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# Next-Generation Transport Networks Leveraging Universal Traffic Switching and Flexible Optical Transponders

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Bodhisattwa Gangopadhyay, João Pedro and Stefan Spälter

Additional information is available at the end of the chapter

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## Abstract

Recent developments in communication technology contributed to the growth of network traffic exponentially. Cost per bit has to necessarily suffer an inverse trend, posing several challenges to network operators. Optical transport networks are no exception to this. On one hand, they have to keep up with the expectations of data speed, volume, and growth at the agreed quality-of-service (QoS), while on the other hand, a steep downward trend of the cost per bit is a matter of concern. Thus, the proper selection of network architecture, technology, resiliency schemes, and traffic handling contributes to the total cost of ownership (TCO). In this context, this chapter looks into the network architectures, including the optical transport network (OTN) switch (both traditional and universal), resiliency schemes (protection and restoration), flexible-rate line interfaces, and an overall strategy of handover in between metro and core networks. A design framework is also described and used to support the case studies reported in this chapter.

**Keywords:** optical transport network, flexible line interfaces, protection and restoration, network planning

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## 1. Introduction

The exponential growth of consumer demands and machine-to-machine network traffic coupled with the downward trend in revenue per bit transported is challenging network operators to adopt a strategy which tackles a twofold problem. The dual nature of the problem, on one hand lies in selecting a network architecture/technology which can efficiently transport

traffic originating from multiple sources, be it time division multiplexing (TDM) or Packet, and on the other hand to make use of an increasingly flexible and heterogeneous optical layer, where the characteristics of the optical light paths to be set up (e.g., modulation format, spectral width) are customized to the specific path properties.

Today, typical transmission networks are a layered combination of dense wavelength division multiplexing (DWDM) equipment (the lowest layer above the optical fiber layer), a subwavelength aggregation and grooming layer and an internet protocol (IP) layer. These layers form server/client relationships and are independent of each other. From a technological point of view, the functions of each layer are very different. Higher layer equipment is typically more expensive per bit transported because it needs to do more processing, so the use of the layers must be carefully balanced to deliver cost-optimized networks. The introduction of coherent 100G (100 Gigabits per second) optical transport was a key catalyst which offered massive performance gains over incumbent technologies to exploit more capacity from a single fiber. Telco operators achieved considerable gains as the cost per bit started going down with the introduction of 100G. But this was not the end, as they eyed newer improved scalable architectures to strengthen network operations and total cost of ownership (TCO). These next-generation network architectures aimed at efficiently grooming and aggregating sublambda data streams resulting in cost-optimized well-packed 100G wavelengths which would allow telco operators to survive within challenging capital expenditure (CAPEX) and operational expenditure (OPEX) cost targets in the near future. However, due to their relatively compact and short reach topologies, an abundance of optical fiber and the requirement to interconnect network elements at 10G rates or less, metro networks still mostly relied on a direct-detect 10G optimized optical transport infrastructure, though this situation is bound to change dramatically [1].

Importantly, the abundant deployment of 100G coherent systems in core networks has been attained at the expense of relatively costly line interfaces, performing electrical-optical (EO) and optical-electrical (OE) conversions. In the meanwhile, optical transport network (OTN) emerged as a key building block to complement the capacity gains unleashed by 100G and coherent optics. Efficiency, predictability, and reliability of the transport world and the agility, programmability of the packet world were blended into the ITU G.709 standard (OTN protocol) [2] and thus became an automatic choice. The demanding service level agreements (SLAs) of private E-LANs, E-Lines, and other packet traffic along with wavelength services from the near future could be met by the many features that OTN was offering. Moreover, traffic processing on IP packet level (layer 3) is much more expensive (per GByte) than switching the same amount of traffic in optical channel data unit (ODU) containers by OTN switches. Therefore, OTN provides a more cost-effective platform for subwavelength services to be multiplexed not only at their source node, but also at selected intermediate nodes and, as a result, reduce the amount of expensive (WDM) line interfaces used without having to resort to expensive router equipment to perform this task [3].

Nevertheless, a continuous steep inverse trend between the data volume and cost per bit being carried and the explosive growth of the traffic between data centers has supported the development of higher-order modulation formats, namely, 8-quadrature amplitude modulation

(8-QAM) and 16-QAM, which provide 50% (150G) and 100% (200G) more capacity than standard quadrature phase shift keying (QPSK) albeit at the expense of reducing transparent reach to around half and one-third, respectively. This catered to the need of extremely high equipment density and maximizing optical transport capacity per fiber and per transceiver. However, there was another need growing up from the continuously shifting traffic pattern. And one answer to all these needs mentioned above was the flexible-rate interface modules, which grant software-switchable modulation (QPSK, 8-QAM, and 16-QAM supported in the same device), flexible channel spectral width, and flexible frequency tunability to provide the ideal balance between performance, capacity, and reliability across the most challenging networks [4].

A key aspect of transport networks is their capability to withstand failure scenarios, given the very large amount of traffic they carry. This requirement is usually met via protection and restoration techniques [5]. Protection is a static mechanism to protect against failures, where the resources for both the primary and the backup paths are reserved prior to the data communication. Restoration is a dynamic mechanism where the backup path is not set up until the failure occurs. Survivability using these techniques is usually provided to handle single/multiple link or node failures in the network with each scheme, claiming a different stake in terms of network resources and recovery time. Moreover, protection/restoration can be supported at different layers of the OTN and the selection of which layer to utilize, either the ODU or the optical channel (OCh) layer, also involves similar trade-offs [6].

This chapter is organized as follows. Section 2 overviews the current role of OTN switching in transport networks and introduces the concept of the universal OTN switch, highlighting the motivation behind it and the key benefits of adopting it. In order to support the case studies presented in the remaining of the chapter, a routing and grooming framework is detailed in Section 3. Section 4 addresses the relevance of mechanisms for failure survivability in transport networks, presenting a case study comparing the cost-effectiveness of supporting restoration at different layers of the transport network. Moreover, the benefits of combining universal traffic switching and flexible-rate line interfaces are investigated in Section 5 and are quantitatively assessed via a case study using reference transport networks. Section 6 elaborates on the prospects of further cost savings in metropolitan and core networks as a result of adopting coherent-detection technology in both network segments. Finally, Section 7 presents the concluding remarks.

## 2. The role of OTN switching in transport networks

Technological advancements have seen different node architectures being proposed, each having their pros and cons. Transponders and muxponders still provide the simplest approach to getting traffic on and off a 100G transmission interface, by multiplexing one or more client interface to a single high-speed line interface. On one hand, this approach incentivizes simplicity and relatively low CAPEX, while on the other hand, penalizes the operator because of its limited ability to groom traffic, inability to perform remote configuration, and being inefficient to combine add/drop traffic with pass-through traffic from other line interfaces.

2.1. First-generation OTN switch

The present day traffic represents a blend of packet traffic and extensively installed legacy TDM traffic. To address this varied traffic pattern and mix, the modern day network architectures requires an OTN switch to cater service-agnostic switching where the multiple client service types can be mapped into ODU frames and the same can be switched at the ODU level. This will not only allow subwavelength services to be aggregated at their source and destination nodes but also allow them to be groomed at intermediated nodes and thus finally contribute to a reduction in the number of expensive WDM line interfaces in use. **Figure 1** depicts the transponder/muxponder and OTN switch architectures. The later architecture introduces a digital OTN switch, which is separated from the WDM box using short-reach optics or integrated with the WDM box to reduce footprint and power consumption [7]. According to Infonetics, the majority of service providers (86%) are choosing OTN switching as the technology best suited to fill 100G optical channels, because it enables efficient aggregation of diverse services and protocols over a single optical link. Noteworthy, it is being embraced and deployed by network providers throughout Asia, Europe, and North America [8].

Another key feature enabled by OTN switching is fast shared protection and restoration schemes with fine granularity, which cannot be achieved with a transponder or muxponder solution. Other than contributing to a reduction of CAPEX, OTN switching does include several other benefits. Among them, high scalability, fast end-to-end service provisioning, multiple traffic type support, subwavelength switching, router port offloading, and client service level mapping are a few to name [7]. But then, certain specific traffic patterns and network topology can result in the switchless architecture to have a CAPEX advantage over

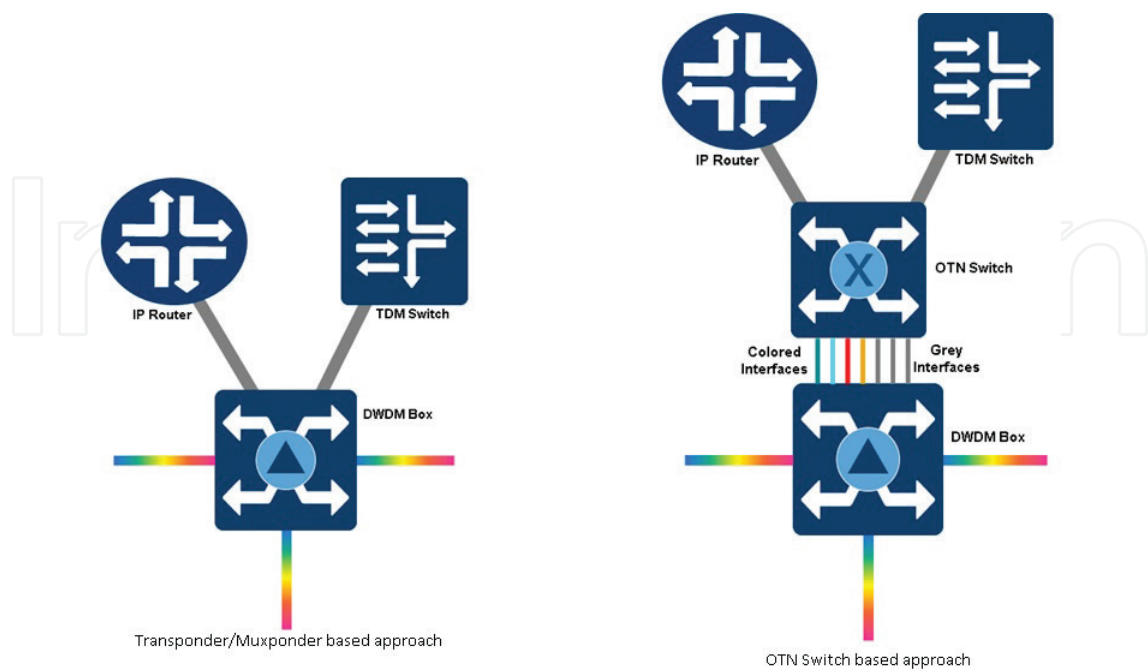


Figure 1. Transponder/muxponder-based approach vs. OTN-based approach.

the switched architecture. The same is witnessed when client services data rates match with the WDM channel data rates or even when the traffic type is not a mix and only comprises of packet data, and in these cases, the overall node architecture can be simplified to a switchless one with simplified equipment spanning L3-L0. Another perspective also challenges network operators while including OTN switch and that is contributed by the additional power and space consumption increasing the OPEX.

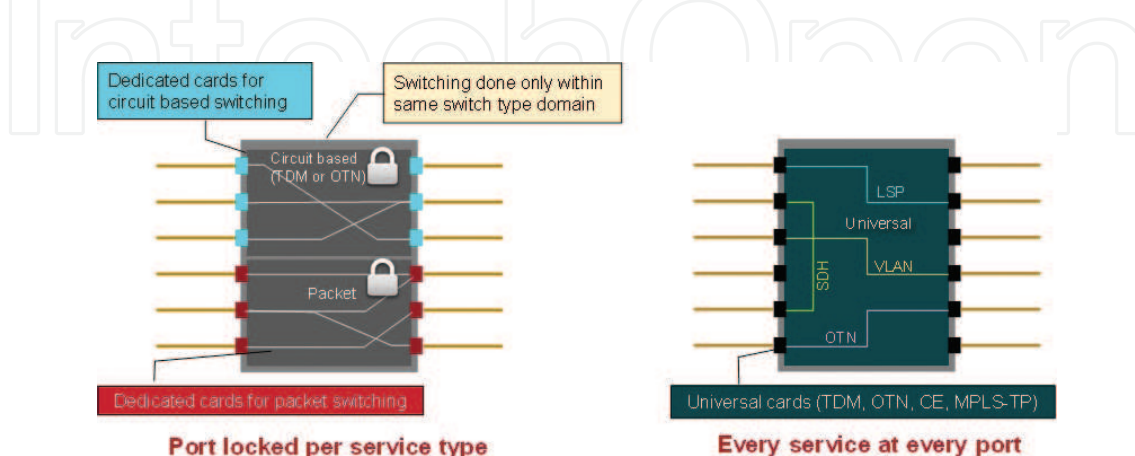
The traditional or first-generation OTN switch focuses only on switching ODUs and involves dedicated cards for circuit-based switching and dedicated cards for packet-switching, as illustrated in **Figure 2**. Consequently, switching is restricted within the same switch-type domain (packet/circuit). Furthermore, within the same switching domain, interworking between different technologies, such as the OTN and the synchronous digital hierarchy (SDH)/synchronous optical network (SONET), may be also blocked. Essentially, traditional OTN switches fail to deliver “universal client port” functionalities, which would allow to support any mix of client interfaces in a single switching domain, further improving the ability to efficiently utilize the transport network resources.

## 2.2. The universal OTN switch

Conversely to the traditional or first-generation OTN switch, next-generation universal OTN switch as shown in **Figure 3** can aggregate different protocols on the client side and enable transparent multiplexing of packet and TDM traffic, allowing a single device to be used in multiple applications efficiently.

The universal OTN switch is backed by a universal transport platform which is capable of switching traffic flows based on any L1-L2.5 protocol and on every port, including multiple protocols on the same port simultaneously. Hence, it can offer network operators the best of both worlds by dynamically controlling every flow on every port as a circuit or packet and providing the most efficient, future-proof solution for virtually all applications [9].

These next-generation OTN switches employ universal cards to handle TDM, OTN, carrier Ethernet (CE), and multiprotocol label switching-transport protocol (MPLS-TP) traffic and



**Figure 2.** Traditional vs. universal OTN switch.

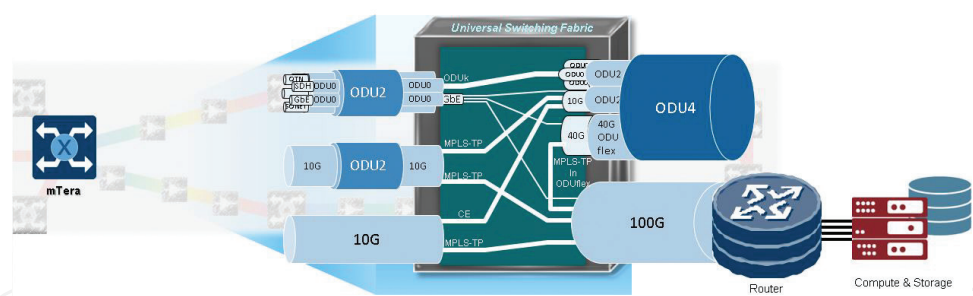


Figure 3. Universal OTN switch.

provide grooming efficiency, granularity, and service classification of a packet switch along with scalability, operational efficiency, and performance of an OTN switch, as illustrated in **Figure 3**. Furthermore, the universal OTN switch can also assist in reducing router ports by distributing services from aggregated router hand-offs with virtual local area network (VLAN) to ODU mapping, as shown in **Figure 4**.

Naturally, several other benefits, common to first-generation OTN switches, are also present and include fast end-to-end service provisioning, rapid restoration, high scalability, sub-wavelength level switching, and easy support of new/multiple traffic types. Likewise, if the service data rates are the same as the data rates of the WDM wavelength channels or when only packet traffic is present, then the universal switch might not have a CAPEX advantage over traditional OTN switch or even the conventional transponder/muxponder with OTN encapsulation.

Depending on the location in the network and the traffic matrix, switching at the packet or STS-1/VC-4 level can have efficiency benefits over switching OTN at the ODU0 (1.25G) level or above, as long as one of two conditions are met. Either there must be a significant number of client interfaces below 1G or there must be the potential for large statistical gains from

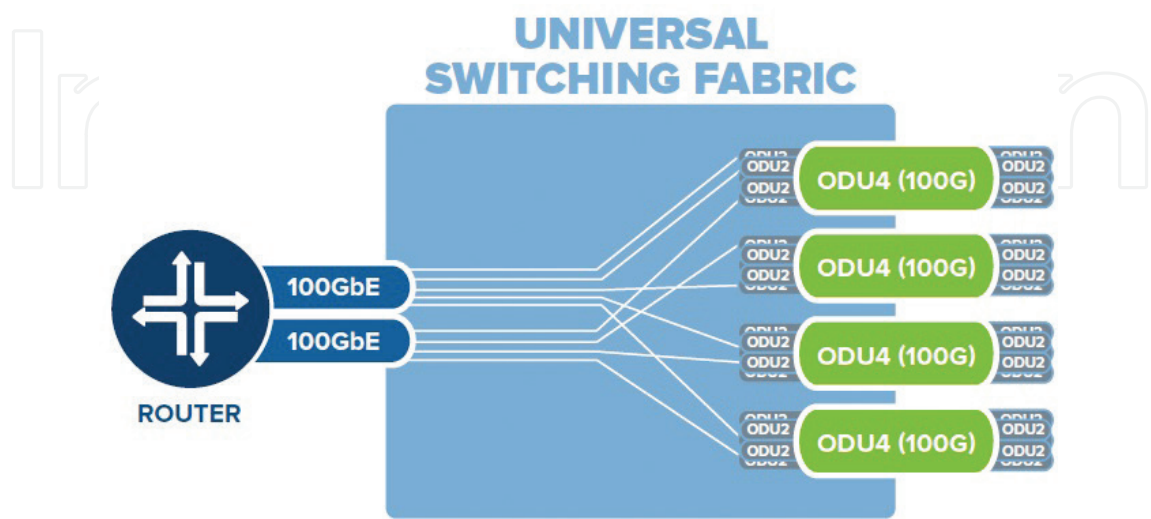


Figure 4. Universal switching fabric [1].

multiplexing uncorrelated bursty traffic flows. These conditions are more likely to occur in a metro network versus the long haul network where statistical gains have often already been achieved at the IP/MPLS layer and client interface speeds are likely to be above 1G.

Importantly, universal switching platforms enable OTN, SONET/SDH, and packet switched traffic to share the same high-speed interface, with SONET/SDH mapped to ODU2, packet traffic mapped to ODU flex, and the remaining capacity available for OTN switched traffic, thus making the most efficient use of each high-speed interface and the optical spectrum it consumes. In addition, universal switching provides investment protection against changes in traffic patterns and client types. With universal fabrics, and the ability to define in software interfaces and virtual interfaces for OTN, CE (Bridging, VLAN cross-connect), or MPLS-TP/virtual private LAN service (VPLS), and without impacting the capacity of the switch, operators can easily evolve from first-generation to universal OTN switching.

### 3. Routing and grooming framework

The planning of a transport network requires appropriate dimensioning algorithms to guarantee that all traffic demands can be successfully supported and at the expense of minimum CAPEX, therefore giving the network operator the best positioning to run a profitable business. Moreover, the multilayer nature of transport networks exploiting both OTN switches and reconfigurable optical add/drop multiplexers (ROADMs) and the additional requirements entailed by protection and restoration mechanisms have to be taken into account by the network design framework.

The multilayer routing and grooming framework developed and implemented to support the different network scenarios analyzed in the remaining of this chapter can accommodate the different constraints imposed by the specific node architectures and available line rates and consists of the following main steps:

**Step 1.** For each node pair  $sd$ , compute a set of  $K$  routing options ( $K$  shortest paths for unprotected demands,  $K$  shortest disjoint cycles for demands with protection/restoration) over the network graph  $G(V, L)$ , where  $V$  denotes the set of nodes and  $L$  denotes the set of links, and store them in set  $\Pi$ .

**Step 2.** Order all traffic demands from the same planning period according to a given criteria (e.g., largest first, longest first).

**Step 3.** For the next ordered traffic demand  $t_d$  perform the following steps:

- a. Set  $k = 1$ . Create an auxiliary graph,  $G(V', L')$ , where each network node  $v \in V$  belonging to routing solution  $\pi_k \in \Pi$  is mapped as node  $v' \in V'$  and where each existing light path overlapping with  $\pi_k$  and with available capacity to support  $t_d$  is mapped as link  $l' \in L'$ . For unconnected nodes in  $V'$ , determine the feasibility of a new overlapping light path with data rates of 100G and 200G. If feasible, map links  $l'_{100} \in L'$  and  $l'_{200} \in L'$ .

- b. Set the cost of all links in  $L'$ , such that their cost verifies  $c(l') \ll c(l_{200}') < c(l_{100}')$ , that is, reusing an existing light path is always preferred over creating new light paths and creating a new 200G light path is slightly more economic than creating a 100G light path (as to give preference to more spectral efficient 200G light paths in case of a tie).
- c. Route over the auxiliary graph to determine the least cost path/cycle and let the routing and grooming solution cost be  $c(\pi_k^*)$ . Increment  $k$ . If  $k = K$ , go to **(Step 3d)**. Otherwise, repeat the steps from **(Step 3a)**.
- d. Return the routing and grooming solution for  $t_d$ , over all  $K$  solutions, with smallest cost. If none is found, the traffic demand is blocked.

**Step 4.** If all traffic demands have been considered, end the algorithm. Otherwise, repeat from **(Step 3)** for the next traffic demand.

Importantly, the framework is ready to support flexible-rate line interfaces, namely, capable of operating at 100G (QPSK) and 200G (16-QAM), and it can easily incorporate more line rates (e.g., 150G and 300G via 8-QAM and 64-QAM modulation formats, respectively) or can be executed for a single line rate by disabling all others. Moreover, in the case of utilizing shared restoration mechanisms to recover from failure scenarios, the fact that network resources can be shared by the backup paths of ODUs/OChs whose working paths are link- or node-disjoint also needs to be modeled. In order to control the degree of resource sharing, the number of ODUs/OChs that can share the same resource is limited by a maximum resource sharing value  $S$ .

## 4. Protection/restoration in transport networks

Due to several failure issues, one of the key aspects to be considered while planning and operating telecommunication networks is resiliency. With the evolution toward 5G, everyday network operators and equipment vendors struggle to come up with innovative network resiliency mechanisms which are robust, faster, and cost-effective. Transport networks are no alien to this behavior and the resiliency schemes for the same dates back to the time when SDH/SONET-based networks were at helm. Currently, OTN is the predominant transport technology. Given the multiple layers defined within the OTN, resilience mechanisms acting at the electrical and optical domains are available, the former being enforced at the ODU layer via ODU switching network elements, whereas the latter are supported at the OCh layer through ROADMs [6].

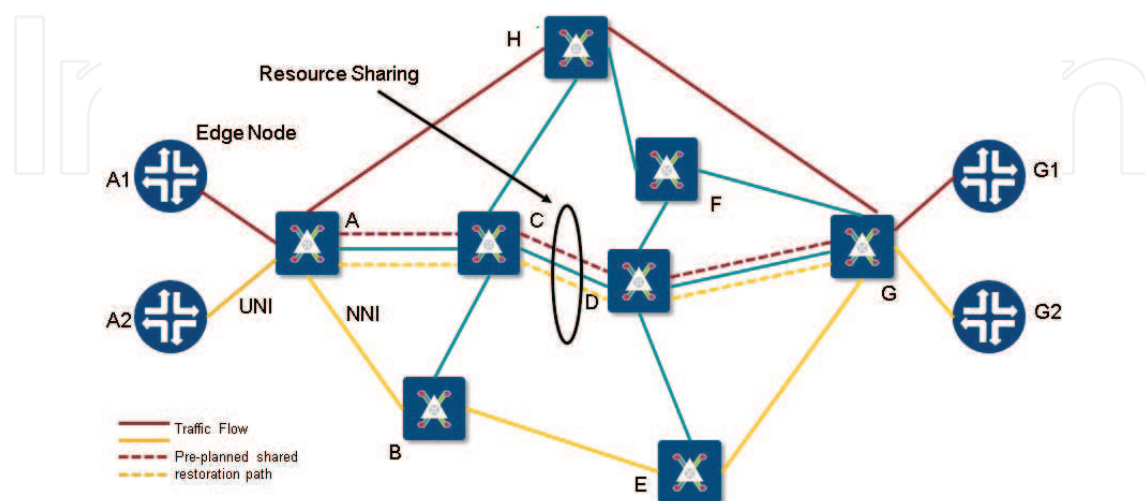
As referred, in addition to the layer at which failure survivability mechanisms are enforced, these mechanisms can be further classified as protection or restoration. Usually, protection relies on dedicated backup resources determined in advanced, reserved, and preconfigured for a particular service and which can be quickly triggered to replace the working resources. On the other hand, restoration does not require dedicated resources, i.e., backup resources can be shared, and the backup path and its resources are only assigned upon recovery from

a failure. Moreover, restoration is typically triggered by the control plane, i.e., via the generalized multiprotocol label switching (GMPLS). GMPLS-based restoration can be dynamic, designated as dynamic source rerouting (DSR) and where backup resources are determined once a failure is detected, or preplanned, named preplanned shared restoration (PSR), in which case the backup resources are known in advance of the failure. The main advantage of DSR is that it can grant (best effort) survivability against a larger number of failure scenarios, namely, when multiple failures take place. On the other hand, PSR provides faster recovery of the failed service/demand since it avoids the time required to compute the backup path and associated resources [6].

The economics and qualitative behavior of PSR in transport networks are evaluated in the following, with particular emphasis on comparing the use of such scheme at the ODU and OCh layers and identifying in which network and traffic scenario is each one of them expected to be a more suitable option for a transport network operator.

Based on the resiliency schemes and the quality-of-service (QoS) they cater to, the working and protection/restoration paths are either link disjoint or node disjoint (the latter forces the links to be disjoint though). Resources on the protection/restoration path (backup path) can be shared among multiple demands contrary to the same being dedicated to a single demand and this is enabled by the shared restoration scheme as illustrated in **Figure 5**. The sharing of resources is a novelty when compared to 1:1 dedicated protection schemes, which increase CAPEX due to a higher number of line interfaces required. Solid red and yellow highlights the working path of both the demands, respectively, while both these demands are using the same backup path. This is only possible when the working paths of both the demands are link disjoint and both the demands simultaneously stay unaffected by a single link failure and thus the same resource can be used for restoring either of the demands.

When resource sharing is enforced, savings are expected with respect to the amount of required additional resources, when compared to dedicated schemes (e.g., 1 + 1 protection), although restoration schemes usually provide slower recovery to failures. Furthermore, a



**Figure 5.** Illustration of resource sharing for shared restoration schemes.

qualitative and quantitative comparison of both schemes (ODU and OCh based restoration) can be performed, addressing key aspects such as restoration time, network element complexity, switching granularity, planning complexity, and line interface count. **Table 1** intends to summarize the qualitative comparison of both schemes.

In order to gain further insight on how PSR at the ODU and OCh level compare in terms of their resource requirements, above all in number of line interfaces, a planning case study is presented in this section. The study is realized over the 31-node backbone network covering Italy that is already used in previous studies [10] and illustrated in **Figure 6**. It is assumed that each network link supports up to 96 wavelength channels and each wavelength is operated at 100 Gb/s (i.e., carries one ODU4). A very simplified performance model is used to determine the transmission reach between regeneration sites: it consists of a maximum transmission reach of 1500 km and a reach penalty of 60 km per node traversed. With respect to the traffic pattern, 30% of the node pairs were randomly selected to exchange traffic demands. Each client traffic demand is mapped into an appropriate ODU  $k$ , with  $k = \{0, 1, 2, 3\}$ , which correspond to data rates of  $\{1.25, 2.5, 10, 40\}$  Gb/s, respectively. The traffic load offered to the network is evenly distributed over the different ODU rates, meaning that each ODU  $k$  accounts for around 25% of all offered traffic load [6]. As to understand the impact of the network traffic load on the effectiveness of both restoration schemes, the total traffic load is varied from 2 up to 20 Tb/s, with load increments of 2 Tb/s.

A comprehensive comparison requires not only to compute the resource requirements of enforcing ODU or OCh restoration for every traffic demand, but also to benchmark these results against the resources needed when the traffic demands are either unprotected or require 1 + 1 protection. The routing and grooming framework of Section 3 is used to plan the network. An upper bound on the number of demands sharing a common restoration resource is set to  $S = 10$ . Importantly, in the case of PSR at the OCh layer, the traffic is first groomed into ODU 4s and afterward the resulting ODU 4 are routed considering also the protection/restoration mechanism being enforced.

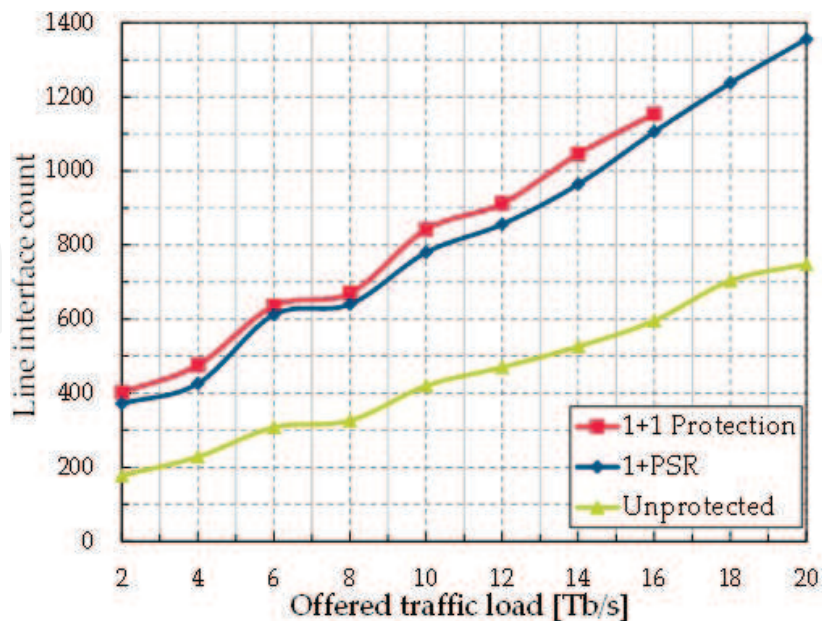
	Restoration layer	
	ODU	OCh
Restoration time	<ul style="list-style-type: none"><li>• Faster: few hundreds of milliseconds</li></ul>	<ul style="list-style-type: none"><li>• Slower: hundreds of milliseconds up to seconds</li></ul>
ROADM complexity	<ul style="list-style-type: none"><li>• Low: can use simple ROADMS</li></ul>	<ul style="list-style-type: none"><li>• High: colorless and directionless</li></ul>
ODU switching	<ul style="list-style-type: none"><li>• Mandatory</li></ul>	<ul style="list-style-type: none"><li>• Not required</li></ul>
Switching granularity	<ul style="list-style-type: none"><li>• Finer: starting from 1.25 Gb/s</li></ul>	<ul style="list-style-type: none"><li>• Coarser: e.g., 40 or 100 Gb/s</li></ul>
Planning complexity	<ul style="list-style-type: none"><li>• Multilayer: with intermediate grooming</li></ul>	<ul style="list-style-type: none"><li>• Single-layer: without intermediate grooming</li></ul>
Line IF count	<ul style="list-style-type: none"><li>• Expected to be higher</li></ul>	<ul style="list-style-type: none"><li>• Expected to be lower</li></ul>

**Table 1.** Qualitative comparison of ODU and OCh restoration.



**Figure 6.** Network topology – Telecom Italia National Backbone 31 Node network.

For both ODU and OCh protection/restoration, disjointness is applied at the link level and the number of candidate routing paths/cycles  $K$  is set to 5 working and backup paths. **Figures 7 and 8** present the line interface count and wavelength channel utilization as a function of the offered traffic load when using resilience mechanisms acting at the ODU layer. The wavelength channel utilization is defined as the fraction of wavelengths being used overall network links.



**Figure 7.** Line interface count for ODU restoration and protection.

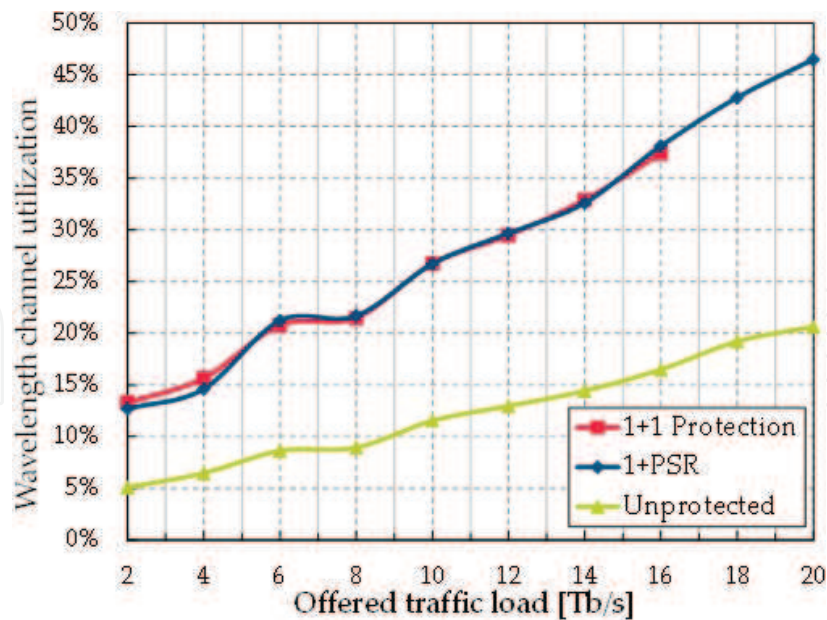


Figure 8. Wavelength channel utilization for ODU restoration and protection.

The equivalent pair of plots when supporting resilience mechanisms that operate in the OCh layer is depicted in **Figures 9** and **10**.

The main outcome of this comparison is that OCh PSR is a more cost-effective scheme than ODU PSR in a network of this size and supporting the traffic pattern defined as input [6]. In addition, it is also clear that PSR enables the network to withstand a single link failure with less resource overprovisioning than that of 1 + 1 protection.

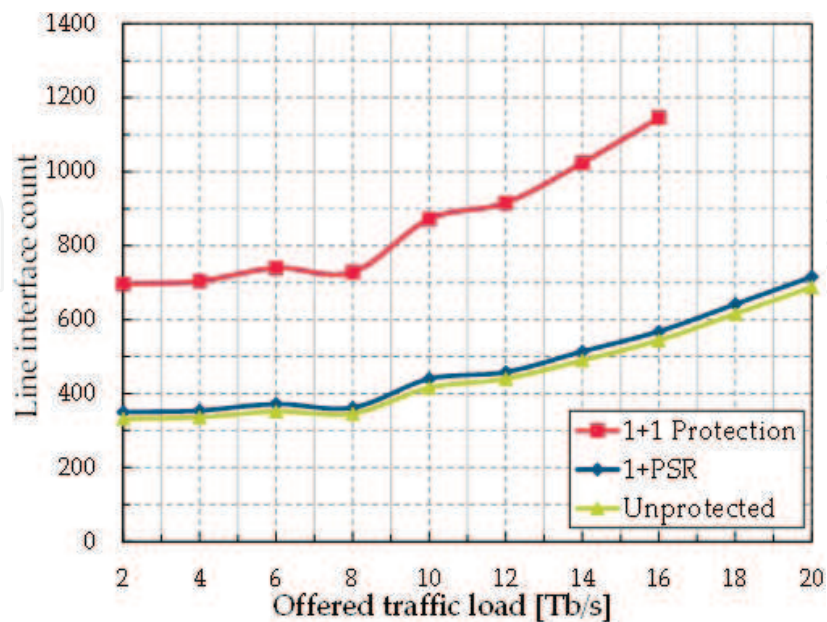


Figure 9. Line interface count for OCh restoration and protection.

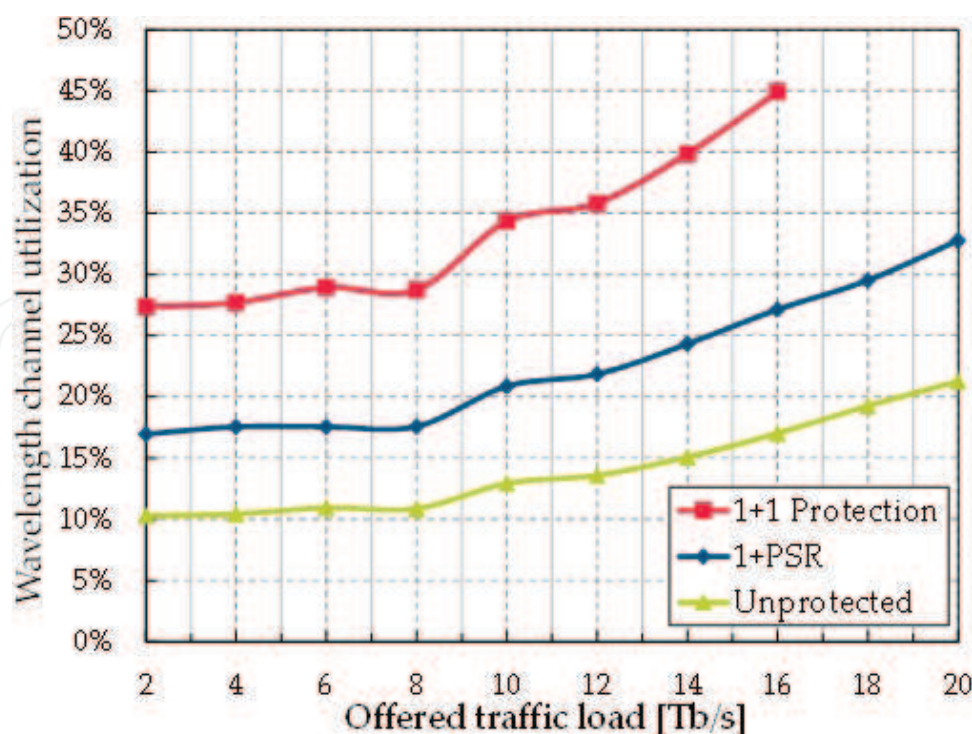


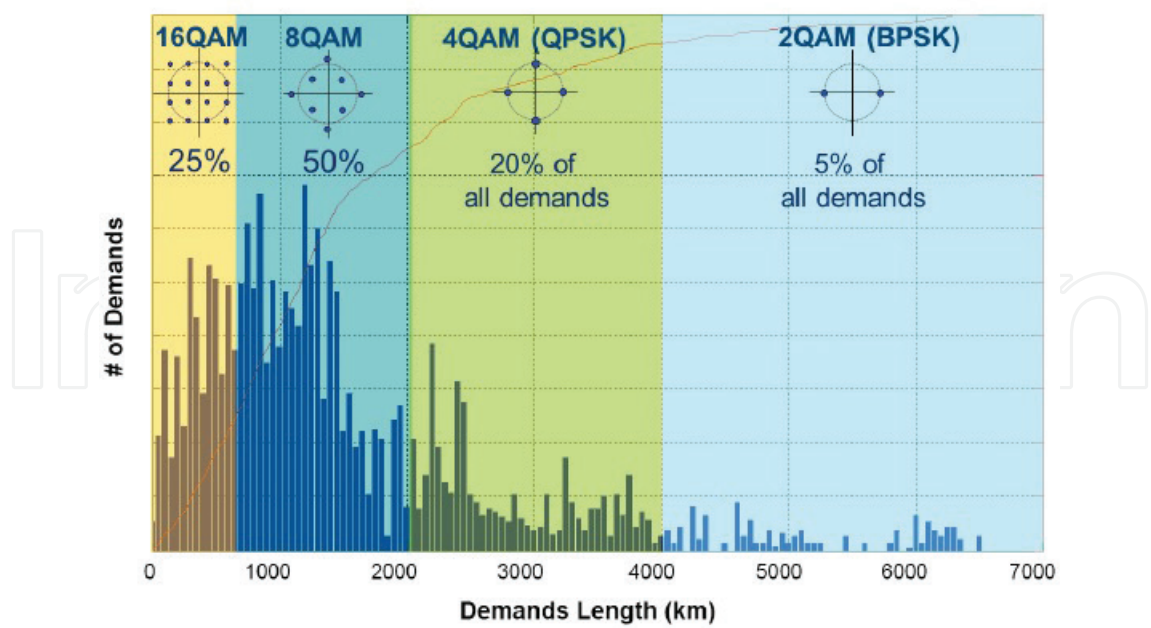
Figure 10. Wavelength channel utilization for OCh restoration and protection.

## 5. Combining universal OTN switching with flexible-rate DWDM networks

The wide deployment of 100G in core networks began with QPSK modulation format, where binary electrical signals are converted to a format with four constellation points, which is transmitted over two orthogonal polarizations. The applied coherent detection and advanced digital signal processing technologies enable detecting arbitrary multilevel schemes, which can be used to transmit more bits per time slot (e.g., 16-QAM, 64-QAM).

To cater network operators with the capability to address continuously shifting traffic patterns and increased capacity demands, flexible-rate interfaces are being introduced to deliver optimal transmission reach, performance, and agility. **Figure 11** exemplifies the demand reach distribution in a variety of long-haul and ultra-long-haul networks along with the expected cumulative distribution of the utilization of BPSK, QPSK, 8-QAM, and 16-QAM modulation formats for a fixed symbol rate providing data rates of 50, 100, 150, and 200 Gb/s, respectively.

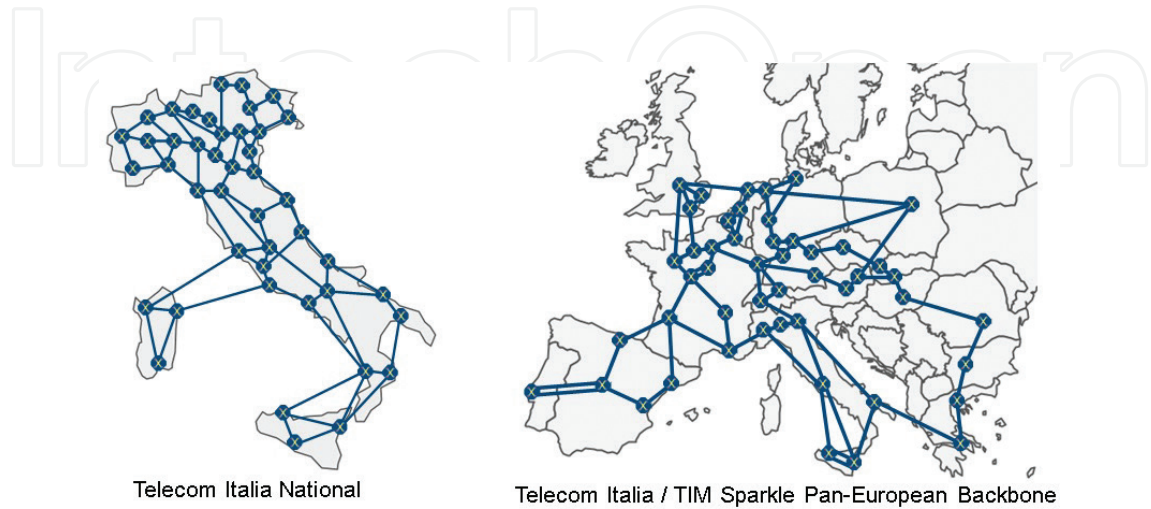
There are several benefits obtained from the flexible-rate interfaces, but to highlight a few will be cost-optimized coverage from intracity data center interconnection (DCI) to ultra-long-haul demands, single sparing blade for all modulation schemes, and restoration of higher reach modulation schemes using higher reach modulation schemes. A joint design considering flexible-rate and universal OTN switching technology can unfold crucial benefits that go beyond the separate claims of improved capacity on the line side (flexible-rate) and more efficient traffic aggregation (universal OTN switching).



**Figure 11.** Example of demand length distribution and expected cumulative distribution of the modulation format utilization in core networks with Raman amplification [11].

Recent work shows evidence that if both features are combined in an optimal way, a considerable reduction of up to 30% could be achieved in terms of the number of deployed light paths, with proportional savings in a number of line interfaces and spectrum used [12]. In the scope of this work, two long distance optical transport networks, as depicted in **Figure 12** and inspired in networks operated by Telecom Italia/TIM, were considered. One is a more recent Italian national backbone, which has 44 nodes and 71 fiber links and has already been used in other studies [13, 14].

It meets the needs of circuits at a national level, mainly for IP router interconnection and for connectivity of big clients. With its shortest paths under 2200 km and backup paths (disjoint

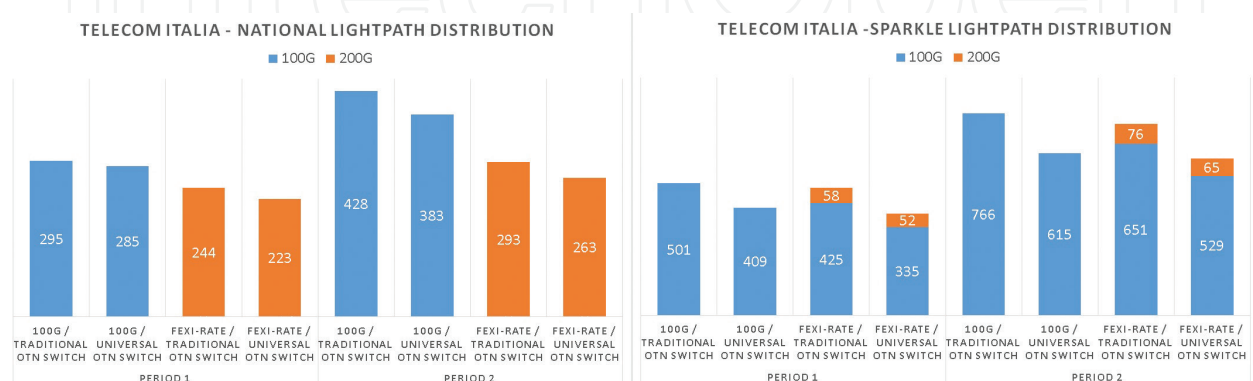


**Figure 12.** Network topologies – Telecom Italia National Backbone 49 Node network and Sparkle.

from the shortest one) under 2600 km, it is between a regional and long-haul network. The other network is TIM Sparkle Pan-European backbone [15], a geographically expanding network that currently covers Central, Southern, and Eastern Europe with 49 nodes and 72 fiber links. It classifies as an ultra-long-haul network (shortest paths under 5500 km and backup paths under 7000 km). With respect to the client rates to be serviced by the networks during their entire lifecycle, the following data rates are considered: 10G, 40G, and 100G for the Italian National Backbone and 1.25G, 2.5G, 10G for the European Backbone. Traffic comprises both Internet Packet traffic and SONET/SDH TDM traffic. Two traffic periods are considered wherein the later phase, traffic was extrapolated to be at the end of 4 years of the current period, with 25% growth for each year. Total traffic for the two periods under analysis and the partitioning of bandwidth among different client rates for the Italian national backbone and European backbone network is as described in Ref. [14]. Using the multilayer optimization algorithm described in Section 3, five routing options were calculated for each node pair ( $K = 5$ ) and the algorithm was run considering all four combinations given by traditional versus universal OTN switching and using only 100G (QPSK) line rates versus optimizing the line rate between 100G (QPSK) and 200G (16-QAM) according to the properties of the routing path [16].

The required number of light paths, which impacts the number of required expensive line interfaces as well as the amount of spectrum used, is shown in **Figure 13**.

As expected, for TIM national backbone network, the benefit of supporting higher data rates with the same line interface is more effective in reducing the number of light paths when compared to the Sparkle network, mostly because the former topology benefits from average shorter routing paths. Noticeably, universal switching always grants savings when compared to its traditional counterpart due to the packet-level aggregation and universal nature of the switch. Moreover, the combined effect of using both universal switching and flexible-rate leads to the highest savings in light path count and, consequently, the most cost-effective solution. Although not shown here due to the lack of space, savings in router port count are also achieved, which further contributes to decrease TCO when leveraging universal OTN switching and flexible-rate line interfaces. Thus, a joint network design considering both flexible-rate and universal switching technology can unfold crucial benefits that go beyond the separate claims of improved capacity on the line side (flexible-rate) and more efficient traffic aggregation (universal switching).



**Figure 13.** Number of light paths as function of the network and node architecture.

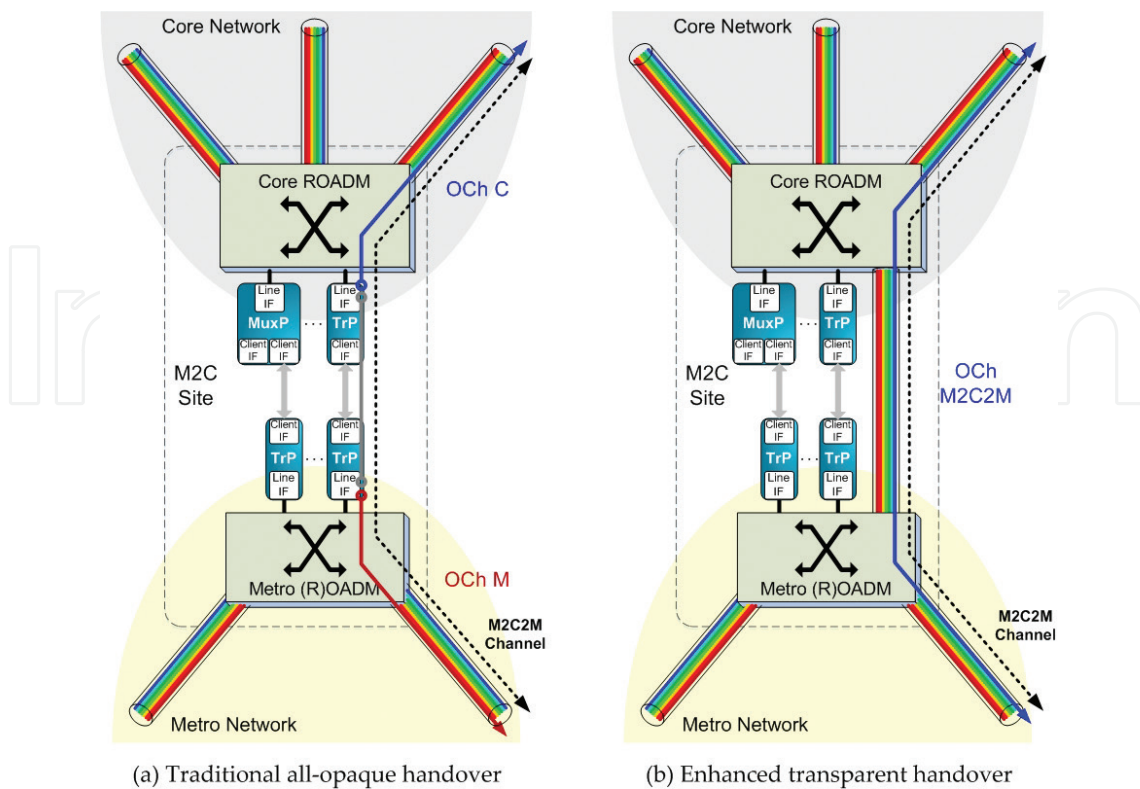
## 6. Transparent handover between metro and core segments of next-generation transport networks

Transport networks can hierarchically be broadly classified into access, metro, and core domain. End-user connectivity is catered to by the access network and a few dozen kilometers could be covered based on the specific technology requirements and the density of user population. In between, the core and the access part, lies the metro network which on one hand aggregates traffic coming from the access networks and on the other hand transports intrametro traffic (e.g., intrametro data center interconnection) and covers often up to a few hundred kilometers. Following the level of traffic aggregation, metro networks could further be segmented into metro aggregation and core. At the end, covering a bigger geographical area (e.g., state or country) is what is called the core network interconnecting the metro networks and typically spans over several hundreds to thousands of kilometers.

In the metro transport networks, the predominant technology and topology are in the form of SDH/SONET rings. But while these SDH/SONET rings had intrinsic scalability limitations, there was always an increasing need for capacity. And this gave rise to the introduction of coarse wavelength division multiplexing (CWDM) and DWDM in these networks catering to wavelength switching support at intermediate nodes thus reducing optical-electrical-optical (OEO) conversions which was initially a cost burden to the operator. In present days, the metro network is mostly infested with 2.5G or 10G wavelengths using direct-detection modulation formats and as always the increasing demand of data will be catered to using higher data rate channels (e.g., 40G and 100G) in the coming days. Compared to these, core network has a different behavior and is severely dependent on DWDM and ROADMs exhibiting asymmetrical meshed topology. The wavelength channels have a good share of 10G, 40G, and 100G. Moreover, QPSK is now the dominant modulation format for the higher data rates of 40G and 100G with coherent-detection replacing direct-detection. The utilization of higher-order modulation formats, such as 16-QAM, enables to increase channel capacity. But, the poor reach performance of these higher modulation formats penalizes a widespread deployment of the same. To mitigate this negative effect, adoption of super channels is being looked upon as an alternative to core networks where multiple carriers are grouped together to realize these higher bit-rates (e.g.,  $2 \times 100\text{G}$  QPSK to create a 200G super channel on a 100GHz spectrum) [17]. Another important aspect to look upon is the optical add-drop multiplexers (OADMs) being used in core and metro networks. Metro networks are comparatively simpler with lesser nodal degrees and thus simpler OADMs of the likes of broadcast-and-select or fixed add/drop ROADMs or to the extent of nonreconfigurable fixed OADMs (ROADMs) are in use today. On the other hand, core networks use much higher capacity and also wavelength channels and thus require expensive OADMs.

The traffic flow between the above described metro and core network at the boundary node is depicted in **Figure 14** and the same is represented by metro-to-core (M2C) in the next part of this chapter.

To be more detailed, let us presume one data channel running from one metro network to another metro network via a core network and is designated as metro-to-core-to-metro



**Figure 14.** Architectures for interconnecting metro and core networks (TrP – transponder, MuxP – muxponder). (a) Traditional all-opaque handover; (b) enhanced transparent handover.

(M2C2M) channel. The current mode of operation forces this M2C2M channel to ride on an optical channel in the metro domain (OCh M) till the metro (R)OADMs. At this (R)OADM node, the same OCh M gets terminated at a line interface only to be transferred to a transponder or muxponder which maps the same into the optical channel (OChC) ferrying inside the core network. At the boundary node in between the core and metro node, a similar process makes sure that the channel is handed over from the core to the metro network. It is to be noted that, these handover sites could be a single site at the same physical location (housing the (R)OADMs) or could be physically separated sites within a comparatively shorter distance hosting each (R)OADM looking toward the core and metro network.

This architecture represents an all-opaque architecture depicting a clear enough demarcation between the metro and core network segments where the hardware (client interfaces) performs the handover. As it already undertakes the OEO operation, these sites are used for grooming substrate data signals into higher data-rate pipes/channels. For example, the M2C2M channel with a data rate of 2.5G can be multiplexed/groomed into 10G and 100G OCh M and OCh C, respectively. Therefore, the M2C2M channel can be multiplexed/groomed in OCh M along with other substrate data channels of equal or smaller capacity starting at the same node and destined to another metro network, while in the core network the M2C2M channel can be multiplexed/groomed with other data channels that start and end in the same metro networks pair. This process directly influences the fill ratio of the core network light paths and thus contributing to the reduction of CAPEX as a result of lesser number of expensive line interfaces and

also the network occupied bandwidth. It is noteworthy that the bandwidth usage in the core network is much more a valuable asset when compared to its metro counterpart due to longer fiber links, higher number of amplifiers, and advanced, larger ROADMs.

In this approach, the M2C2M channel crosses one line interface pair in the first metro network where they originate and client interface pair in the first M2C site, line interface pair in the following core network, client interface pair in the second M2C site, and finally a line interface pair in the terminating metro network, thus spending in total 6 and 4 line and client interfaces, respectively. But still these are being shared with other smaller data rate M2C2M channels. But this is not the entire scenario because soon we start encountering higher data rate M2C2M channels (e.g., 10G or even higher) which cannot be multiplexed/groomed into the already existing OCh C due to nonterminating OChs in the same metro networks or capacity non-availability in the existing channels. Such use-cases foresee savings by the transparent handling of M2C2M channel between metro and core networks, which is possible if an additional fiber link exists in the M2C site in between the (R)ROADMs and this higher data rate M2C2M channel is mapped on it. This transparent M2C interconnection can only be deployed by augmenting nodal degree of each (R)ROADMs and additional booster/pre-amplifier deployment for each direction while employing one extra port of splitter/combiner and wavelength selective switches (WSSs) [18, 19]. Adding an optical switch between add/drop ports subset and using them directly for the optical bypass will be a good alternative [20].

In order to gain insight on expected design, implementation, and operational differences between a metro core network with traditional all-opaque M2C handover versus the same network with enhanced transparent handover, a subset of these differences is highlighted in **Table 2**, to highlight the different aspects to be assessed with care before opting for either of

	All-opaque M2C handover	Enhanced transparent M2C handover
Interface requirements	<ul style="list-style-type: none"><li>• Separate (local) optimization of line IFs required in the metro and core networks</li><li>• Intensive usage of client IFs at M2C sites</li></ul>	<ul style="list-style-type: none"><li>• Joint (global) optimization of line IFs used at metro and core networks</li><li>• Savings in client IF count at M2C sites</li></ul>
(R)ROADMs at M2C sites	<ul style="list-style-type: none"><li>• All traffic handover done via the add/drop ports of both (R)ROADMs</li></ul>	<ul style="list-style-type: none"><li>• Both (R)ROADMs have to be augmented with one additional degree</li></ul>
Spectral efficiency	<ul style="list-style-type: none"><li>• Independent channel format selection at the metro and core networks</li><li>• Best suited (cost-wise, performance-wise) format can be selected in each network: e.g., direct-detect 10 Gb/s in metro, more spectral efficient but expensive 100 Gb/s in core</li></ul>	<ul style="list-style-type: none"><li>• Format used in OCh M2C2M impacts spectral efficiency of both networks</li><li>• Additional spectral inefficiencies associated to coexistence of direct detect and coherent formats in the core network: extra spacing between neighboring channels [20]</li></ul>
Planning complexity	<ul style="list-style-type: none"><li>• Lower: due to sequential planning of metro networks first and core network afterward</li></ul>	<ul style="list-style-type: none"><li>• Higher: requires integrated planning of metro and core networks</li></ul>

Resource provisioning	<ul style="list-style-type: none"><li>• Separate provisioning of resources at each network segment</li><li>• Easy support for deploying different vendors hardware (e.g., line interfaces, common equipment) and software (e.g., network management systems) in the metro and core networks</li></ul>	<ul style="list-style-type: none"><li>• Requires end-to-end provisioning of the OCh M2C2M</li><li>• Complex support for deploying different vendors equipment: interworking between optical and network management systems, limited interoperability between control plane instances, use of alien wavelength concept, shortening transparent reach</li></ul>
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**Table 2.** Qualitative comparison of all-opaque metro-to-core handover with enhanced transparent handover.

these strategies for a M2C traffic handover. Further, the analysis targets to capture technology landscape influenced differences in today’s metro and core networks [21].

7. Conclusions

The overriding purpose of this chapter is to depict the relative importance of the universal OTN switch and flexible-rate line interfaces in the context of different network scenarios and traffic conditions. To accomplish the same, results from different network studies were presented. It is evident that, when the traffic pattern involves multiple substrates coming from varied data sources (TDM, Packet), universal OTN switch yields the maximum savings from CAPEX point of view. This is contributed by the reduced number of light paths and router port savings. Needless to mention here that, the more is the mismatch between the client traffic rates and the line-side rate(s), more savings could be achieved by exploiting a multilayer optimization approach. Furthermore, exploiting the higher capacity light paths enabled by flexible-rate line interfaces and combining the same with universal OTN switching, the better of both worlds can be achieved. But it is important to mention that flexible-rate line interfaces supporting 16-QAM, for example, will be less important when the network links are very long due to the limited transparent reach with this modulation format. On the other hand, the role of these state-of-the-art node architectures in the context of protection and restoration was also visited and different alternatives were presented. It could be inferred that OCh restoration would be preferable from a CAPEX point of view, with lesser resources being required, while opting for a better QoS (e.g., in terms of recovery time), ODU restoration can be a better choice. At the end, this chapter overviews the present day metro-to-core network scenario which enforces all-opaque traffic engineering and also prospects the economic and technological feasibility of transparent handovers. Recent technological developments, for example, metro core spectral efficiency gap narrowing, alien wavelength/black link standardization aided by state-of-the-art multivendor and multilayer resource provisioning platforms will overcome the hurdles of transparent handovers, and thus exploiting the big saving potentials in terms of interfaces at these boundary nodes.

## Author details

Bodhisattwa Gangopadhyay<sup>1\*</sup>, João Pedro<sup>1,2</sup> and Stefan Spälter<sup>3</sup>

\*Address all correspondence to: bodhisattwa.gangopadhyay@coriant.com

1 Coriant Portugal, Amadora, Portugal

2 Instituto de Telecomunicações, Lisboa, Portugal

3 Coriant GmbH, Munich, Germany

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