An Operator's view on introduction of White Boxes in Optical Networks

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Abstract—Hardware and software disaggregation is a recognized strategy for achieving efficiency and cost reduction within datacentre warehouse. More recently this approach has been applied to high-bandwidth inter-datacentre connectivity at transport layer. Telecom Operators look with great interest at this approach which promises savings that could make the difference in years of ever decreasing margins on revenues. This paper presents and analyses the disaggregation models in the WDM transport layer to replace the established aggregated model based on single vendor systems. Three optical disaggregation models are considered implying different levels of involvement of the Telecom Operator in WDM system design, assembly and integration. The impact on network lifecycle of each model is then analysed with particular reference to the roles of the Operator, the equipment Vendors and the System Integrator. The issue of organizational changes and heavy redefinition of processes is addressed and a comparative techno economic analysis is also proposed.

Index Terms— Partially disaggregated network, Optical white boxes, Software Defined Networking, Open Line System, Optical Transport.

I. INTRODUCTION AND CONTEXT

Over the last decade western hyperscale operators (Facebook, Amazon, Microsoft, Google and Apple) have consolidated their storage, computation and networking assets within warehouse scale datacentres [1] across their global estate to exploit the economies of scale occasioned by the confluence of several trends most notably: the continued influence of Moore's Law to underpin increases in the density of logic cells in semiconductor hardware elements (CPUs, memory, switching ASICs, etc.); the disaggregation of the operating system software that controls and manages the storage, compute and networking elements; and the emergence of open Application Programming Interfaces (OpenAPIs) that abstract the complexity of the underlying hardware.

They have displayed a relentless focus on reducing capital and operation expenditure (CapEx and OpEx) by sourcing directly, and in sizeable volumes, from original design

manufacturers (ODM) of hardware (HW); and selectively exploited and adapted free and open source software (SW). The most prominent activity is Facebooks Open Compute Project (OCP) in 2009 [2]. Some hyperscale operators have adopted the 'bare metal' model - where the ODMs physical HW is sourced separately from the SW operating system (open or commercial). This presumes some in-house competence, or external expertise, for HW-SW integration and ongoing lifecycle support. Other hyperscale operators prefer a 'white box' approach where the ODM pre-installs an operating system of choice and provides some level of support.

The 'hyperscalers' have now started to extend these models to support high-bandwidth interconnectivity between their datacentres including the transmission and switching of optical frequencies. The most notable initiative is Facebooks Telecom Infrastructure Project (TIP) that commenced in 2016 [3].

Telecommunications operators (TELCOs) appreciate these trends and now seek to adapt them to fit both their own datacentre estate and their decentralised physical infrastructure. The latter spans across both fixed/ wireless access networks through metro aggregation to national and international core networks. One notable initiative from AT&T - central office re-architected as a datacenter (CORD) - envisions an overlay of higher-layer Virtual Network Functions (VNFs), as modular microservice applications within containers hosted atop virtualised compute servers within their central offices/ telephone exchanges [4]. Underpinning this is a white box, packet-switched HW fabric forming part of an access network underlay. Attention is now turning to understand how white box optical HW might be utilised in TELCO's networks to address their business ambitions, mainly the ability to cope with the margin squeeze; the ability to diagnose and pre-empt service disruption; the prospect of being able to turn-up tailored services to customers in an automated manner. This might also introduce opportunities for customers to self-provision their requirements directly via a network service API.

But the execution of these ambitions is not straightforward. TELCOs have traditionally maintained close relationships with vertically integrated network equipment vendors who provide support during the lifecycle of their product. This begins with the initial tendering of equipment to match a TELCOs requirements; the ongoing maintenance and upgrade support during the operational life of the equipment; and culminates in eventual decommissioning at the end of life. This is the traditional vertically-integrated vendor black box model where both the HW and SW are closely aggregated; the

oversight of HW components is also assumed by the vendor. The vertically-integrated vendors actually source most of their branded HW from ODMs and are now starting to offer branded white box HW - often termed 'brite boxes'. Brite boxes, like white boxes, disaggregate the operating system and application software from the hardware. They come pre-installed with a third-party operating system of the operators choice with provision for a tailored level of lifecycle support from the vertically integrated vendor.

The four models: bare metal; white box; brite box and black box are schematically depicted in Fig. 1 together with the graded 'spectrum' of lifecycle support that a TELCO must sustain. The bare metal and white box models requires the most commitment from the TELCO and pre-suppose some in-house resource and lifecycle commitment. This may prove challenging to some operators in the near-term as the software engineering talent and skills, in particular, are a scarce resource. Notwithstanding, some TELCOs are already introducing these new paradigms especially to address L2/L3 applications and services, facing the skills issue with initiatives to reskill their workforce [5]; others are working closely with systems integrators (SI) to the same ends.

The extension of these lifecycle models to include also the WDM transport layer is an exciting new possibility recently gaining momentum and interest among TELCOs [6], with an open and lively debate between supporters and sceptical [7].

In fact traditional system vendors are adding SDN management solutions to their WDM transport network portfolio, to abstract and expose resources at a North Bound Interface (NBI) enabling enhanced network programmability and flexibility. But, often, these solutions are still dedicated to mono-vendor optical domains and thus imply a black box lifecycle approach: direct access to the control and monitoring of single Optical Network Elements (O-NE) is precluded and is fully mediated by the system vendor SW. These solutions are certainly suitable for large optical transport networks due to the complexity of managing physical layer impairments in a vendor agnostic way; but vendor 'lock-in' is still present.

On the other hand, especially targeting the metropolitan or regional network segments, where distance between nodes is reduced, and degradation effects due to fibre transmission are more manageable (the algorithms to recover transmission impairments are potentially less sophisticated, and can be more easily implemented at the SDN control level), a new ecosystem of optical white/brite boxes is quickly arising triggered by initiatives like OpenROADM, OpenConfig, OOPT [8][9][10] and the introduction to the market of new
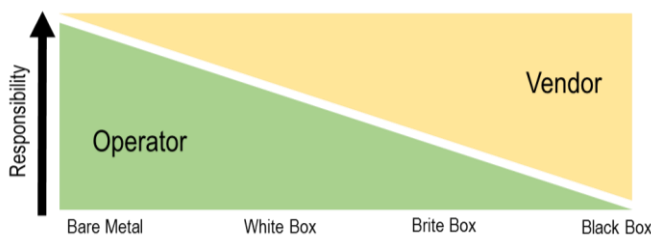

Fig. 1. Schematic graphical representation of relative level of responsibility in network equipment lifecycle of TELCO and equipment vendors for different operational models.

disaggregated equipment from some WDM equipment vendors (e.g. among others [11][12][13]).

This is paving the way for the ability to 'disaggregate' individual optical domains, enabling also the use of HW from different vendors interchangeably, opening new opportunities for equipment vendors traditionally less strongly focused on transport including new actors: pure white boxes on blades vendors, control and management SW developers, integrators.

Opportunities exists also for TELCOs in the form of claimed cost reduction, vendor lock-in elimination and expected enhanced flexibility and modularity, but it is still to be fully demonstrated and may depend on the specific use case considered.

This paper is organized as follows: in section II we introduce the concept of optical disaggregation from the perspective of a TELCO: the focus is on the metro-regional network segment. Section III gives a brief overview of the most relevant HW, and SW, specifications, and automation tools supporting or needed for the introduction of full or partial disaggregation in the optical domain. Section IV discusses the process of designing, developing and testing of WDM transmission systems, a TELCO have to face if undertaking a disaggregation approach in the optical network. Section V analyses the impact of optical disaggregation in the processes of network creation and operations. Section VI complements the discussion with a techno-economic comparison of full optical disaggregation and the traditional black box approach. Section VII concludes the paper.

II. DISAGGREGATION IN THE OPTICAL DOMAIN

The term 'disaggregation' in the context of WDM transport network is often used to collectively designate all the operational models in which TELCOs are actively involved in the design, assembly, testing and lifecycle management of the WDM transport Systems (WDM-Sys) deployed in their networks (spanning across all the operational models of Fig. 1 bar the Black Box). This involvement is conceivable mainly for the metro regional networks, as already discussed in the introduction, and only if a mature ecosystem of O-NEs, optical subsystem blades, control, management, design and planning software exists, together with standards or multi source agreements (MSA) for multi-vendor vertical (between O-NEs and management and control SW) and horizontal (among O-NEs) compatibility.

For a metro/regional WDM-Sys, the relevant O-NEs are pieces of equipment housing homogenous network functions, possibly made by several shelves or blades, but seen by management and control systems as a single management entity through a suitable OpenAPI, often termed South Bound Interface (SBI).

With reference to Fig. 2, O-NEs can be broadly classified into the following categories:

• Client to WDM adapter (TP): including the network functions of Transponders (1-1 mapping of clients to line side interfaces); Muxponders (N-1 mapping and multiplexing); Switchponders (N-M mapping, switching and multiplexing).

Within this paper we will designate this type of O-NE simply as 'Transponder' (TP).

• M-ROADM: Multi-degree Reconfigurable Optical Multiplexer, including Add&Drop, switching, amplification and equalization optical functions. In some implementations the node is assembled from several separate modular subsystem blades, one for each line degree or Add&Drop chain.

• Line Terminal (LT): a single line side optical multiplexer often fitted with colourless functionalities. Often several LT blades may by interconnected to form a M-ROADM.

• In Line Amplifiers (ILA): inserted in a long transmission line between LTs or M-ROADMs to recover optical attenuation.

A suitable interconnection of these O-NEs with the addition of a WDM transport controller/management SW makes a complete WDM-Sys (fig. 2): TPs constitute the 'Digital to WDM adaption layer' (DtoWDM), being in charge of the adaption of digital client signals to analogical 'media channels'; while M-ROADMs, ILAs and LTs constitutes the actual 'WDM Analog transport layer' (A-WDM).

Disaggregation implies that TELCOs are, directly or indirectly (through SIs), involved in the process of design, assembly, integration and testing of a whole WDM-Sys starting from a Control SW together with already assembled DtoWDM and A-WDM layers; or from all or some O-NE category as elemental bricks; or even from subsystem blades on bare metal HW.

Several degrees of TELCO involvement could therefore be envisioned as discussed more deeply in next paragraphs.

A. Fully Aggregated Optical Domains

This is the current evolution of mono-vendor WDM-Sys, with the introduction of an open NBI for control and managing the whole network island in a more flexible way (Fig. 2). The optical system lifecycle management is responsibility of the system vendor in the pure black box approach. System vendor provides both a proprietary WDM transport controller and all the O-NEs. SBI to O-NEs may run proprietary protocols with tailored equalization algorithms. Typically these networks support digital transport services (e.g. Ethernet or OTN from client side ports of TPs): mapping of digital clients and activation of network media channels is under the control of the proprietary domain. NBI translates sufficient information of the underlaying optical network in a
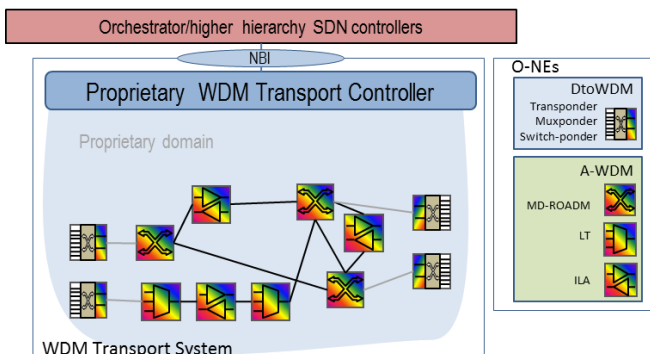

Fig. 2. Fully aggregated WDM transport System: Controller and O-NEs are form the same vendor. A black box lifecycle model is implied. Only the NBI need to be specified/standardized. The inset classifies O-NEs (see text).
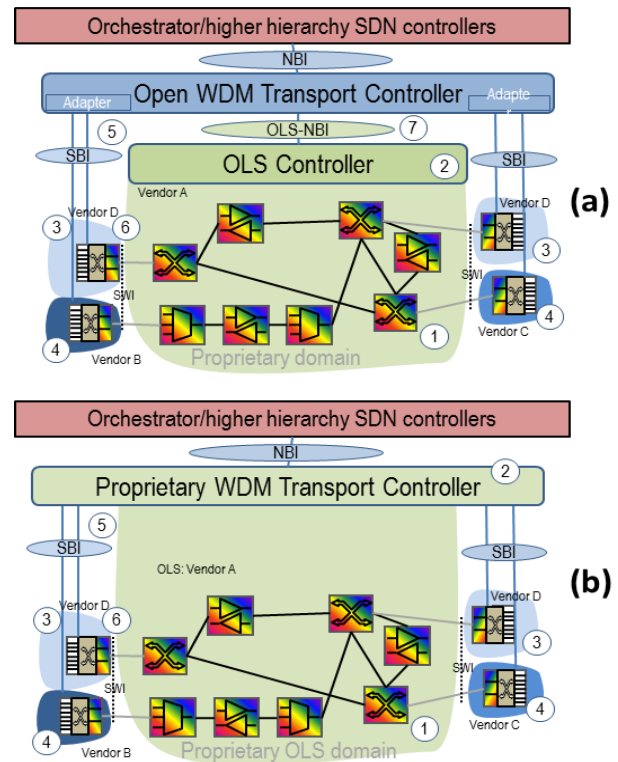

Fig. 3. A) An Open Line System as part of a partial disaggregated WDM transport system: OLS and controller are from a single vendor (1-2); TPs may be in pair form the same supplier (3) or mixed (4); the WDM Transport Controller interfaces directly with TPs (5) and through a NBI (7) to the OLS. Single Wavelength Interface (SWI) need to be standardized (6);

B) Alternative partial disaggregated WDM transport system: OLS and WDM controller are proprietary from a single vendor (1-2); TPs may be in pair form the same supplier (3) or mixed (4); the proprietary WDM Transport Controller interfaces directly with TPs with standard SBI (5). Single Wavelength Interface (SWI) (6) and SBI (5) need to be standardized.

simplified abstract model to be used by higher order controllers or orchestrators. Only this NBI needs to be standardized.

B. Partial Disaggregation: Open Line System and Multi-Vendor Transponders

In this approach (Fig. 3A and B), the disaggregation applies to the DtoWDM layer (i.e. to TPs) whose lifecycle is decoupled from that of a mono-vendor and proprietary A-WDM layer. The A-WDM layer remains a proprietary black
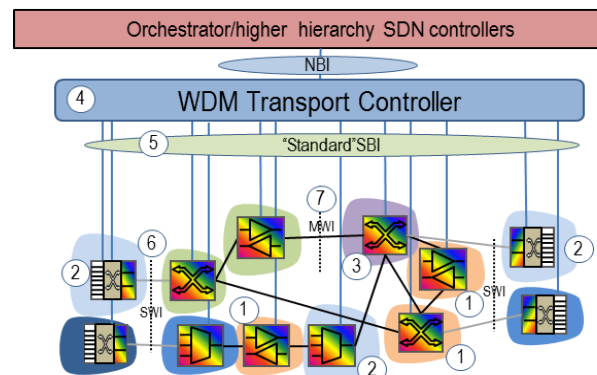

Fig. 4. Fully disaggregated WDM transport system: O-NEs can be from the same (1-2) or from different suppliers. No separation between DtoWDM and A-WDM layers exist. A standard SBI (5) is needed to simplify the direct control of the whole WDM-Sys by the controller (4). Both Single Wavelength (6) and Multi Wavelength Interfaces (7) need standardization.

box analogue transport system (boxes 1-2 in Fig. 3) supporting Optical Channels from external TPs as client signals. Thus, to this Open Line System (OLS) applies all the considerations made in the previous paragraph; the term 'Open' refers to the fact that it is open to be used by any signal which follows a given behaviour, specified by the Single Wavelength Interfaces (SWI). An OLS-NBI API (6 in Fig. 3A) is needed to configure and report events from the OLS. The standardization of this OLS-NBI is of great help in the process of vertical integration with the Open WDM Transport Controller of the whole WDM-Sys.

The rationale behind this approach is that the operational life of an A-WDM is much longer than that of TSs, the latters useful life governed by the continuous increase in capacity needed, requiring a very strong pace of innovation and therefore obsolescence. Furthermore, leaving the analogue domain (including M-ROADMs, LTs and ILAs) under the responsibility of a single vendor means leaving the development, testing and management of complex control, equalization loops and analogue heurestics solely the responsibility of the vendor. Also horizontal interoperability issues among analog O-NEs, again implying analog optical design (including linear and non-linear transmission impairment control), are left to the system vendor responsibility.

Furthermore the multi-vendor environment in the DtoWDM layer leaves to TELCO the freedom to choose the best supplier for each specific application favouring form time to time performance, cost or other metrics.

Transponders or pluggable modules on L2 switches are more easily integrated and controlled directly by a WDM transport controller, even without a SBI standard (dedicated drivers/adapters for SDN controller, may be developed by the transponder vendor itself).

However with a standard SBI it is possible for the OLS Controller itself to take charge of TPs, thus assuming the role of the controller of the whole system, and eliminating the need for a OLS-NBI and strongly simplifying the integration process and network operations (Fig. 3 B).

A standard for interoperability among different vendor TPs is not strictly needed (TPs might be matched pairs from the same vendor), but is welcomed to relax, as much as possible constrains in the purchasing process and simplify the process of horizontal integration. However TP interoperability, may limit the transmission performance and hamper the introduction of innovations in the TP. On the contrary a standard at the Single Wavelength Interfaces (SWI) is mandatory and suitable monitoring and equalization functions should be added at the interconnection points to clearly separate the DtoWDM and A-WDM domains, ensuring stable operation and easy troubleshooting.

Concerning the DtoWDM layer, all lifecycle disaggregation models may be applied including the brite box one, for example in the integration of matched pairs of TPs with proprietary features (TP supplier involvement in the integration process may include the development of the needed SDN driver/adapters and some dedicated application

SW). The small involvement of the TELCO in the lifecycle of the OLS itself is conceivable, for example in the form of a process of joint customization with the vendor of some specific features of the system (a weak form of brite box).

C. Full Disaggregation: Multi-Vendor Optical Network elements

In this approach (Fig. 4) the involvement of the TELCO in the WDM-Sys lifecycle is strong, certainly not limited to vertical integration of control and management SW. Actually O-NEs from both the A-WDM and DtoWDM layers are potentially purchased from different vendors, leaving interworking at the control and data plane to the system integrator. Therefore most of the control intelligence is moved to the WDM controller (necessarily vendor agnostic) which becomes the most critical element of the whole chain, having to face also all the analogue transmission issues (equalization, transient suppression, etc.).

Furthermore detailed specification for both SWI and Multi Wavelength Interface (MWI) is needed to support horizontal integration; likewise a standardization of the SBI is paramount.

Planning and design of such a multi-vendor network requires specialized technical skills that often only vendors have. Alternatively vendor agnostic automatic planning and design tools could be employed if they were available to the market (an initiative in TIP is ongoing [14]), and sufficiently comprehensive to be used by a skilled user and not necessarily an optical design expert. A TELCO could profitably utilise them to automatically provide bill of material, equipment configuration and interconnection schemes for a multi-vendor disaggregated environment.

D. Full disaggregation : Multi-vendor Optical subsystems

This extreme case addresses the situation, albeit hypothetical, of an ecosystem of exclusively optical, low level functional subsystems (EDFA, WSS, Attenuator, etc…), on separate compatible standardized blades (with control and management interfaces, power supply, cooling etc.) for rack mounting (Fig. 5); O-NEs like M-ROADM are an assembly of several of these subsystem blades, possibly from different HW suppliers. Potentially each subsystem could be directly
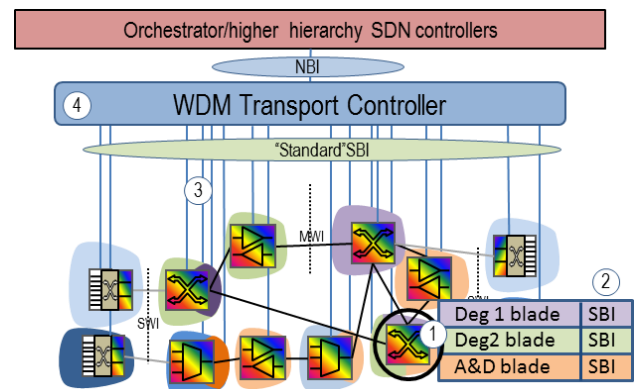

Fig. 5. Full disaggregation: Multi-vendor optical subsystems assembled in O-NEs. (1) shows a M-ROADM assembled from three subsystem blades from different vendors; each blade has its own SBI (2) implying multiple parallel control communication sections (3) with the network controller (4).

controlled and managed by the WDM transport controller of the whole WDM-Sys, but this would be at the expense of more complexity in the controller, due to the lower level of abstraction, and a greater number of concurrent communication sessions.

If a single control and management SBI to the network controller is desired at the O-NEs level (e.g. only one for each M-ROADM), several subsystem blades should be 'virtually assembled' and connected to a local NE controller (e.g. a separate blade) which will implement an adaptation and control software for the whole 'virtual' O-NE. The result is a simplification of the network controller with the introduction and a hierarchy of controllers and more complexity and SW in the O-NE.

A more realistic scenario is a hybrid approach, with multi-vendor optical subsystem disaggregation limited to M-ROADM (Fig. 5); other O-NEs are still multi-vendor, but not disaggregated at the subsystem level. This is motivated by the appearance on the market of the so called ROADMs on a blade (line degrees and Add&Drop complete subsystems on separate blades) (e.g. [11][12][13]). It seems a reasonable compromise enabling a multi-vendor approach inside a M-ROADM, but standardization of several low level physical, optical and management/control interfaces remains an issue to be solved; furthermore the implications that the bare metal or white box approach is critical for a TELCO, CapEx and OpEx advantages in particular, compared to other form of disaggregation is not proven and currently difficult to quantify.

III. TOWARD AN OPEN DISAGGREGATED OPTICAL ECOSYSTEM

Three of the four disaggregation alternatives outlined in Section II are disruptive to the status quo of the mono-vendors that support Fully Aggregated Optical Domain. The vertically integrated 'Tier 1' optical mono-vendors distinguish themselves by apportioning appreciable investment and resource to the in-house design and development of proprietary hardware components i.e. ASICs, photonic integrated circuits etc. that are at the cutting-edge of performance. Of course, when appropriate, this may be complemented by commodity, off-the-shelf components too. Access to the API of the proprietary hardware components is tightly controlled by the 'Tier 1' mono-vendor via a closed element management systems (EMS) and network management system (NMS). Considerable resource and effort is dedicated to development, integration, procurement, standardization, customer engagement and lifecycle support of their integrated product portfolio.

In contrast, vertically integrated 'Tier 2' optical mono-vendors have smaller market share and so are more dependent on commodity, off-the-shelf hardware components which they control by a similarly closed EMS. This can explain their

interest and direct involvement in initiatives supporting a disaggregated optical ecosystem and the introduction by them of disaggregated pieces of equipment.

Disaggregation is contingent on the availability of open APIs that are, in turn, dependent on the development of open YANG service and data models [15] for managing optical and packet network services. There are two levels of management granularity or scope to consider: a) coarse-grained Network-wide services, where the O-NEs are considered as nodes that are interconnected by links; and b) fine-grained O-NE devices proper. A Layer 0 service path is a directed graph formed from a subset of nodes and links subject to network resource constraints and service demands. An inventory of discovered nodes and links; and the associated resources and constraints is stored in a traffic engineering database (TED). The analogue nature of impairments particular to optical propagation with path length i.e. attenuation, dispersion, non-linearities, amplifier and receiver noise are additional constraints unique to Layer 0 because all-optical 3R regeneration is lacking. In the case of multi-hop or mesh optical networks the lack of wavelength conversion adds an additional constraint to maintain non-blocking end-to-end wavelength continuity. Optimisation is performed by a dedicated path computation element (PCE).

Open specifications and abstractions for the management and control layers of end-to-end network services and individual O-NE devices via the NBI and SBI, respectively of the WDM Network Controller are progressing. At the heart of these endeavours are the definition and development of service data models and device data models. Preferably these are open, vendor-independent, and specified in a modelling language such as YANG [15]. For SBI application, in the context of optical systems, the protocol of election is NETCONF [16] A very useful recent overview and comparison of optical network YANG service and data models is provided in [17] to which we refer for details on the subject.

In parallel to the standardization bodies several 'open' initiatives are gaining importance in specifying all the relevant aspects of an open disaggregated optical ecosystem. In the following the most relevant ones are briefly introduced.

OpenConfig [9] is focused on open data models and is driven by hyperscale operators and TELCOs. It is less of a standard and more of an informal grouping of actors with likeminded interests. Code is posted directly on github including a base YANG device data model. It encourages vendors to provide open vendor-specific YANG model extensions that can augment the base model. Although OpenConfig is indifferent to the RPC API, Google's gRPC is well-represented. The YANG device data models provide a layer of indirection to 'hide' low level details of the O-NEs. From this a variety of REST APIs NBIs can be generated.
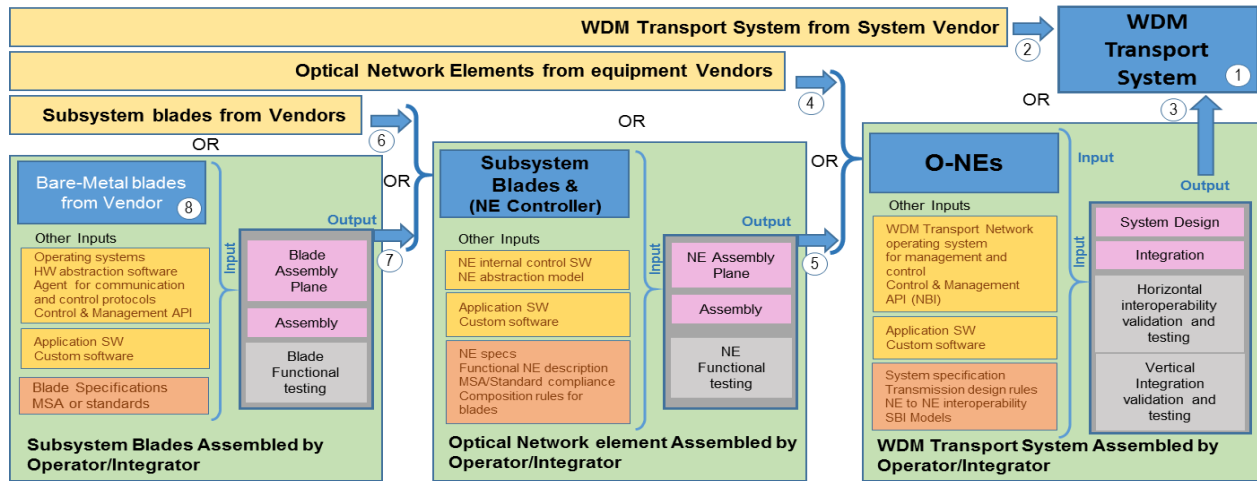
Fig. 6. Alternative processes for assembly a WDM transport systems starting from components (Bare metal blades, Subsystems or Network Elements). Each making process relies on different external inputs (see text), and is in charge of a specific player depending on the disaggregation model adopted: i) Full subsystem disaggregation: all processes are in charge of TELCO and SI; ii) Partial disaggregation or full multi-vendor O-NE disaggregation. Vendor is responsible of processes up to subsystem blades making, TELCO and SI are responsible for WDM system integration; iii) Fully aggregated optical domain: Vendor is responsible of all processes, including WDM system making. Hybrid scenarios are obviously also possible.

The Open ROADM Multi-Source Agreement (MSA) [8] is created to define interoperability specifications for Reconfigurable Optical Add&Drop Multiplexers (ROADM). Founded in 2015 by AT&T, Ciena, Fujitsu and Nokia, currently it counts fifteen members including world leading vendors and Continental scale TELCOs. The objective of this group is the specification of optical interoperability and YANG data models, for ROADM switch as well as transponders and pluggable optics.

Telecommunication operators allocate appreciable capital- and operational-expenditure (OpEx/CaPex) to TPs in their optical line systems. It is the key O-NE for driving the development of the optical white box ecosystem associated with Partial disaggregation: OLSs and Multi-vendor TPs (Fig. 3). The availability of commodity, off-the-shelf optical and packet switching hardware components outfit TPs with open northbound APIs, modulation formats and forward error correction schemes with interoperability through multisource agreements (MSA) or standards bodies.

The Open Optical Packet Transport (OOPT) project group [10] of TIP allows vendors to enter the market with competitive TPs for bookending point-to-point dark optical fibre transmission links of modest span (~100km.) The Facebook Voyager [18] is a variant of the Facebook Wedge 100 data centre Ethernet switch [19], the variation being commodity, merchant silicon modules to drive the fixed lineside ports supporting up to 200Gb/s and a switching chip re-purposed in point-to-point, rather than default bridging mode, to accommodate pluggable transceivers.

The EdgeCore Cassini is another example which conveniently supports pluggable CFP2 analog coherent optical and digital coherent optical lineside modules offered by competing merchant optical component vendors. Just like the Facebook's Voyager it has leveraged the development of an existing merchant silicon-outfitted packet switch [20] and it too, has been submitted to TIP [3].

The Voyager and Cassini essentially reframe the TP as a 'hardware-modified' commodity, off-the-shelf merchant compute server with a commercial CPU running an open linux-based operating systems. This allows a software development ecosystem to support client- and line-side, fixed or pluggable optical hardware modules.

Open merchant-based LTs, ILAs and 'on a blade' ROADMs are also commercially available [11][12][13]. It must be emphasized that these offerings are simple to integrate in point-to-point, single-hop optical line systems. Consequently deployment of the technologies is most likely to first occur for datacentre interconnect in metropolitan areas. This explains the interest of the hyperscale operators - most notably Facebook - through their support of the open compute project and TIP activities.

Also the Open Networking Foundation (ONF) has recently commenced the Open Disaggregated Transport Network (ODTN) activity [21] to extend and complement existing work to disaggregate telephone exchanges/central offices through the CORD activity [4] centered on the vendor agnostic ONOS controller [22].

IV. DESIGN AND DEVELOPMENT PROCESS FOR WDM TRANSPORT SYSTEM

Disaggregation implies some level of TELCO involvement in the processes of designing, developing and testing WDM transmission systems. These processes are described schematically in Fig. 6 with the aim of emphasizing the role of the TELCO. It identifies: the main inputs and outputs, the actors involved, and the existing alternatives.

A. WDM Transport System assembly from Optical Network Elements

In the black box approach the entire lifecycle of the WDM-Sys (Fig. 6, box 1) is controlled by the system vendor (box 2) including SW and HW upgrades and bug fixes. The pace at which new releases are introduced is driven by the vendor,

with modest TELCO involvement to steer developments to their needs.

The alternative is the direct assembly of the WDM-Sys by the TELCO (box 3) acting now as a SI or relying on a trusted external SI. In this case the main HW input is a collection of complete O-NEs possibly from several suppliers. They come as standalone devices completely equipped and with an open SBI (HW white boxes). Depending on the model adopted by the TELCO, either all the O-NEs of the WDM-Sys are involved in the process, or only the TPs devices. In both cases vertical integration is needed.

From the SW perspective the main input is the WDM controller/management subsystem. The SI must work closely with the supplier of the SW for vertical integration (adaptation layers; drivers for devices; suitable application software; integration with TELCO's automation BSS/OSS; etc..).

Other essential input ingredients are a collection of standard specifications for vertical and horizontal interoperability and a clear transmission design criteria.

The system assembly involves mainly the SI in all the phases of design and integration, leaving the TELCO directly responsible for validation and testing. Engineering and innovation departments are responsible for adding and continuously updating/replacing the equipment from a 'catalog', from which other departments can participate in the process of network creation and upgrade.

The system vendor role becomes that of a supplier of certified sortware and hardware, including the specification rules for configuration, interconnection and operations. The assembly and integration then becomes the responsbility of the TELCO, or its chosen SI.

The system development phase is continuously running in background with feedbacks from the field, the client needs, new HW and SW releases or even new technology and the evolving of standards. It is exactly the continuous interaction between developers (TELCO engineering and innovation departments/SI) and operators (e.g. network operation departments) in a synergistic way (in the information technology world this approach if often termed DevOps [23]) that can add value to all the process and can justify TELCO involvement in system design and assembly.

However the 'in-sourcing' of these activities alone may be of small benefit or even add unwanted overhead and constrains, while its synergistically incorporation in a leaner and autonomous service and network lifecycle process, should give TELCO the readiness, flexibility and freedom from vendor lock-in often wished.

Of course the key and critical role is played by the SI in strict combination with testing and innovation departments, which are virtually the 'system vendor' for the TELCO. In order that this intermediary not become the bottleneck, a careful selection of personnel and skills is paramount, and we believe this is the fundamental challenge for the TELCO.

B. Optical Network element and Subsystem blades assembly

The process of O-NE assembly under TELCO responsibility is identified by box 5 in Fig. 6, as opposed to the direct supply of O-NE white boxes from equipment vendors (box 4).

Likewise the process of subsystem blades assembly starting from bare metal blades (box 8) is shown in box 7; the alternative process of purchasing fully equipped white box subsystem blades from component vendors is identified by box 6. Obviously both approaches are compatible only with a full disaggregation approach for the optical domain.

Such a deep involvement in the design and assembly chain, from blade to systems, is an even greater challenge for a TELCO and, at present, difficult to quantify economically.

It is conceivable that the role of 'open consortia' could be of great importance in this respect, as they are managing to seriously address the problem of a white box ecosystem in all of its facets. A further stimulus that could lead TELCOs to start a direct involvement in blades/O-NEs assembly may be the availability on the market of a set of competitively priced equipment with pre-certified on-board SW compatible and ready to be integrated with modest effort, but, this scenario seems unrealistic in the short term.

V. Deployment and operational issues

Fig. 7 shows a general network planning and design deployment, operation and maintenance process in an evolving perspective during the entire life of the network. Process depicted in Fig. 7 holds for any kind of disaggregation model adopted by the TELCO, but differences exists as regard the actor who is responsible each singular activity. The model proposed in Fig. 7 is a simplified vision which assumes network planning and design (P&D) as a single activity (box 4). This is motivated by an expected future highly dynamic and uncertain environment in terms of changes on both service demand and technologies. The new challenging environment requires quick changes and adaptations of the network, not only in terms of reconfigurations, assured by the control plane, but also in terms of new HW and SW installations and updates. The traditional approach, which assumes a phase of long term planning followed by design and engineering phases as separate steps, seems unsuited to react effectively in such a fast changing context.

Referring to numbered boxes in Fig. 7, inputs of the whole process are the service demand, i.e. the list of client circuits to be allocated with the required QoS (box 1), and the WDM transmission system (box 2). WDM transmission system (i. e. the updated equipment catalog available for the network creation) is as results from the scheme of Fig. 6 and depends on the disaggregation model chosen. The process to obtain the WDM-Sys is analysed in deep in Section IV and is summarized in Fig. 7 by the box 3.

The first step of the process is a new P&D (box 4) activity: in the first period of the network life (T=1) P&D gives the guidelines for the early deployment of the network with equipment installation and service activation (provisioning) of the initial set of demands (box 5).

In following periods (T>1), triggered by the change of the demand or the availability of new functionalities on equipment (trigger point, diamond 8), network P&D gives the update on equipment installation (new equipment), the upgrade on
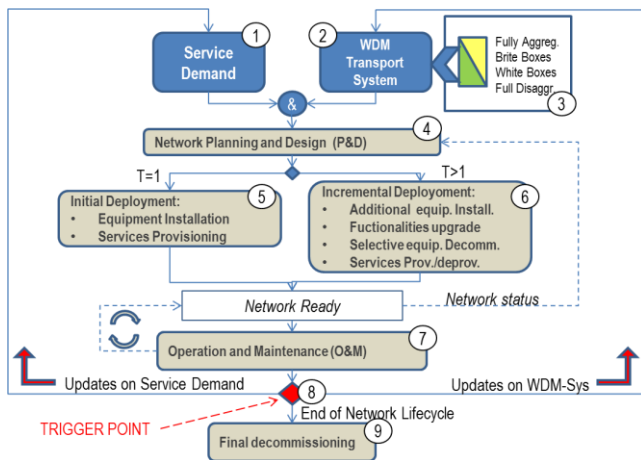
Fig. 7. Planning and Design, Deployment, Operation and Maintenance process flow during the Network Lifecycle.

functionalities (new HW or SW on already deployed equipment), provides equipment to be uninstalled and services to be activated or released (box 6). In doing so, the Network design takes into account the current state of the network before the required upgrade.

Network P&D (box 4) is under the responsibility of the TELCO for any type of disaggregation model. Nevertheless, while in case of full aggregated option the design tools are usually provided by the vendor, in case of disaggregated options the operator has to develop ad hoc design tools taking into account the heterogeneous WDM transport system which is made of pieces of equipment assembled with parts from many sub-systems vendors. As regards this point, the disaggregated options could be a critical issue for the operator.

Installation, upgrades and decommissioning in an initial and incremental deployment phases (box 5 and 6) is under the responsibility of the vendor for the whole network in case of full aggregated optical domain option, or for the only OLS in case of partial disaggregated option. The same tasks are under the responsibility of the operator or the SI in case of disaggregated options (all network for full disaggregation and TP part only for partial disaggregation).

When the network is ready after the implementation of a given cycle of planning and design, deployment and service provisioning, it is operated and maintained by the dedicated function of operation and maintenance (O&M) that, for simplicity, is grouped in a single task (box 7).

O&M is another crucial and potentially critical task. Normally under the responsibility of the operator, the way in which O&M is implemented changes noticeably for the different disaggregated options. In case of the fully aggregated option O&M can relies on specific services that the vendor deliver to the operator and which is tailored on the homogeneous deployed WDM transport system. In case of disaggregated options the operator have to develop its own O&M applications and services which, as it is for P&D tools, have to take into account the heterogeneous environment of a disaggregated solution. Operator have to handle this task with the SI and complexity and cost could be important issues in doing that. During the O&M cycle, maintaining a Service Level Agreement (SLA) in the TELCO networks requires self-healing capabilities, able to reconfigure the O-NEs automatically upon failures. Network operators, with the deployment of control plane intelligence have witnessed a significant decrease in the number of service outages upon failure events, such as fiber cuts. The self-healing capabilities need to be maintained when disaggregation is applied.

Optical restoration is the ability of the optical network control plane to react to catastrophic events affecting services configured with the capability of being restored into a different network path. In the partial disaggregated option, a cooperation between OLS and transponders is needed to complete the restoration. Performance information and alarms need to be exchanged in order to take the appropriate decisions.

The P&D is required to be applied in a new cycle when something relevant happens. Trigger point (box 8) models three types of events that can require modifications on the network. The first is the change in the service demand (here intended as an important change in the demand which imply possible interventions in the network equipment to be installed or upgraded). The second triggering event is the availability of an upgrade in the WDM transport system and in this case a replacement of equipment or an upgrade of functionalities is required. Finally, when the network ends its lifecycle, the corresponding trigger event starts the final decommissioning of the network (box 9).

VI. Techno economic analysis

It is yet to be demonstrated, that the introduction of disaggregation in optical networks can lead to economic savings on both CapEx and OpEx, and then in Total Cost of Ownership (TCO) of the network, when the reference is the consolidated fully aggregated model [24]. The main argument brought for this potential expenditure saving is the removal of the vendor lock-in. Freeing itself from the single vendor and putting in competition many suppliers, a TELCO would reduce the price of equipment, especially for the HW components. On the other side adopting a disaggregated option introduces the cost for the system integration and for the internally development, or the buying from third parties, of SW for network control. Such costs are very hard to predict because they depend on the Operator's strategy on which activities are carried out internally, and which to outsource. Where the operator chooses to do it internally the development of control SW, for instance following the DevOPs [23] methodology, the costs required for re-skilling personnel and for company organizational changes have to be taken into account. A dispute that involves TELCO and ICT service providers, when they have to decide their plans for the network development, concerns the most efficient way to achieve CapEx and OpEx reduction through the introduction of SDN and, possibly, white boxes. It is important to underline that a reduction of OpEx can be achieved by the introduction of SDN, regardless of the aggregation model adopted. Indeed, it is very hard to assess how disaggregation and softwarization would concur in the OpEx reduction.

A paradox, also named 'cognitive dissonance' in [25], is raised

because on one side the introduction of disaggregation and softwarization is recognized as the way to extract significant OpEx reduction in the mid- and long- term. But, conversely, it requires significant up-front investment and so a high CapEx to be accomodated in the short term. Under the pressure of increasing capacity to be provided with limited budget, the investment for the network paradigm transformation (i.e., softwarization and disaggregation) are delayed, and the benefits for OpEx shifted into the future.

In this section we present an evaluation limited to a comparison of CapEx for the two options: the Fully aggregated (Fig. 2) and the Fully disaggregated WDM system (Fig. 4). Both the options assume a centralized SDN controller and the difference are on the controller and its interfaces: proprietary control system or WDM open control system, possibly developed by the operator itself. The approach followed is inspired to the method applied in [26] to estimate the saving of a disaggregated packet transport network based on SDN when it is compared to a conventional IP/MPLS network. While in [26] the comparison is between the presence and the absence of SDN in a packet transport network, in this section a CapEx analysis is performed on a SDN WDM network in the two options of fully aggregated and full disaggregation as regard optical equipment.

Two types of network models with its own WDM transport equipment and related control system are considered for the two selected scenarios under comparison. In the first, the fully aggregated scenario, pieces of equipment (ROADM, TP, ILA, OLT) are provided by a single vendor together with the control SW, which is accounted separately. In the second, the fully disaggregated scenario, pieces of equipment of the same type can be provided by more than one vendor, and their cost is assumed to be lower of a certain percentage (named HW discount, a parameter) of the piece of equipment which performs the same functionality in the fully aggregated scenario.

The cost model is applied to a network scenario of metro/regional WDM network of 50 nodes linked by 90 fibre links and carrying a mix of 1, 10 and 100 Gb/ s client circuits (about 1,000 in total). The diameter of the network is of the order of 300 km and assumptions on TP and line systems

assure, on all the paths, to route optical circuits in the WDM layer without regeneration. An OTN layer for the grooming of lower rate circuits is also present. The Unit of Cost (UC) for this evaluation is the cost of a coherent 100Gb/s TP. All other costs of HW and SW components are referred to this UC. The cost model and cost parameters for WDM and OTN equipment have been taken from [27].

After an approximate network dimensioning, which provides the bill of materials, the total network cost is calculated for the two scenarios under analysis. The bill of materials is the same, in terms of WDM and OTN equipment, and costs differ between the network scenarios analysed only for the prices of HW and basic SW components, and for the presence in the disaggregated scenario of the cost of the development of control SW and of the system integration.

Fig. 8 gives the cost in UC of the compared configurations. The bar on the left shows the cost components for the fully aggregated model. Control plane SW cost (two slices on the top, for common SW and for licenses of SW on equipment respectively) is about 15% of the total cost. The second bar from the left, labelled as HW Equicost, is for the disaggregated solution characterized by the same HW cost (HW discount = 0%) as the Fully aggregated case (highlighted by the horizontal arrow in Fig 8) and integration and SW development nominal costs. HW Equicost disaggregated case shows a total cost 10% higher than the fully aggregated solution, essentially for the presence of integration cost which is not compensated, in this specific case, by a cheaper HW. Nominal cost case (third bar from the left of Fig. 8) reaches a reduction of 7% taking advantage of a discount of the HW of 20%. The other three configurations on the right of Fig. 8 show how combinations of cost parameters can change from a situation of significant disadvantage (+20%) to a situation of big benefit (-32%) as regard the total cost for a network solution based on disaggregation. In general, according with the assumptions made, CapEx reduction for the fully disaggregated model can be reached if a moderate cost reduction of the order of 20% or more is available for HW, the control SW cost is the same, and the Integration cost does not exceed the 15% of the total CapEx.

To complete the analysis on TCO an evaluation on OpEx should be also considered. A reduction of OpEx can be achieved thanks to the introduction of SDN and, assuming that SDN is present in all the solutions including the fully aggregated one, this reduction will be enjoyed regardless of the disaggregation model adopted for the network implementation. Impact of disaggregation on OpEx, which could make the difference between models, is difficult to evaluate and it is highly dependent to the specific context (e.g., the process and organizational models of the TELCO company). Such topic is left for a further dedicated analysis.

VII. CONCLUSION

In an endless era of continuously growing traffic, but with margin on revenues that shows the opposite trend, TELCOs are looking with high interest in 'disaggregated' models for the cost-reduction opportunities they seem to promise. Setting
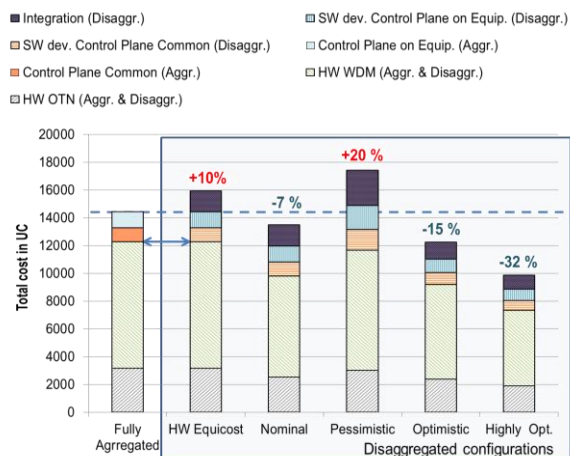

Fig. 8. Cost of Fully Aggregated optical domain solution (bar on the left) compared with costs of Fully Disaggregated solutions (five bars in the box).

aside L2/L3 applications and services, this article focused on disaggregation at the WDM transport layer. Four models with different degrees of disaggregation at the WDM layer were identified and discussed, namely: full disaggregation based on bare metal blades; full disaggregation based on white boxes; partial disaggregation (OLSs and multi-vendor transponders); and full aggregation (this last one is the common mono vendor scenario based on a black box approach, characterizing the legacy). In all these operational models (except the last) TELCOs are actively involved in the design, assembly, testing and lifecycle management of the WDM transport Systems deployed in their transport networks: each disaggregation model has a different 'spectrum' of lifecycle support that a TELCO must sustain.

The roles of the Operator, the system Vendor and the Integrator (the last is an important player supporting TELCO, which is required to ensure that different parts of a system are designed and properly assembled) have been analysed with the support of a model for the processes of system integration and network creation, operation and maintenance.

The key question is if the advantages envisaged by the disaggregation are justifiable from technical, organizational, and economic viewpoints. Actually, embracing the disaggregation implies for a TELCO a radical change of the consolidated paradigm in planning, engineering, deploying, operating and troubleshooting the network. Well established processes have to be abandoned while new skills, especially in SW development, require development, and new mode of operation, for instance adopting the DevOps methodology, must be introduced. TELCOs that embrace disaggregation will need to rely less on the vendors and re-build their knowledge of the optical network and devices. This transition, if chosen, is a big challenge.

As a further element, a preliminary CapEx analysis was performed comparing a disaggregated solution to an aggregated legacy one. The results critically depended on a reliable estimate of the SW development and integration costs. In fact, the expected cost saving achievable with the disaggregation, can be totally absorbed and replaced by the high costs of integration and ad hoc SW development for the control plane. An OpEx, analysis was not carried out in this article but, in a first approximation, the opportunity to benefit from the introduction of SDN for operational cost reductions applies to all models, no matter the level of disaggregation. Specific drivers for OpEx reduction due to disaggregation require a further investigation.

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