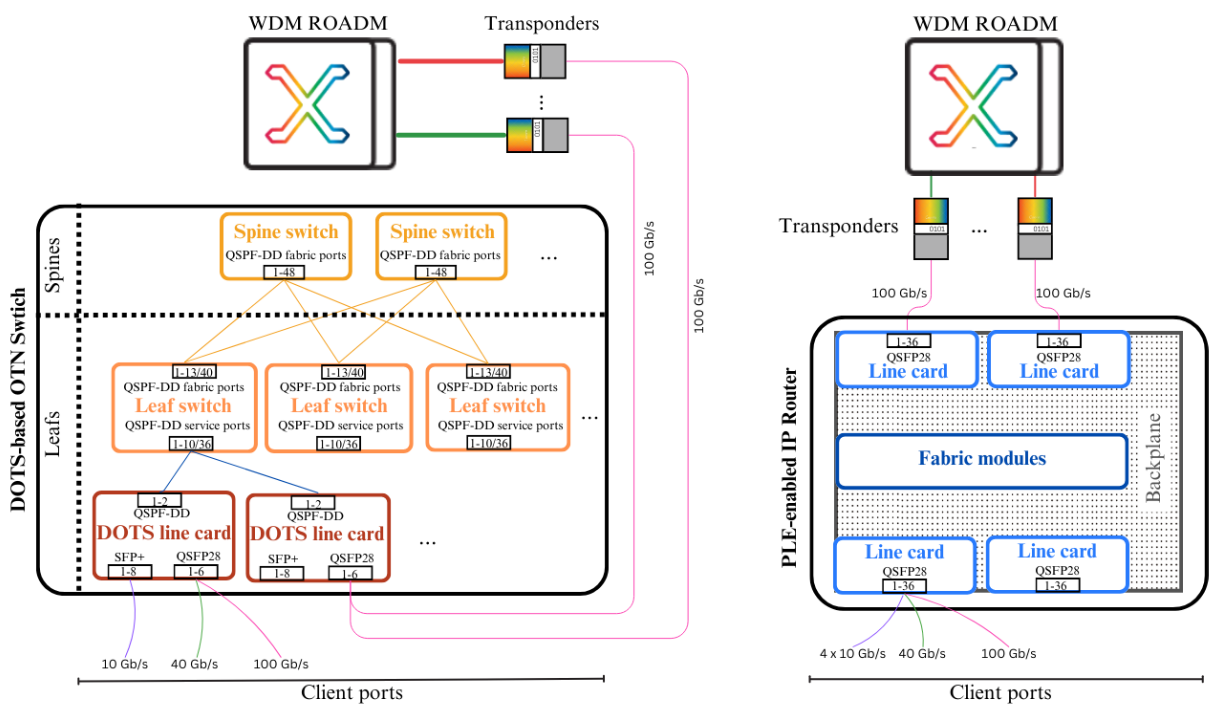

Fig. 2: DOTS-based OTN switch and PLE-enabled IP router.

are deployed within the ROADMs and every 80 km along each WDM link. The dimensioning of the WDM layer was carried out following the guidelines in [6]. As for the electrical layers, the following design considerations apply (see Fig. 2):

- MOTS-based OTN-over-WDM architecture: The MOTS-based OTN switches employ a monolithic chassis with capacities of 8, 16, or 32 LC slots. Depending on the speed requirements of the clients, three types of LCs are used: LCs with 48 x 10 Gb/s ports, LCs with 25 x 40 Gb/s ports, and LCs with 10 x 100 Gb/s ports.

- DOTS-based OTN-over-WDM architecture: DOTS-based OTN switches are designed with white-boxes configured in a leaf-spine topology. The leafs are made up of DOTS LCs and Ethernet switches of types A or B (see Table I). Type A switches have 13 fabric ports and 10 service ports, whereas type B have 40 fabric ports and 36 service ports. Fabric ports connect leafs to spines while the service ports connect to the DOTS LCs. These LCs support port speeds of 10 Gb/s, 40 Gb/s or 100 Gb/s. The leafs perform traffic mapping, grooming and switching by applying the CBRI and OPSA protocols. The spine switches connect to the leafs in a redundant $M+1$ configuration, meaning that M spines are installed with one backup switch, which is used in case one of the M switches fails. AOCs are used to link leafs to spines, and LC ports to client interfaces and WDM transponders.
- PLE-based IP-over-WDM architecture: PLE-enabled IP routers are installed as monolithic chassis systems with modular LCs, each providing 36 ports with speeds of 40 Gb/s or 100 Gb/s. These ports connect to client interfaces and WDM transponders. The PLE-enabled IP fabrics can support 4, 8 or 16 LC slots.

The LoM provided by the capacity dimensioning step is used to assess the TCO with the component costs in Table I. The costs are expressed in cost units (CUs) and are obtained by normalizing the component costs to the cost of a 100 Gb/s transponder. Market consultations show that this cost may vary between 5000 and 9900 USD. We use as normalization factor the average cost of 7450 USD. The costs (in USD) for the components of the DOTS switch and the PLE routers were obtained from quotations and global price lists. Additionally, for the DOTS-based architecture, an additional cost of 0.14 CU per switch is added to account for software integration costs [7]. As for the MOTS-based OTN switch and the WDM components, their unit costs were derived from [6], where the costs are normalized to the cost of a 10 Gb/s transponder in the year 2012. To use these costs, it is necessary to forecast them in the year 2024 and to re-normalize them to the cost of a 100 Gb/s transponder. The forecast was calculated with the method applied in [6]. For the re-normalization, the cost of the 10 Gb/s transponder used in [6] is not publicly available. However, market consultations show that this cost in 2012 may have varied between the numerical values of the above-mentioned range of current costs for a 100 Gb/s transponder. Thus, in principle, re-normalization would result in unit costs similar to those forecast from the costs normalized to a 10 Gb/s transponder. We therefore assume that these unit costs use the average normalization factor of 7450 USD. The TCO of the architectures is compared under this assumption. A sensitivity analysis is then carried out to assess the accuracy of the assumption if the re-normalized unit costs vary between 5000 and 9900 USD.

The calculation of the energy costs is based on the power consumption defined by the component datasheets, as well as by information published in [7], [8]. These calculations consider an electricity cost (as of 2024) and an anticipated annual inflation rate of 0.33 USD/kWh and 2.5% for Coronet30, 0.17 USD/kWh and 3% for Cost266, and 0.44 USD/kWh and 2.3% for Germany50 [9]–[11]. Maintenance and reparation costs assume an hourly wage of 80 USD in 2024, which is the salary incurred by the personnel involved in the reparation process. The MTBF and MTTR values - expressed in hours (h) - are obtained from the component datasheets and from [12]. A description of the mathematical models used to calculate the energy consumption and maintenance and reparation costs is found in [12].

Figure 3 shows the 10-year cumulative TCO for all networks with the three recovery schemes (NP, SP, 1+1P) and architectures. For each network, the TCO is normalized to the TCO of the MOTS-based design without protection (NP). The DOTS-based designs attain the lowest TCO and OpEx. They also slightly incur higher CapEx than the MOTS-based solutions, as the unit component costs are higher. The MOTS-based solutions attain the highest OpEx related to EC, due to the high power consumption of the LCs. For this architecture, EC represents over 62%, 43% and 67% of the TCO for Coronet30, Cost266 and Germany50, respectively. The percentage is lower for Cost266, since the traffic carried is low compared to the other networks, which translates into a smaller number of LCs. The PLE-based designs are the most expensive and show an OpEx similar to the DOTS-based solutions but with a CapEx significantly increased due to the higher unit costs of the IP routers. Across all networks, the CapEx of the PLE-based designs is more than 2.77 times the CapEx of the MOTS-based solutions. Besides, since the MR costs depend on the component costs, the PLE-based designs incur higher MR

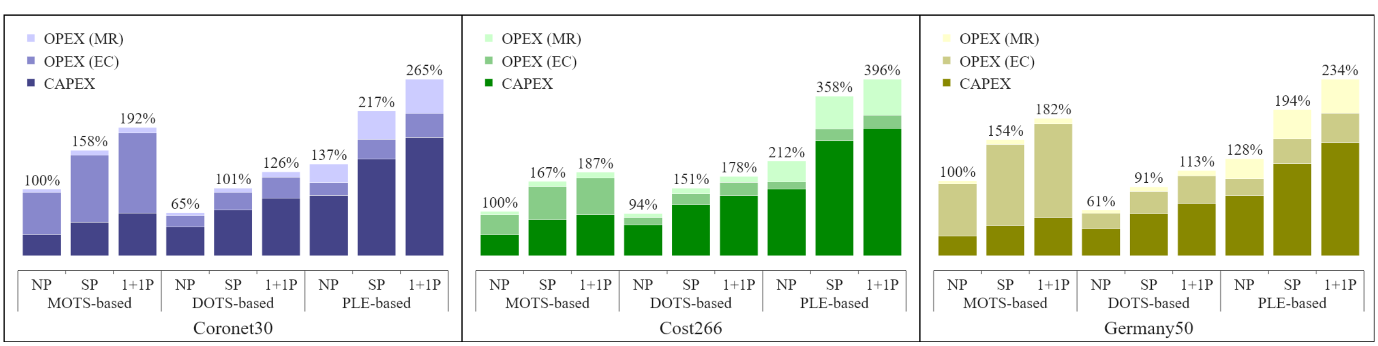

Fig. 3: Cumulative TCO at the end of the 10-year planning period - The TCO breakdown is shown.

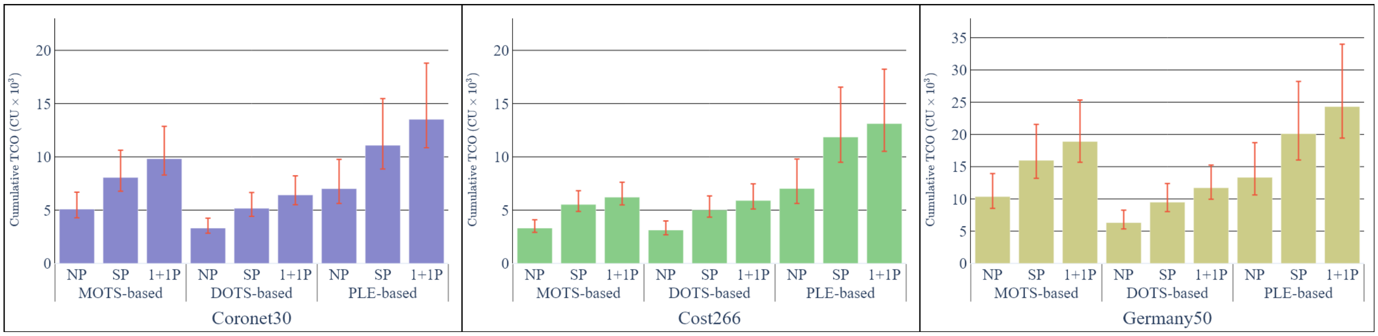

Fig. 4: Sensitivity analysis of the cumulative TCO at the end of the 10-year planning period.

costs than the other approaches. With respect to the MOTS-based solutions, the DOTS-based designs achieve average TCO savings of 35%, 7% and 39% for Coronet30, Cost266 and Germany50, respectively. On the contrary, the PLE-based designs show - w.r.t the MOTS-based solutions - average cost increments of 37%, 113% and 28% for the same networks. Although the CapEx was more than 2.77 times higher than the MOTS-based architectures, the OpEx (considering both MR and EC) is lower for the Coronet30 and Germany50 networks. It is worth noting that - for each network - the difference in CapEx between the three architectures is only influenced by the electrical layer components, since their WDM components in the LoM are the same.

The sensitivity analysis in Fig. 4 shows the impact of the re-normalization of the unit costs of the components of the MOTS and WDM devices. In the analysis, the assumption is now made that these unit costs (in CUs) correspond to normalization factors that vary between 5000 and 9900 USD. For the DOTS switches and the PLE-enabled IP routers, their costs are re-normalized within this range. The re-normalized unit costs are listed in Table I. The bar heights in Fig. 4 represent the TCO in Fig. 3, expressed in CUs and normalized to 7450 USD, while the red error lines represent the TCO variability, with the upper and lower bounds representing the TCO for the normalization factors of 5000 and 9900 USD, respectively. From the analysis, it follows that the cost savings and increments w.r.t the MOTS-based designs remain similar as in the baseline case in Fig. 3. In particular, considering the normalization interval with the mean TCO calculated with the normalization factor of 7450 USD, the estimated cost savings for the DOTS-based architecture are then 35% $\pm$ 2%, 7% $\pm$ 3%, and 39% $\pm$ 2% for the Coronet30, Cost266, and Germany50 topologies, respectively. In contrast, the PLE-based architecture reflects cost increments of 37% $\pm$ 9%, 113% $\pm$ 28%, and 28% $\pm$ 5% for the same networks.

V. Conclusions

The techno-economic proof of concept in this paper shows that - amongst the studied architectures - the DOTS-based architecture achieves the lowest TCO, followed by the MOTS-based and the PLE-based counterparts. The MOTS-based networks incur the highest OpEx, driven by the significant power consumption per OTN port. In contrast, for the DOTS- and PLE-based architectures, the OpEx is dominated by maintenance and reparation, which shows that these two solutions are more energy efficient. The PLE-based architecture exhibits the highest TCO, which is driven by the CapEx. This cost factor is more than 2.77 times higher than the CapEx of the MOTS-based designs. Thus, the results indicate the feasibility of deploying OTN-over-WDM networks as disaggregated systems built by white-box devices. PLE might become a promising alternative once the technology has gained a maturity level that reflects in more cost-efficient devices.

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