Network Management Challenges and Trends in Multi-Layer and Multi-Vendor Settings for Carrier-Grade Networks

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***Abstract*—The exponential growth of Internet traffic gives no respite to the telecommunications industry and is visibly shortening the life-cycle of the technologies used for core networking. To cope with the traffic demand, the industry has primarily focused on the evolution of the data and control planes, and has rapidly made progress in both subjects. However, the innovations in the market have not reached the management plane at the same speed. This stems from a number of factors, most of which point to the segmentation of competencies in managing multi-layer infrastructures. Current carrier-grade networks are organized as multi-layer infrastructures, typically composed of two layers: IP routers deployed in tandem with optical transport nodes. In turn, each of the two layers is typically composed of devices from different vendors, each of which usually supplies its own (proprietary) network management system (NMS). In practice, the lack of broadly accepted mechanisms for enabling interoperability among the different NMSs has led to the isolation of these proprietary systems. As a result, the operation and maintenance tasks on the network are becoming increasingly complex, which is leading to duplication of functions, higher OPEX, and significant delays in the coordination of multi-layer provisioning processes. In this paper, we examine in detail the interoperability challenges of managing multi-layer and multi-vendor carrier-grade networks, and review the current trends and recent standards in the area, with strong focus on industrial advances. We cover the Multi-Technology Operations System Interface (MTOSI) as well as OpenFlow, and analyze their potential impact and reach. We also discuss some of the reasons why relevant carrier-grade management proposals have not been able to fulfill the requirements of Internet service providers (ISPs), and identify a set of features that might help pave the way to market for new management products.**

***Index Terms*—Networks, management, multi-layer, multi-vendor, IP, optical, interoperability.**

I. INTRODUCTION

To cope with the ever-increasing bandwidth demand, current carrier-grade networks have evolved to multi-layer infrastructures, typically composed of IP switching and routing devices deployed in tandem with optical transport gear. Indeed, the convergence of IP and optical transport networks has been at the heart of telecom carriers' strategies and investments, not only for improving the scalability and switching efficiency in the IP core, but also for achieving higher switching capacities at lower costs. This trend is actually leading to the utilization of "more optics" in the network, since carriers are gradually offloading transit traffic from expensive high-end routers toward cheaper and more energy-efficient optical nodes [1]–[6].

For the sake of clarity, in the context of this article we will refer to the "*IP Layer*" as the IP framing layer in the TCP/IP reference model [7], i.e., a layer ruled by packet-based switching, whilst the "*Transport Layer*" refers to the optical network providing the physical transmission layer, i.e., a layer ruled by optical-based switching. Observe that the latter is different from the Layer 4 (L4) of the traditional Open Systems Interface (OSI) and TCP/IP reference models. Fig. 1 illustrates the mapping between the classical OSI and TCP/IP reference models and the layered model of a multi-layer carrier-grade network. Observe that we present three possible approaches for the layering model of a carrier network, which are representative of different deployment scenarios—mainly indicating the time progression from left to right. The term *Intelligent Optical Transport Network (OTN)* in Fig. 1, typically refers to an optical network endowed with more advanced control planes, such that it can offer rapid circuit provisioning, service flexibility, multi-vendor interoperability and enhanced survivability [8].

Overall, carrier-grade networks are currently experiencing considerable changes. In the process of evolving to multi-layer infrastructures, the telecommunications industry has made remarkable advances in the data and control plane technologies. The former is evidenced by the advances made from IP over optical transmission at 10G to 40G, and now 100G and beyond, while the latter is reflected in the increasing supply of equipment supporting cross-vendor interoperability in conformance

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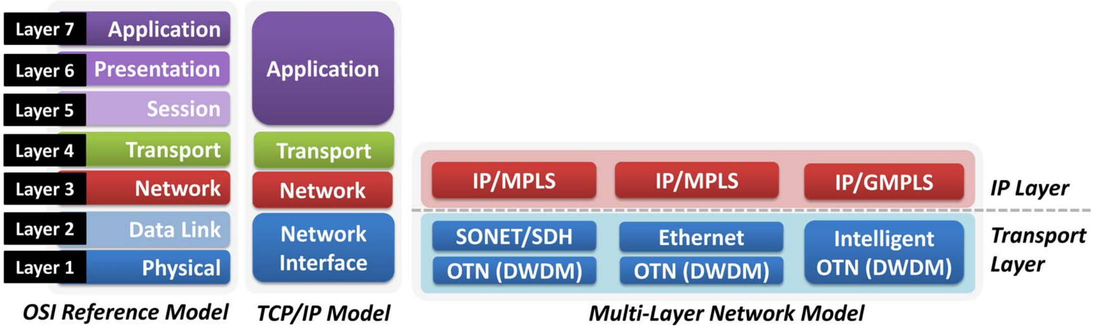

Fig. 1. Mapping between the classical OSI Reference model, the TCP/IP model, and the Multi-layer network model.

with major standards, such as the Generalized Multi-Protocol Label Switching (GMPLS) [9], and the Automatically Switched Optical Network (ASON) architecture [10]. However, the innovations in the management plane have not been able to keep that pace. Indeed, the advances in this area lag far behind carriers' expectations, and they are making network management tasks increasingly more complex. This complexity lies in part on the rich set of functionalities that network management entails, in addition to the heterogeneity of current network settings [11].

In a nutshell, network management covers a broad functional area that typically includes the Operation, Administration, Maintenance and Provisioning (OAM&P) functions required to monitor, configure, interpret, measure and control the network and the services it offers. Network Management has long been targeted by carriers as a means for achieving effective and efficient service monitoring and resource administration, reducing operational costs, delivering guaranteed network performance, recovering from outages (faults) and maximizing the control and security of a network. The proper management of a network results in a secure, reliable and dynamic system, capable of detecting and reacting to critical scenarios that can highly affect the performance of the network [12].

From a management point of view, the IP and optical transport layers are typically composed of devices supplied by different vendors, each of which is managed by its own (proprietary) Network Management System (NMS). This separation of management systems and tasks, along with the inherent technological differences between these two layers, have deeply segmented the operation of the IP and optical transport networks [13]. In addition to this, the lack of widely accepted mechanisms for interoperation of the different NMSs has led to administratively independent ecosystems (i.e., from a management perspective, each layer operates in complete isolation). This raises the need for interoperability between these network management ecosystems, to enable overall administration and maintenance of a multi-layer network [14].

In this framework, one of the central questions that arises is: *Why is management interoperability so important in the first place?* The European Information & Communications Technology Industry Association (EICTA) defines interoperability as "*The ability of two or more networks, systems, devices, applications or components, to exchange information between them and to use the information so exchanged*" [15]. Interoperability—in the context of multi-layer network management—is the key component for enabling communications between the IP and the transport layer management systems, thereby allowing coordinated monitoring, provisioning and execution of cross-layer operations in an automated fashion. Without such interoperability, cross-layer provisioning tasks are limited to manual means, which is precisely the case nowadays. The downside is that this considerably increases the complexity and the costs for operating and maintaining multi-layer networks at the backbone of many large Internet Service Providers (ISPs), wherein even simple management tasks require multiple and repetitive manual procedures, leading to long provisioning time scales.

A closer look into the management interoperability problem in multi-layer networks reveals that it has actually two dimensions. As depicted in Fig. 2, the interoperability problems extend not only vertically between the IP and the optical layers but also horizontally, i.e., even within a single network layer. Matters relating to technical aspects, as well as financial and business strategies induce telecom service providers to avoid single vendor dependencies, which yields multi-vendor network environments, such as the one shown in Fig. 2. Hereafter, we will refer to the vertical interoperability issue in Fig. 2 as the *Multi-Layer Interoperability* (**MLI**) problem, indicating interoperability issues between different management planes or layers. Additionally, we will refer to the horizontal interoperability issue in Fig. 2 as the *Multi-Vendor Interoperability* (**MVI**) problem, indicating interoperability issues due to the need of managing devices supplied by different vendors within the same layer. Note that the MLI problem is itself subject to the multi-vendor problem, since the devices used for the IP layer are often purchased from vendors different than those that supply the optical nodes. In any case, the MLI problem is broader in scope than the MVI problem, as it covers, and inherently deals with multi-vendor issues across layers. Accordingly, the MVI problem subject of study in this paper refers to interoperability issues among different management systems within the same layer.

Overall, the aim of this article is to provide a comprehensive description of the challenges and the interoperability issues in managing multi-layer carrier-grade networks. We review the current trends and recent standards in the area, with strong focus on industrial advances including: the Network Configuration Protocol (NETCONF) [16], the Multi-Technology Operations System Interface (MTOSI) [17] as well as the implications and potential changes derived from the adoption of OpenFlow [18], among others. We also analyze and discuss why some solutions in this field have not gained momentum, with the

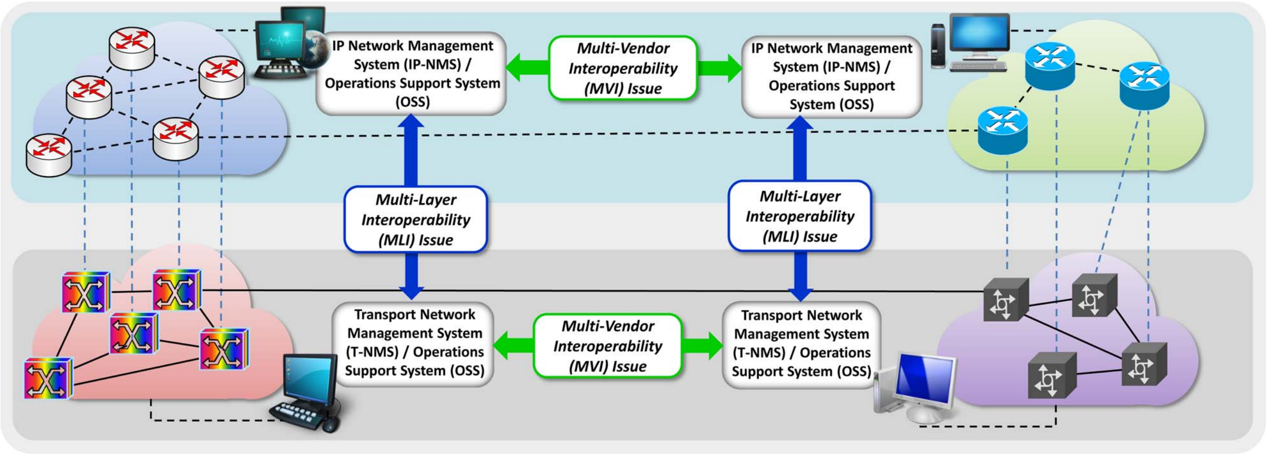

Fig. 2. The Multi-layer and Multi-vendor interoperability problems that make the different NMSs operate in isolation—note that the Multi-layer problem entails itself Multi-vendor interoperability issues.

aim of at least partially identifying the set of features and requirements for next generation management solutions. In fact, while some of the solutions described herein might not be part of a new wave of emerging technologies in the field, the problems that these technologies have tried to address remain largely unsolved. For example, consider NETCONF, the most recent effort of IETF to standardize IP network management configuration. Indeed, it is not a new technology and has even been implemented by numerous vendors and already released in their commercial products. However, in practice many network administrators are still managing and configuring their routers using proprietary Command-Line Interfaces (CLIs). According to industry sources, near 95% of network devices are still configured through proprietary CLIs [19]. This paper analyzes the reasons why this happens in practice, not only for NETCONF but also for other technologies, as an effort to understand which problems remain open, and most importantly, determine the most promising paths toward the future management of multi-layer carrier-grade networks.

Fig. 3 presents a schematic view of the topics addressed in this paper. Note that, we will deal with numerous technologies and the interrelations between them. We will analyze traditional approaches to multi-layer network management issues, delve into the most relevant aspects of newly emerging trends, and draw the lines for future multi-layer approaches, based on coordinated strategies through promising mediation technologies, e.g., supported through Software Defined Networking (SDN) [20], [21].

The remainder of this paper is organized as follows (cf. Fig. 3). Section II describes in detail the MVI and MLI problems in the context of carrier-grade networks. Section III overviews the current strategies in the field, and presents an analysis on how these solutions can face the interoperability problems in network management. Section IV presents a more advanced perspective, covering new research trends in multi-layer network management, and also provides insights into the limitations of these new lines of work. Section V highlights the importance of integrating third-party management subsystems in current multi-layer network management solutions, as enablers of specific cross-layer management functionalities. Section VI, provides the authors' views on the potential directions for future research in the context of multi-layer network management. Finally, Section VII concludes the paper.

II. INTEROPERABILITY ISSUES IN MULTI-LAYER AND MULTI-VENDOR CARRIER-GRADE NETWORKS

Network management has been the subject of study and one of the central targets of the telecommunications industry since the earliest days of networking. However, the overall management of multi-layer infrastructures still remains an open field for research, primarily because of the scarce interoperability between NMSs. In the context of multi-layer networks, management interoperability issues arise mainly due to the heterogeneity of technologies (i.e., IP and Optical) and the diversity of device manufacturers, coupled with the absence of standardized and broadly accepted mechanisms that enable both cross-layer and intra-layer communication of NMSs. A clear proof of this situation is the complexity of current Operations Support Systems (OSS). OSSs were originally conceived as the elements bridging business logic for service provisioning and network management, but in practice they have had to incorporate several layers of "Umbrella NMSs" (as described later in Section III-A) to provide a minimum degree of workflow automation. Cutting down OSS complexity is among the most important efficiency objectives of practically all telecom operators.

The isolation between the IP and transport management ecosystems is exacerbated by the functional segmentation of standardization bodies, which are not necessarily working in the same direction. While, the Internet Engineering Task Force (IETF) is the organization playing a critical role in the scope of IP-driven network management standards [22], the International Telecommunication Union (ITU) [23], the Optical Internetworking Forum (OIF) [24], and the TeleManagement Forum (TMF) [25], are the most active organizations working toward the development of standards in the field of optical transport networks. In this section, we provide a detailed analysis on the MVI and MLI issues for carrier-grade networks and outline the complexities that emerge as a result of the isolation of their management ecosystems.

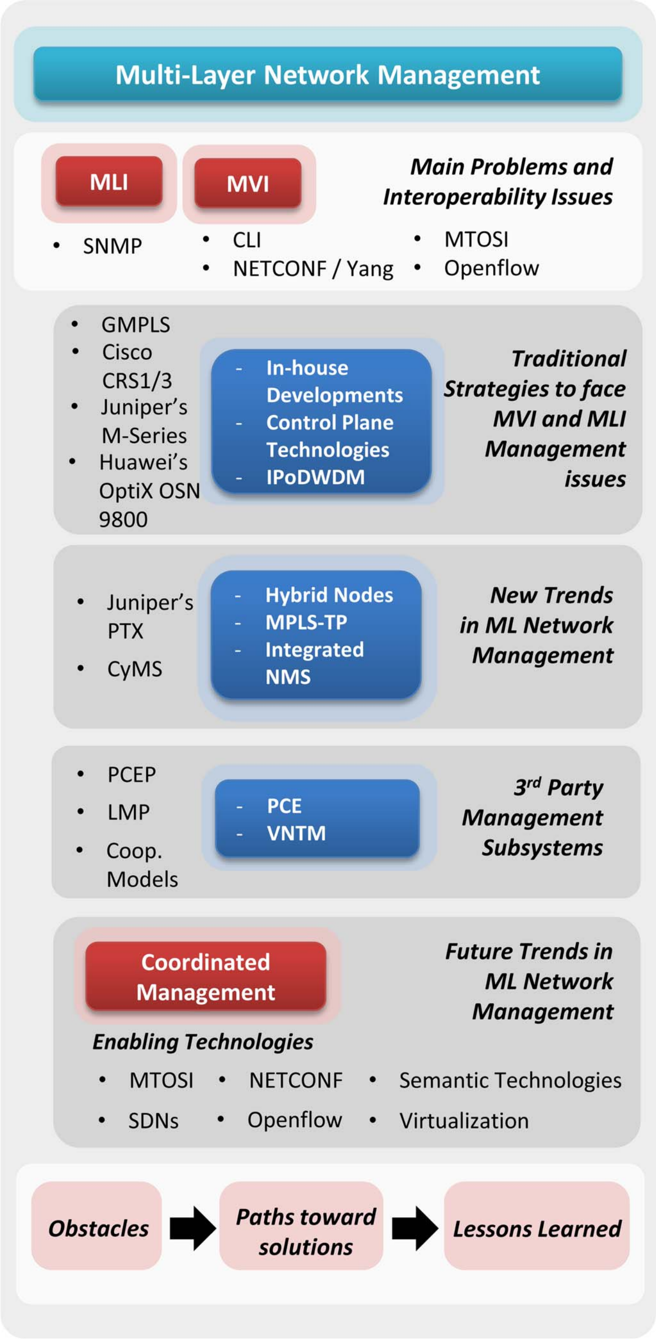

Fig. 3. Scheme of the topics covered and organization of this paper.

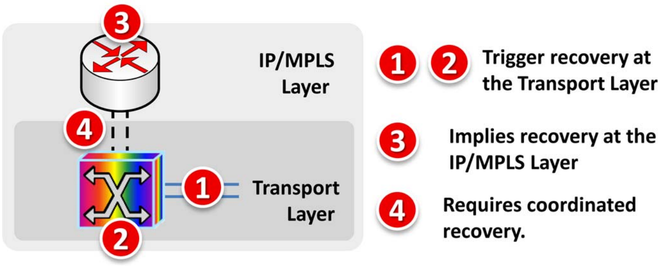

Fig. 4. Typical failure scenarios in multi-layer networks.

A. *Multi-Layer Interoperability (MLI) Issues*

The MLI issues between the IP and transport NMSs arise primarily due to the development of systems targeting individual network layer functions in the Open Systems Interconnection (OSI) model. While the use of the OSI model has ensured that the technological diversity in lower layers does not affect the operation of the upper layers, the lack of mechanisms for enabling coordinated management between them has led to the replication of critical functions. Restoration mechanisms are a clear example of the redundancy produced by independent (i.e., per-layer) management functions in multi-layer settings, as they are featured by both layers to restore traffic onto alternate paths in case of failure. Indeed, the scarce efficiency for protecting and recovering multi-layer networks is the result of the absence of communication mechanisms between management ecosystems, which leads to the activation of restoration functions in individual layers based on the utilization of static time thresholds. In typical deployments, transport network restoration is attempted first, and restoration at the IP level is usually delayed by a static time threshold, which can lead to significant losses in case that restoration in the transport network fails [26].

Let us consider the example shown in Fig. 4, which summarizes the possible failure scenarios in a multi-layer network. Link and node failures at the transport layer (denoted as (1), and (2), respectively) can be typically recovered by the optical network without manual intervention, provided that the spare resources and capacity are sufficient for that end. A failure of a router (3), on the other hand, can be recovered by the IP/MPLS layer. However, whenever a failure occurs at the interconnect point (4)—i.e., when an inter-layer failure occurs—a coordinated strategy is required for safe and efficient recovery. It is worth mentioning that, currently, this coordination is not dynamically resolved; quite on the contrary, it is predefined and meticulously pre-configured during network planning cycles. Observe that for failures (3) and (4), if no backup router is available at the IP layer, the transport layer could reactively attempt to optically bypass the affected router. Unfortunately, the lack of cross-layer management mechanisms does not allow dynamic cross-layer recovery, which leads to an unnecessary duplication of resources and restoration mechanisms at both layers. Indeed, enabling communication between NMSs of different layers would derive in much more efficient restoration strategies, and could help alleviating in the future part of the duplicity in current carrier-grade protection schemes.

Another important aspect is that the MLI issue also hinders the automation of multi-layer tasks between the management ecosystems of the different network layers. Hence, only manual means are attainable for coordinating cross-layer operations. By manual means we refer to the human interactions between administrators in each network domain. To illustrate this, consider the multi-layer setting shown in Fig. 5. In practice, for setting up an IP service (e.g., the provision of IP links), the Planning or Sales Department must first issue a new service request to the IP Network Management Department (1), which in turn performs the corresponding actions to check for the availability of IP resources (2). If the required resources are available at the IP layer, then the administrator will issue a request to the Transport Network Management Department for the set up of new optical paths (3). It is worth highlighting that, as the IP and Transport networks are typically managed separately

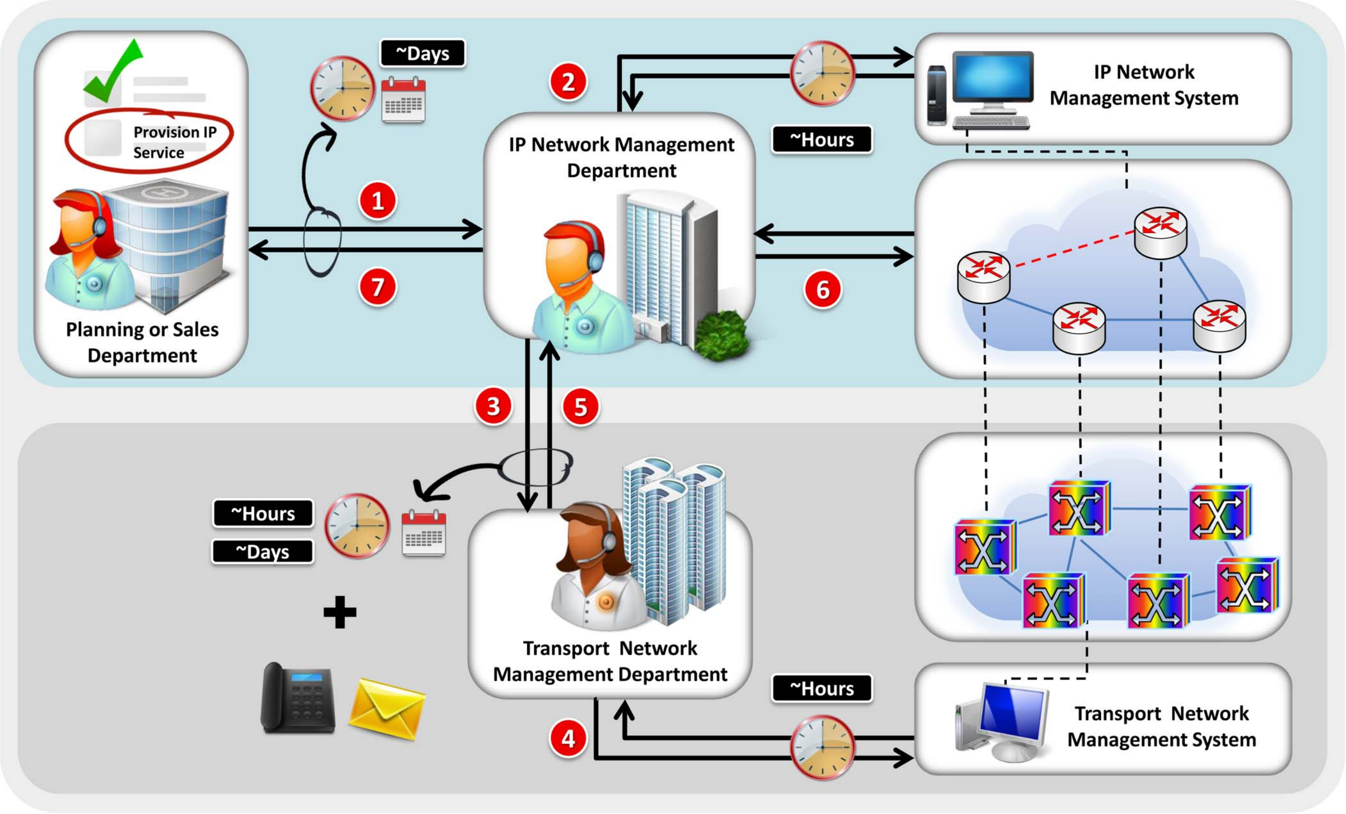

Fig. 5. Current workflow for provisioning an IP service involving configurations at both layers.

and independently, they require to comply with formalities and procedures for information exchange, a fact that often results in high provisioning timescales. Once the request is properly received by the Transport Network Management Department, meaning by this that the request satisfies all the requirements from both parts, the Transport Department completes a series of actions, including confirmation of available resources and their subsequent provisioning at the transport network (4). After the Transport Department has fulfilled the incoming request, an acknowledgement is sent back to the IP Department (5). From this response, the IP Network Management Department completes the corresponding configurations of IP devices in their domains (6), and finally, notifies the completeness of the IP service request (7). As seen in Fig. 5, the manual coordination process is very slow, so even the simplest cross-layer operation, such as the establishment of a single IP link, can take hours or even days. As depicted in Fig. 6, in large carrier-grade networks routers A and B may perfectly belong to different “IP management domains” (e.g., when router A is supplied by router vendor V_A and router B by vendor V_B). Likewise, Fig. 6 also shows that, the lightpath required in the transport layer for supporting the IP link may also need to traverse different “Transport management domains” (e.g., from vendor $V_X \to V_Y \to V_Z$).

In the scope of cross-layer operations for multi-layer networks, services that could be provisioned in a scale of minutes, currently range to the scale of days or weeks, a fact that beyond its technical and functional implications translates into higher operational expenditures (OPEX). Moreover, the configuration of fixed or dynamic policies for proactive cross-layer operations (e.g., for dynamic traffic management) are not openly supported by current multi-layer settings.[1] Indeed, if more advanced cross-layer operations were developed, they could further contribute to make significant progress in aspects such as multi-layer recovery and self-healing. By self-healing we mean coordinated protection mechanisms that could provide network reliability and automated restoration actions to recover from unplanned failures. Moreover, another significant challenge is the automatic discovery of interlayer connections, as for now network administrators rely on manually built topological databases. Finally, the advent of third party systems makes integration to multi-layer environments more important than ever, as current external tools could be combined to automatically interact with the multi-layer environment, so the latter can benefit from the services of external subsystems, such as multi-layer Path Computation Elements (PCE) [29], monitoring tools, accounting systems, etc.

Accordingly, the absence of standard management interfaces for inter-layer communication not only results in duplication of network functions and lack of automation for cross-layer provisioning tasks, but also derives in slow provisioning timescales, lack of proactive policy-based and failure-related interactions, as well as limited integration of third party management subsystems [14].

Although several efforts are underway for overcoming the MLI issues described above, the overall progress is slow. Most

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[1] There are some proprietary solutions, but they are naturally constrained to single vendor settings, for example, Juniper’s solution based on hybrid nodes [27] or Huawei’s Hybrid MSTP OSN 7500 II [28]. In Section IV, we will cover some of these solutions.

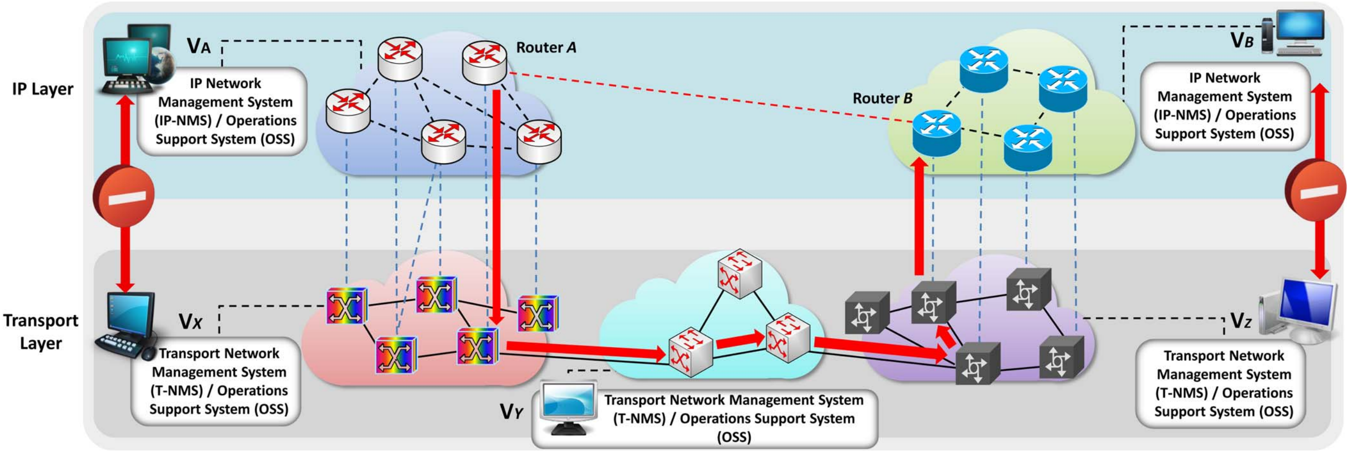

Fig. 6. An example of network management interoperability issues involving cross-layer resource provisioning of an IP link between routers A and B of a carrier network.

of the solutions proposed thus far have not had enough echo among ISPs, so it is hard to assert that there is a clear trend toward tackling the MLI issues at a management level. In Sections III and IV, we will provide an analysis of the main limitations of current research trends, in order to set the ground for future research lines in the area.

B. Multi-Vendor Interoperability (MVI) Issues

Various bodies such as the International Telecommunication Union (ITU-T) and the Internet Engineering Task Force (IETF) are working toward developing standard specifications of control and data plane functions enabling interoperability between different vendors. However, in practice vendors compete with each other trying to gain higher market share by implementing specific non-standard functionalities in their equipment, a fact that unquestionably leads to customer lock-in. This in turn creates a buyers dependency on the seller. According to the report released by the market research firm *Infonetics Research* in the second quarter of 2013 [30], Cisco had the highest market share for carrier router and switches, followed by Huawei who has gained the most market share over the past two years. Overall, Alcatel-Lucent, Cisco, Huawei and Juniper account for 90% of the market share, while the remaining 10% is split among several other equipment vendors.

The demand for new functionalities has led to vendor-interoperability requirements in the data as well as the control and management planes. A classical example of interoperability challenges in the data-plane can be seen in the 100G optical solutions available in the market today. While standards propose the use of different configurations of single 100G or multiplexed 40G and 10G lightpaths using fixed spectrum slots of 50 GHz, vendors such as Ciena, have developed custom 100G optical solutions that employ larger spectrum slots to provide longer reach, but makes it limited in terms of interoperability with other vendors' equipment.

MVI issues related to the management plane are primarily reflected as the lack of standardized interfaces for communication between NMSs from different vendors within a single layer. Let us consider the following example to illustrate the MVI problem. As shown in Fig. 6, nowadays, when a service provider requires to configure a service spanning across different vendor (management) domains (e.g., between Ciena $[V_X]$ and Huawei $[V_Y]$ at the transport layer) the configuration process is done *ad-hoc*, mainly due to the lack of means for interoperation between NMSs, which translates into high operational and maintenance expenditures. The forces driving service providers to buy both Ciena and Huawei are two-fold: firstly, better costs when negotiating prices (lower CAPEX) and secondly, avoid single vendor dependency (which lowers CAPEX but increases OPEX). This is a typical example of the MVI issue, a problem suffered by almost every service provider, and which will remain present while purchase policies remain the same. Another scenario that reveals such incompatibility between NMSs is the designation of skilled software development teams, committed to develop dedicated software agents to enable interoperability between NMSs and network devices of different vendors. For instance, this case is well-known at ADVA Optical Networking, where the management interoperability issues with Nokia-compliant technology are tackled through *ad hoc* software developments.

In this paper, we refer to the MVI problem in two dimensions, firstly the communication between NMSs in a single network layer (i.e., within IP or within the Transport layer) and secondly, the communication between a NMS and multi-vendor devices (i.e., routers, Optical Cross Connects (OXCs) or any other network elements), for example, for performing configuration tasks. This dimension of the MVI problem has led to the development of standard open interfaces, thereby enabling hardware independency (e.g., OpenFlow)—a hot topic in the field which will be further discussed in Section VI.

As for the first dimension of this problem, despite the numerous efforts for providing *multi-vendor support*, at present many network management software solutions are constrained to interoperate with other management systems, a problem which normally leads to high stresses in internal implementations and increased costs [31]. As mentioned previously, proprietary network management protocols as well as vendor-specific management data representations are the hallmark of many manufacturers to distinguish from other vendors. However, these business and market driven decisions result in serious interoperability limitations for managing heterogeneous networks. This problem goes beyond the scope of standard protocols for network management and steps into the field of device-vendors, many of which strongly reject the belief of being as good at managing the competition's products as their own [32].

As for the second dimension of the MVI problem, let us consider the following example. In IP networks, the primary interface used for configuration is the Command Line Interface (CLI), a vendor-specific technology which can even change between devices of a single vendor, e.g., according to the Operating System (OS) version used. Due to the customization degree per vendor, under this scenario, achieving truly integration of multi-vendor device configurations is a rather challenging task. Even in the presence of standardized communication protocols and mechanisms, the data models used by different vendors can vary significantly giving place to interoperability challenges. For example, the Simple Network Management Protocol (SNMP) [33], [34] is used as a standard protocol to communicate with devices in order to facilitate inventory management, alarm notification, and performance monitoring. However, different vendors specify extended Management Information Bases (MIBs) for SNMP to facilitate advanced features that are not described in the standard MIBs. This means that operators have to modify their management systems whenever they introduce new devices in the network or change devices to a different vendor. The explanation for the prevalence of proprietary approaches in industry, is that they are the result of forces driven by vendors rather than by service providers, thus, it highlights the divergent interest of both parties. While operators target the interoperability in heterogeneous networks, manufacturers clearly target their own business interests.

Two technologies, the Network Configuration Protocol (NETCONF) [16] and the Multi-Technology Operations System Interface (MTOSI) [17] are positioned as promising technologies for the IP and Transport Network Management ecosystems, respectively. On the one hand, NETCONF seems the expected standard for remote IP device configuration. This protocol aims to overcome the limitations of SNMP-based configurations as well as proprietary CLIs to reduce complexity and lower operational expenditures—according to industry sources network device configuration is actually the greatest contributor to OPEX [19]. NETCONF is defined for providing configuration state maintenance, concurrent configuration, transaction across devices and roll-back support. Initial implementations of NETCONF in vendor equipment have already been developed (e.g., see Juniper, Cisco and tail-f [35]–[37]). Nevertheless, it is important to note that NETCONF only foresees the access protocol and configuration of network elements, but it does not take into account the definition of configuration information, i.e., an explicit way of expressing its payload.

For a complete definition of the configuration model, a data modeling language is also required, to provide the means for defining and declaring the network elements particularities (e.g., interfaces, addressing, bandwidth, etc.). In other words, a concrete and precise way of expressing what can be read and written over the configuration is needed. The lack of a standard data model across all vendors led to a new challenge around NETCONF. Indeed, even if NETCONF is implemented by all vendors' equipment, its future depends on the adoption of a standard modeling language, allowing a common view and knowledge of network equipment. The initial implementations of NETCONF relied on proprietary data models, which in turn raised clear interoperability issues. Examples of data models that have been proposed and tested for its use within the NETCONF framework are: the XML Schema (XSD) [38], Relax NG [39], Ontology Web Language (OWL) [40] and YANG [41].

More specifically, XML-based languages, such as XSD and Relax NG, were initially considered as potential candidates for NETCONF content definition. They were evaluated and compared with YANG [41], in order to assess their suitability as network management data models [39], [42]. These studies compared language data models according to their level of expressiveness, elements of construction, readability and interoperability, and revealed that XML Schema languages were suitable for general constructions, but they had neither the adaptability to model hierarchical data in a clear and concise way, nor the level of expressiveness provided by YANG [41]—a data model that has been specifically designed for the NETCONF protocol. According to these studies, YANG also outperformed schema languages in terms of readability, due to its likeliness to programming languages. Furthermore, XSD and Relax NG were shown to be too general for domain-specific data modeling in the context of network management.

On the other hand, OWL [43]—a W3C specification for authoring ontologies—was also proposed as a modeling language for network management information [40]. The proposal is to define OWL modules for common concepts of any NETCONF configuration model, as well as operations and notifications, and to agree on a standard serialization method, while suggesting RDF/XML for this purpose. The initiative proposed in [40] also exposes how OWL fulfills NETCONF's main requirements, such as the capability to define NETCONF operations and newly derived ones, error annotation capabilities, human readability, meta-data support, reusability, support to basic types and relationships, etc. Nevertheless, OWL as well as other XML-based initial approaches have failed to position as the best candidates for network configuration data definition either because of their lack of semantics or their intricate use.

At present, YANG [41] is positioned as the strongest candidate to a standard data model language for NETCONF. It is the IETF's proposed standard to create a common language for data modeling definition, and although some YANG compliant software applications have already been developed, there is still a long path before YANG and NETCONF become leading standards in the network configuration arena.

As for the transport ecosystem, MTOSI emerges as a protocol aimed to overcome the interoperability issues of SNMP and it operates with unified network data models and operations supported by Web Services. However, a limitation is envisioned for MTOSI. Despite the fact that there is a standardized data model specification, the representation of devices within this data model is different, thus, vendor interoperability becomes a major challenge. In Section VI, we will delve into the potential of MTOSI for enabling interoperability in multi-layer infrastructures.

III. TRADITIONAL STRATEGIES TO FACE THE MLI AND MVI PROBLEM IN NETWORK MANAGEMENT

Initial efforts led by industry and academia to overcome the MLI and MVI problems in network management have put into practice several strategies. In-house developments, IP over DWDM (IPoDWDM) [44], and control plane technologies [9], [10], are some of the main solutions currently deployed by many large ISPs with the aim of simplifying the missing management functions in multi-layer and multi-vendor settings. Nevertheless, these developments either solve partial problems or target them in a temporal and local way, hindering the possibilities of becoming absolute trends in the field of multi-layer network management. Either way, they provide valuable foundations for: (i) providing basic support of missing management functions, (ii) envisioning new requirements for future approaches targeting interoperability and (iii) bringing to light the real needs of network operators as they evidence the existence of numerous interoperability problems.

A. In-House Developments

As stated in the previous section, the choice of large telecommunication service providers to defeat mono-vendor settings is usually a business and market-driven decision, which has naturally led to heterogeneous network infrastructures. The problems arising from such inherent heterogeneity have resulted in the development of in-house applications, aimed to locally address the management limitations in multi-vendor and multi-layer settings (see Fig. 7). These platforms are developed as internal network management engines and are also known as Umbrella NMSs. They are custom-made and they are typically centralized solutions built to temporally address the specific needs of network administrators. They follow a Manager of Manager (MoM) architecture, an alternative that has always been available for network managers to "smooth" the limitations around existing management solutions.

Umbrella NMSs lack of flexibility, efficiency or means for exchanging or enabling interoperability between layers in a multi-layer setting. They usually perform as central systems with no top-to-low layer communication or vice-versa. As shown in Fig. 7, these umbrella systems typically offer custom interfaces to existing NMSs developed in each network layer (*A*). In many other cases, the umbrella NMSs directly interact with the network elements (*B*) to avoid the complexity, the high costs and administrative delays that derive from requesting new functionalities to be developed over proprietary NMSs. This allows to achieve the required management functions at lower costs, reduced time-scales, and higher levels of customization. In-house developments are not efficient and have brought to light the inadequacies of current network management tools for targeting the problems that arise in the context of multi-layer settings. Umbrella NMSs are just an example that discloses the fact that current NMSs lag far behind the requirements faced in practice by network managers.

B. IP Over DWDM

IP over dense wavelength-division multiplexing (IPoDWDM) [45], [46] is a solution for approaching the core network architecture in order to support the ever-increasing volume of IP traffic. This architecture proposes the convergence of IP and DWDM transport technology by integrating colored transport interfaces directly in the IP routers and photonic switching into DWDM platforms. Integration of transponders onto routing platforms eliminates external layers of transponders between the IP and optical transport layers. The overall goal is to simplify the network while lowering costs. This integration highly contributes to capital and operational savings due to the reduction in the number of network elements, space occupation, and energy consumption. It also leads to simplification of the network by eliminating SDH/SONET boxes. Furthermore, it provides inherent protection capabilities, due to the knowledge shared between layers, as IP devices can monitor the optical path. However, the final goal for full multi-layer integration assumes support of the control plane to complete cross-layer network provisioning and monitoring—we will delve into these aspects in the following section.

C. Control Plane Technologies

Several network device suppliers already provide GMPLS support in their carrier-grade equipment (e.g., Huawei's OptiX OSN 9800, Juniper's M-series or Cisco's CRS-1/3), and some carriers have even fostered the early adoption of this technology. For instance, the major operator in Japan, namely, NTT, has been a leading promoter of the GMPLS technology [47]. Despite these advances, technologies such as GMPLS are still not widely deployed in practice [48]. The true fact is that telecom providers are not under a big pressure for deploying GMPLS—at least not until the latter acquires more momentum. This means that, in the meanwhile, IPoDWDM solutions are restricted to scenarios where mainly manual transport paths are established, arising clear interoperability issues between layers. Indeed, the proprietary nature of most IPoDWDM solutions, conditions the network infrastructure in many cases to mono-vendor settings. Integrated management under this particular scenario would be restricted to end-to-end provisioning for a single-vendor solution.

In addition, signal compatibility is also a limitation of these solutions, since standardization efforts are still required to ensure a perfect match between transponders and transport equipment. Accordingly, the value of these solutions is limited in scope to signal compatibility and interoperability constraints. The lack of standardization at the signal transmitted by the transponder is an important issue in the integration of transponders at the IP/MPLS cards [44]. There are some standardization efforts at the ITU G698.2 [49] to solve the problems of the so called "Black Link". A Black Link is defined as a link where the transponders (source and destination) and the intermediate optical equipment may be from the same or from different vendors. This standard defines the signal parameters for the input and output interfaces in such network. There are two different kinds of wavelength connections: 1) "Friendly Wavelength" and 2) "Alien Wavelength". A Friendly Wavelength is a lambda connection not created in the optical system, but it is known and managed by the optical management system. This Friendly Wavelength may be created by a router, but the optical

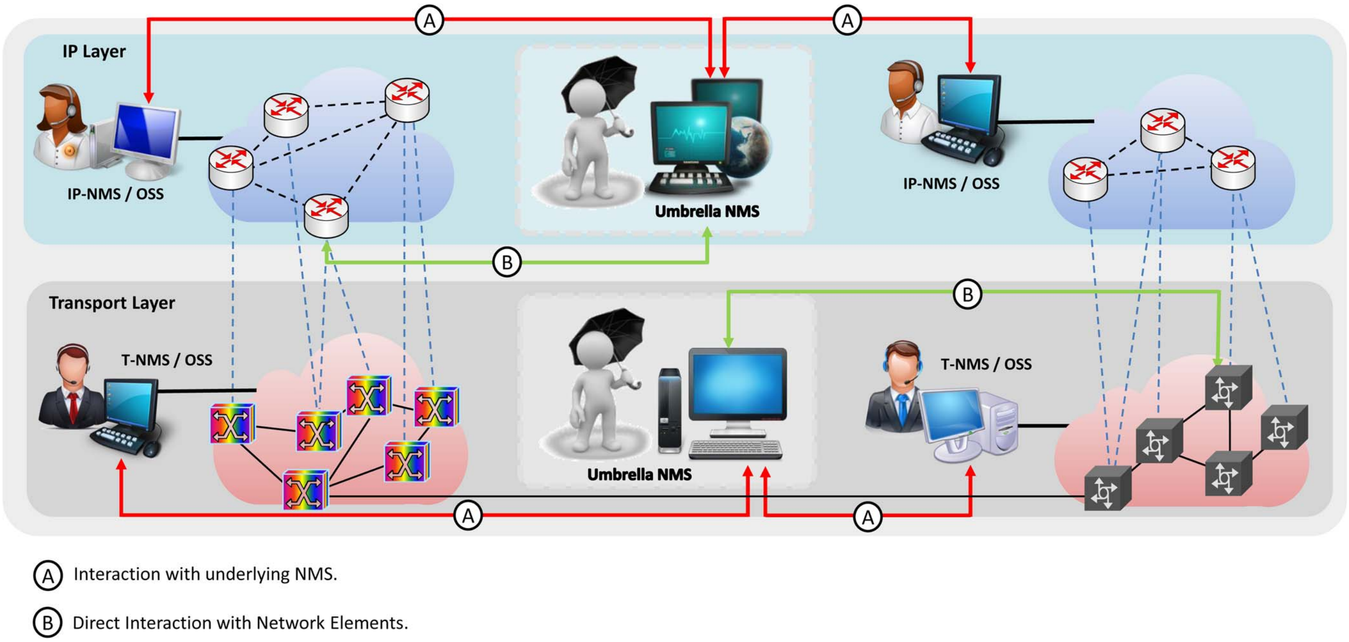

Fig. 7. Facing the interoperability issues with in-house developments.

management system exchanges information with the router to know the status of the connection. Usually this is done in mono-vendor solutions with virtual transponders from the optical management system point of view. On the other hand, an Alien Wavelength is a connection created outside the optical domain (e.g., from an IP Router), but it is not managed by the optical network management system, hence, the DWDM system has no early knowledge of signal parameters (e.g., bandwidth, wavelength). In such scenario, the optical management system is signaled to configure the intermediate OXCs, but it does not have information about the signal quality. Hence, intermediate integrated solutions open new issues such as the optical signal information exchange between the IP/MPLS and the optical management systems.

Overall, IPoDWDM strategies have been driven by several device manufacturers (e.g., Cisco, Juniper and Alcatel-Lucent) setting the trend of next generation networks. Whether the management of a network with IP/WDM integration with coloured interfaces is simpler than todays network management is still an open issue, as most routers do not deal with transport specific issues and some problems are still open to resolution.

IV. NEW TRENDS IN MULTI-LAYER NETWORK MANAGEMENT AND CHALLENGES FACED

Aside from the strategies traditionally deployed by service providers to face the MLI and MVI problems, recently, new trends have emerged in the field of multi-layer network management. These solutions follow one of two lines. They either represent new ways of approaching the multi-layer network management problem [50], [51] or they feature new emerging technologies [27], [52], which demand new forms of interaction and pose different challenges from the management point of view.

While service providers pursue new trends for targeting the convergence of IP and Optical layers, research efforts shall consider all the newly emerging challenges and complexities in order to enable interaction between layers at the highest level of abstraction. Thus, solutions within the scope of multi-layer network management should provide the flexibility for delivering true full systems not compromised to specific technologies.

To this end, we present an analysis on new trends in the scope of multi-layer networks. We firstly introduce MPLS-TP a profile of MPLS for transport networks, then we comment on various solutions based on integrated network management systems for multi-layer networks, such as the solution developed by Cyan [50], and finally, we delve into hybrid solutions for achieving IP over Optical integration, e.g., Juniper's PTX [27] or Huawei's Hybrid MSTP OSN 7500 II [28].

A. *MPLS-Transport Profile (MPLS-TP)*

Multi-Protocol Label Switching Transport Profile (MPLS-TP) [51] has been built as a joint effort between ITU-T and IETF. Its goal is to extend and enhance the concepts of MPLS [53] and create a profile that can be used in the context of transport networks. MPLS-TP not only adds a set of extensions to MPLS, but also disables those capabilities neither required nor consistent with transport technologies. An example of such suppressed capabilities are Label Switched Path (LSP) merge [54], Penultimate Hop Popping (PHP) [55] and Equal Cost Multi Path (ECMP) [56]. These features are removed because they hinder the Operation, Administration and Maintenance (OAM) functions, which are mandatory for transport networks. For example, the PHP functionality, which consists on removing the label at the penultimate hop—i.e., before reaching its destination—would remove significant information required by OAM functions to work accurately. Another major difference between both technologies is that, unlike MPLS, MPLS-TP LSPs are bidirectional, therefore, the forward and backward LSPs follow the same path. This provides the ability to communicate back to the source if any problem is encountered, thus simplifying troubleshooting.

In a nutshell, MPLS-TP aims to enable MPLS on transport networks, while keeping their operation as close as possible to already existing transport technologies (e.g., SONET/SDH networks). To this end, MPLS-TP—like is the case of most transport network platforms—is not constraint to conveying IP packets, meaning that, MPLS-TP functionality can be fully provided regardless of the packet-layer technology used. MPLS-TP has been designed to provide a rich set of control plane-independent OAM features. In MPLS-TP all OAM functionalities run inband, hence, OAM packets are sent over the same path of the user payload in the MPLS-TP forwarding plane to manage and monitor the transport network and the services being delivered. Some of the OAM features include, Continuity Check (CC), Connectivity Verification (CV), delay and loss measurements as well as fault notification. An overview of the MPLS-TP OAM framework can be found in [57].

In addition to OAM enhancements, MPLS-TP provides two modes of operation. Firstly, configuration of LSPs based on network management plane technologies, which are usually referred to as "static" configuration (i.e., not based on a dynamic control-plane), and secondly, dynamic provisioning based on control plane technologies (e.g., GMPLS). The main advantage of the former approach is that MPLS-TP networks can be managed through a centralized NMS as in traditional transport environments (e.g., in ROADM-based optical networks), which makes it quite appealing for network operators who are used to manage and provision their services in that way. The latter approach, suggests the use of the GMPLS control plane to provide automatic setup of MPLS-TP LSPs. For more details on MPLS-TP's components and its technical specifications the reader is referred to [51], [57]–[60].

In light of all this, MPLS-TP is foreseen as a technology to leverage traditional transport technology to support packet-based services in a more efficient way, while embracing the features of traditional transport environments (e.g., QoS, centralized operation, etc.). Over the recent years, network device manufacturers and network operators have progressively begun to provide support to standard-based MPLS-TP solutions (e.g., Cisco, Nokia Siemens Networks, ZTE, Verizon, Bharti Airtel, Huawei, Telecom Italia, China Mobile, etc. [61]), while early applications have already been discussed and deployed. Service Providers are considering the migration of traditional SONET/SDH networks to packet transport technology. Along this path, MPLS-TP appears to be a well-suited technology to overcome the inefficiency of these networks when transporting packets—basically due to constant bit rates even in the absence of traffic. Indeed, plans for deploying dynamic MPLS-TP over OTN/DWDM in Verizon's core network were reported in [61]. The goal was to provide connectivity to edge services by interconnecting Ethernet and IP/MPLS domains through MPLS-TP.

Furthermore, MPLS-TP has been considered a candidate for replacing Ethernet in the access network. Data plane compatibility between MPLS-TP and IP/MPLS could make interoperability with the backbone of large ISPs rather simple, while providing end-to-end OAM. In this context, the selling point is that by deploying MPLS-TP—along with already existing deployments of IP/MPLS—ISPs will have simple and consistent ways of provisioning and managing their networks edge-to-edge. However, technical comparisons in 2012 between both technologies seem to favor Ethernet, claiming that MPLS-TP still lacks of maturity and security to yet dominate access networks [62]. If MPLS-TP is ready to replace Ethernet or other packet transport technologies in the access or the core network is yet to be seen.

Overall, one of the driving forces of MPLS-TP is the possibility of deploying a unified MPLS strategy, wherein ISPs can use MPLS in its different flavors (i.e., IP/MPLS, MPLS-TP, etc.) from core to aggregation and access to improve end-to-end convergence. At the same time, the dual mode of operation of MPLS-TP brings flexibility into the design of transport networks as static configurations may be used while control plane technologies are not yet in place or required. However, the requirements in the scope of network management go beyond the provisioning functionality and instead require even more complex interactions (e.g., scheduling, alarm correlation, and self-healing, among others) to really address the key issues in multi-layer network management.

B. Integrated Multi-Layer Network Management Systems

An integrated NMS for multi-layer networks has been for some time among the research interests of academics [63]–[65] and most recently launched by Cyan under the figure of Cyan's Multi-Layer Management System (CyMS) [50]. The aim of these solutions is to provide a unified network management plane to effectively manage (i.e., configure, provision, monitor, etc.) multi-layer networks regardless of the technological differences.

Early works such as [64] and [65] proposed an integrated NMS capable of providing multi-layer connectivity services based on the use of management functions supported by single layer control plane technologies—whenever available. This approach mainly focused on supporting basic configuration management functions to provide end-to-end IP connectivity derived from Service Level Agreements (SLAs). In addition, some of the same authors devised a policy-based architecture [66] supporting security policy definition, storage and enforcement. Moreover, the authors in [63] developed a prototype implementation of an integrated platform based on standard technologies, to address the issues of multi-layer network management. In that research initiative, the authors defined their own XML-based management information modeling language, adopted a new XML-based management protocol and developed mediation modules to interact with legacy protocols (e.g., SNMP). They also featured policy-based management capabilities while providing an open interface through which basic support to services was provided. That prototype was assessed under a simulation environment to prove support to multi-layer network optimization tasks, fault management and restoration functionality.

Beyond the scope of research, Cyan has actually commercialized its product release of an integrated network management solution, namely, CyMS. CyMS provides a software solution for integrated three-dimensional view of the physical and logical connections in all network layers. It is adapted and designed to comply with TMF Multi-Technology Network Management

(MTNM) and ITU G.800 principles [67]. Additionally, it features three-dimensional heat maps for enabling proactive network monitoring and control, while gradient-color coding indicates the existence of critical conditions—for instance, for anticipating future faults or service degradation. Indeed, CyMS provides enhanced functionalities for Cyan-compliant devices. However, its potential and dynamics is limited to its own optical gear. This proprietary solution is restricted in scope to multi-vendor environments, a fact that makes it an unsuitable solution in the context of most common and heterogeneous network deployments. The constrained multi-vendor reach also contributes to high costs of maintenance and updates due to new technologies or requirements.

C. Hybrid Node

Several hybrid solutions drawn from industry and academia have emerged in the field of multi-layer networks [27], [28], [68], [69]. The Juniper PTX converged supercore [27] unveiled on March 2011 is Juniper's hybrid solution to multi-layer networks. Juniper's PTX stands for "packet transport switch", and, unlike the IPoDWDM solutions described earlier in Section III, this hybrid approach takes integration a step further by combining optical and electronic technologies in a unique box. The combination of hardware and software to develop a single hybrid solution aims to provide integration of IP/MPLS and optical control and management planes. This integration allows to enable coordinated provisioning, planning and modeling, avoiding traditional duplication of management functions. This transport strategy assumes that IP and Optical layers will no longer be isolated ecosystems. In this sense, Juniper's PTX points in the direction of an integrated approach for multi-layer network management. The convergence of packet/optical layers within a single platform derives in seamless integration of their control planes based on GMPLS technology and UNI+, which facilitates multi-layer provisioning, management and restoration. However, an integrated approach aligned to the foundations of Juniper's PTX converged supercore has a number of limitations: (i) integration is constrained to a single vendor—at least with current available technology, hence not solving the MVI problem; (ii) it represents a disruptive approach which requires of new network infrastructures; and (iii) ISPs will quite likely keep buying optical equipment to other transport vendors as well as routing devices to other IP manufacturers, meaning that, this would also have important implications from the business and operational points of view.

Moreover, other hybrid approaches have been researched in academia [68], [69]. The authors in [69] developed a hybrid optoelectronic router in which optical and electrical technologies and complementary metal-oxide-semiconductor (CMOS) electronics are combined into a single router. They demonstrated that such an architecture enables reduction of power consumption and latency while still providing the capabilities required in optical packet switching. R. Cafini *et al.* [68] proposed a modular programmable router architecture to provide dynamic management and configuration of services and resources. Indeed, a relevant contribution of this work is to consider *network programmability* to achieve dynamic network layer functions. The value of featuring network programmability is that it has actually become a must for next-generation networks, and is the main driver for Software Defined Networking (SDN)—more details on network programmability and SDNs as a means to provide flexibility and openness for network infrastructures are given in Section VI-C. Certainly all these approaches for developing hybrid devices are aligned with the belief of improving network management and resource consumption while integrating the management and control planes of different network layers. Conversely, coordinated strategies diverge from this view, based on the belief that an intermediate system should "coordinate" functions in multi-layer environments. In Section VI, we will delve into the future trends in multi-layer network management, and contrast integrated approaches against coordinated ones.

V. THE ROLE OF THIRD PARTY MANAGEMENT SUBSYSTEMS IN MULTI-LAYER NETWORKS

The advent of complementary management subsystems has enabled specific cross-layer management functionalities in the context of multi-layer networks. The Path Computation Element (PCE) [29] and the Virtual Network Topology Manager (VNTM) [70] address cross-layer path computation and cross-layer topology management, respectively. In this section, we will describe the basics and outline the reach of these management subsystems in the context of multi-layer network management.

A. Path Computation Element (PCE)

The Path Computation Element (PCE) [29] is a standardized solution for facilitating optimal constraint-based path computation in (G)MPLS networks. In this architecture, a Path Computation Client (PCC) can request the computation of a path under specific constraints to the PCE, which in turn uses its Traffic Engineering Database (TED) to compute the requested paths. The communications between the PCC and the PCE have been standardized by the IETF in the form of the Path Computation Element Protocol (PCEP) [71]. Note that, providing a detailed description of the PCE is out of the scope of this paper. Instead, our main focus is to position the PCE in the context of multi-layer settings. Readers are referred to [72], [73] for further details on this subject.

There are different choices for the implementation of the PCE, wherein a PCE server can be implemented within a Label Switched Router or as an external PCE that is implemented as a third-party subsystem. The use of a centralized server (i.e., an external PCE) is especially beneficial in networks requiring complex path computation such as Wavelength Switched Optical Networks (WSON). In these networks, the implementation of specific functions for path computation with high complexity in each switch can drive up equipment cost. On the other hand, centralized servers on dedicated hardware designed for path computation would be a more cost-effective solution, especially in large networks. A unique selling point of the PCE architecture is its ability to extend path computation capabilities across multiple domains, including multi-layer networks. PCEs preserve topology confidentiality, which is essential in commercial network scenarios. Also, the decoupling of path computation from network devices means that operators can employ third-party boxes and can control path computation mechanisms and policies with ease, even in a multi-vendor scenario.

To date, the PCE protocol has been standardized for use in MPLS networks and current standardization work is focusing on extending the protocol for supporting networks using the GMPLS control plane [74], and for wavelength assignment in WSON networks [75]. Extensions to the PCE protocol have also been proposed to compute optimal inter-domain paths on a fixed domain chain using the Backward Recursive Path Computation (BRPC) [76].

Current standardization work is also focusing on the use of PCE for multi-layer path computation [70]. PCE has positioned as the candidate solution to overcome the limitations of such networks for providing effective multi-layer TE, which are primarily attributed to the lack of shared network resource knowledge between layers [77]. In this network scenario, multi-domain path computation is not a high priority, but multi-layer path computation is especially relevant as most large carriers typically run a transport as well as an IP/MPLS infrastructure, and would benefit significantly from automated multi-layer path computation. While no definitive solution for multi-layer path computation with the PCE is available today, [70] defines three different mechanisms for the same, namely (i) Single PCE Inter-Layer Path Computation, (ii) Multiple PCE with Inter-Layer Path Computation and (iii) Multiple PCE without Inter-Layer Path Computation.

The Single PCE Inter-Layer Path Computation uses one PCE to compute paths between multiple layers. The PCE has the global knowledge of all topologies and can compute paths across different layers. The Multiple PCE with Inter-Layer PCE communication approach uses PCEs on each layer, having topological visibility restricted to their own layer. This model adapts to the Inter-Domain path computation scenario, where different PCEs are chained to compute a strict path from source to destination. In the case of PCE without Inter-Layer PCE communication, each PCE computes loose paths from ingress to egress LSP, in this case higher level LSP to lower level LSP, building the path traversing every PCE until the destination is reached—referring again to the PCE Protocol model of Inter-Domain path computation with loose hops. Out of these mechanisms, the single multi-layer PCE has the best performance, but the Multiple PCE with Inter-Layer PCE communication approach is better suited for most carrier-grade networks, given the administrative segmentation between the IP/MPLS and transport network in most carrier organizations. The implementation of the same is demonstrated in [78] where the authors use the existing standards to facilitate inter-layer path computation in a MPLS over WSON network scenario.

Aside from the already mentioned schemes for multi-layer path computation, the algorithmic issue for computing such paths is of utmost importance. The main challenge that multi-layer path computation algorithms face is combining different layer-specific constraints to find optimal or near-optimal cross-layer paths [79]. The majority of constraints that condition the set up of a lightpath in an optical network (e.g., wavelength continuity, attenuation, etc.) demand solutions that differ from traditional circuit-based computation methods. In light of this, algorithmic solutions in the context of multi-layer networks must take into account other variants, for example, network device capabilities for performing multi-switching and wavelength conversion in order to compute cross-layer paths under given constraints. In the literature, various multi-layer path computation algorithms have been proposed [79]–[85].

In [80], [81] B. Jabbari *et al.* discuss on the constraints and possible solutions for computing traffic engineering paths in multi-layer switched networks. They propose a solution in which a network graph is transformed into a channel graph that explicitly exposes the constraints of nodes and links, which otherwise are not visible. Authors in [82] extend this approach by combining the transformation technique with a simple heuristic aimed to cope with the increased complexity of the new graph. They also introduce and evaluate a Constrained Breadth First Search (C-BSF) technique where constraints are evaluated on-a-fly fashion based on the BSF search algorithm. Authors in [83] developed an heuristic called *Min-phys-hop* routing and a wavelength assignment algorithm, which assigns a weight to each optical path that corresponds to the number of physical links that comprise it. Based on the belief that an efficient path goes over the minimum number of physical network devices, the least-cost path is chosen. One of the main limitations of this algorithm is that it does not consider network nodes capabilities such as Optical-Electrical-Optical (OEO) conversion or wavelength conversion as considered by other algorithms [80], [81].

In Table I, we summarize the main approaches toward solving the algorithmic issue of multi-layer path computation. Note that, this table does not intend to provide an exhaustive study on multi-layer path computation algorithms. Instead, it provides an introductory and representative list of solid contributions in the field. We have categorized constraints into prunable and non-prunable classes as defined by authors in [80]. The prunable category refers to all those constraints that can be met by simply discarding the elements that do not comply with the required feature from the path computation process, e.g., bandwidth requirements, wherein potential paths not meeting a bandwidth constraint can be excluded from the path search process. The non-prunable category, on the other hand, usually comprises the set of constraints that require more complex computation strategies taking into account multiple network attributes along the whole path. For instance, in networks where certain nodes are endowed with wavelength converters, the lack of a common wavelength along the entire path is not sufficient to discard the latter as a potential candidate, since we must also assess the wavelength conversion capabilities at intermediate nodes along the path. Indeed, determining whether a constraint is prunable or not is also subject to design requirements. Multi-constraint path computation algorithms generally follow one of two approaches, namely, computing paths over the raw network graph and then performing robust runtime constraint evaluation (e.g., algorithms based on linear programming), or graph transformation techniques, where network graphs are transformed into elaborated graphs capable of representing a set of given constraints [82]. For more details on the algorithmic issues we refer readers to the references found in Table I.

TABLE I
MULTI-LAYER PATH COMPUTATION ALGORITHMS

Constraint Type		Proposed Path Computation Algorithms
Prunable	*Based on bandwidth requirements* *Based on protection requirements* *Based on policy constraint requirements*	• Several variants of CSPF (Constrained Shortest Path First) [86]
Non-Prunable	*Additive (e.g., attenuation, dispersion, delay, etc.)*	• KSP (K Shortest Paths) [87], [88], [89]
	Non-Additive (e.g., wavelength continuity, switching capability, etc.)	• Common Vector [80] • Constrained Breadth First Search (C-BFS) [82] • Channel Graph-based solution [80], [81] • Label-Layer Graph-based solution [82] • Auxiliary Graphs [90], [91] • Dynamic VNT Configuration Algorithm [79]

Note that, despite of all the ongoing standardization efforts in the field of cooperative path computation—some already discussed herein—many issues still remain open for research. Consider for example, the computation of a cooperative path between several PCE's based on proprietary objective functions operating on non-standard constraints. Current framework does support encoding of standard and proprietary objective functions [92]. However, there are no available mechanisms in the current definition of PCEP for conveying vendor-specific information on which proprietary objective functions rely. Authors in [93] have recently proposed a mechanism for conveying vendor-specific constraints in PCEP in which they define a dedicated object—the "vendor information object"—to convey vendor-specific information. In light of this, there is still many to be done in the scope of multi-layer path computation. The realization of all these efforts and proposals are indeed required in the way for achieving a truly mature technology suitable to the complex requirements of multi-layer and multi-vendor carrier-grade infrastructures.

B. Virtual Network Topology Manager (VNTM)

The Virtual Network Topology (VNT) is the network topology formed by lower layer LSPs and the logical view of these connections in the upper layer [52]. The relationship between both layers is created with "virtual TE links" [94]. The virtual TE links are potential connections between two nodes at the upper layer, which are based on possible connections at the lower layer (i.e., not fully provisioned LSPs). The Virtual Network Topology Manager (VNTM) is an entity in charge of maintaining the topology of the upper layer by connections in the lower layer [70].

To optimize the overall use of network resources in multi-layer environments, there are basically two requirements: (*i*) a cross-layer path computation strategy to compute end-to-end inter-layer paths and (*ii*) mechanisms to control and manage the VNT by provisioning and releasing connections in the lower layer. In this regard, the VNTM and the PCE are both key entities for coordinating and managing multi-layer paths. While the PCE is responsible for computing the path between endpoints, the VNTM initiates the signaling for circuit setup or decommissioning in the transport layer [78].

There are two possible cooperation models for inter-layer path computation, namely, the *PCE-VNTM* or the *NMS-VNTM* cooperation models [70]. To illustrate the relationship between the PCE and the VNTM for multi-layer path computation in a PCE-VNTM model, let us consider the example shown in Fig. 8. In this case, a single PCE is used to compute paths between both layers (i.e., a single inter-layer path computation strategy, as described in the previous section). Let us assume that, the single-layer PCE fails to compute an inter-layer path because no logical connection is set up in the upper layer (IP; PCE). In such conditions, the PCE can request or suggest to the VNTM additional connections in the lower layer (OXC; VNTM). If the PCE has visibility of the lower layer topology it can explicitly suggest a given path or it can just exchange information on the upper layer request and wait for the advertisement of the new virtual TE link. Moreover, the VNTM could change the connections to the upper layer if its policies indicate that a better configuration exists. The operation mode of the VNTM could be any solution even using another PCE to compute lower layer LSPs.

Another approach to inter-layer path computation is when the VNTM is part of the NMS (NMS-VNTM model [70]) (cf., Fig. 9). This model assumes that the VNTM can be embedded within the NMS to cooperate in the set up of lower layer LSPs. In this scenario, the NMS requests the PCE to compute a path and upon receiving the result of such computation, the NMS is able to request the VNTM to create a new connection. The interface to request a connection is not currently described or defined in any RFC (this is why we represent the interface between the NMS and the VNTM in Fig. 9 with an interrogation mark). In [70] a TMF standard interface is proposed, while authors in [78] propose the utilization of the PCEP protocol with a new message to suggest a new route to the VNTM, so the VNTM can decide, based on its policies, if creating the connection or not.

Based on the previous definition of the VNTM, the virtual TE link creation is done from the source IP/MPLS router to the destination router. This means that the VNTM must have information not only about the lower layer, but also about the interlayer connections between the IP/MPLS routers and the OXCs. However, automatically building and accurately keeping updated the inter-layer connections remains an open issue. State-of-the-art protocols, such as the Link Management Protocol (LMP)

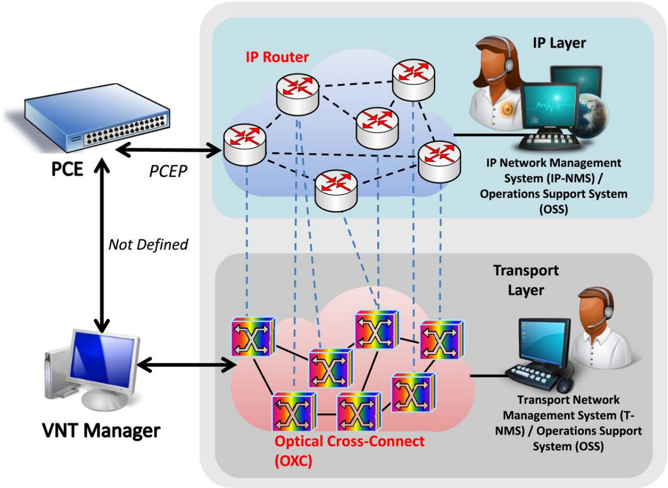

Fig. 8. An example showing one possible PCE/VNTM configuration.

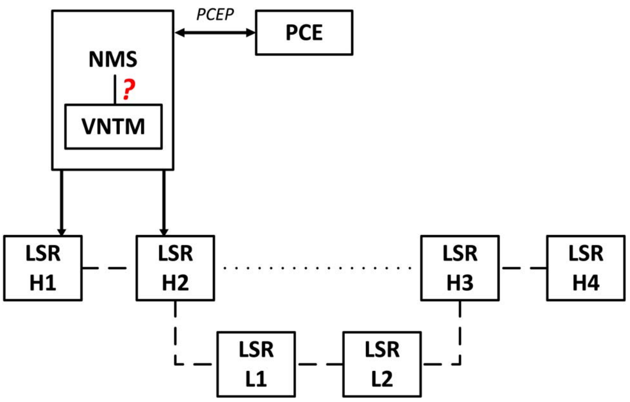

Fig. 9. Another example of a PCE/VNTM configuration with a VNTM entity embedded within the NMS.

[95], offer palliative solutions. This point-to-point protocol, defined by the IETF, is used by GMPLS devices to feature link discovery, i.e., determine data plane connectivity of network nodes to and from its neighbors. Link verification and fault isolation are also featured by this protocol to check on the status of links and to isolate faults that may occur, respectively [96]. Nevertheless, LMP is not widely used by ISPs mainly because current deployed multi-layer networks do not provide full integration of GMPLS technology. Actually, in practice most ISPs remain relaying on databases, most of which require human intervention for feeding and updating inter-layer topological data.

In summary, the emergence of management subsystems was envisioned to simplify and partially fulfill a set of management functionalities that were not covered by existing solutions. This makes mandatory to consider the integration and future requirements of third-party subsystems in multi-layer management infrastructures.

VI. FUTURE TRENDS IN MULTI-LAYER NETWORK MANAGEMENT

A. *Coordination vs. Integration*

Integrated and coordinated approaches both offer a path for addressing current multi-layer network management challenges. The integrated approach (cf. Fig. 10(a)) proposes to unify the two separate NMSs into a single entity, enabling management automation and reduction of operational expenditures. This figure shows two possible configurations. In the first one, the IP and Optical devices are part of separate layers—as in traditional multi-layer deployments—but their management planes are unified under a common NMS. In the second configuration, the IP and Optical equipment are integrated into a single box with a unified management plane. Examples of the former are the integrated control plane and management plane frameworks [50], [63]–[65], and for the latter, the case of Juniper's hybrid node [27].

Unfortunately, these approaches pose complex challenges both technically and operationally. For instance, multi-layer network management issues cannot be fully addressed by the integration of network control planes per-se, as they do not fulfill all management competencies. Therefore, under this scenario, the management planes of both layers would also require a level of integration; otherwise, cross-layer service management operations (i.e., provisioning, monitoring, alarm correlation, scheduling, etc.) will not be possible. Furthermore, the integration of network management systems aggregates a measure of disruption. More specifically, the integration of the IP-NMS and T-NMS entails a change of perspective in current carriers' practices, and therefore, a major investment must be done to acquire and adapt to the new management environment. The traditional separation between the IP and transport network layers has demonstrated significant resistance to such a game change, given its implications on the operational, functional and business strategies. Moreover, a successful network management integration can only be useful for a single domain, since domain administrators are reluctant to sharing performance information about their networks.

In light of all these limitations, coordinated network approaches (cf. Fig. 10(b)) are positioned as reliable solutions for multi-layer network management. Coordination of cross-layer network operations can help not only to reduce operational and capital expenses, but also to significantly simplify operational processes and reduce administrative burdens. A coordinated approach is based on the idea of a mediator system (shown in Fig. 10(b)) capable of overcoming the barriers of protocol differences and network equipment heterogeneity. A mediator can address the MLI and MVI issues without requiring major changes in network practices or the technologies currently being used by network operators on both layers. Additionally, the coordinated approach can easily be adapted to meet future application demands, as its adoption does not cause any disruption to current network practices.

One emerging initiative in this direction is the *ONE Adapter* [97], a solution for enabling interoperability in a coordinated fashion. The ONE adapter is based on a mediator model, which has been designed to operate between the IP/MPLS and the transport layer NMSs. It allows system automation and coordination of cross-layer network management functions. This initiative proposes a non-disruptive solution that only requires to interface with the IP-NMS and the T-NMS. Furthermore, it does not require changes to current carriers'

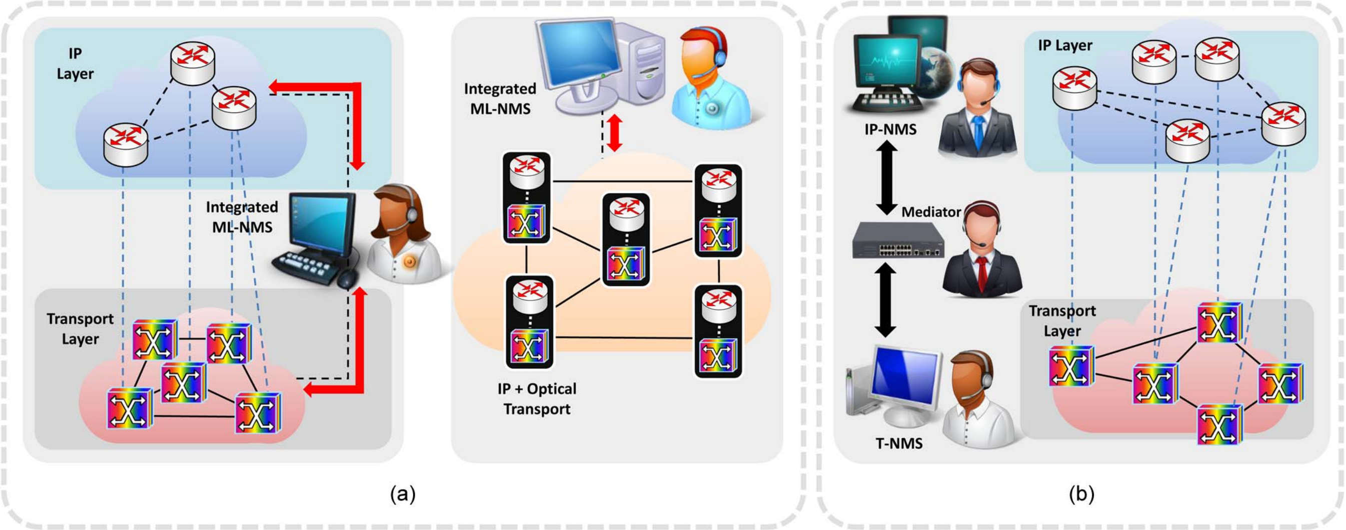

Fig. 10. Integrated vs. coordinated approaches for multi-layer network management.

TABLE II
ADVANTAGES AND DRAWBACKS OF INTEGRATED VS. COORDINATED MULTI-LAYER NETWORK MANAGEMENT SOLUTIONS

Approach	Advantages	Drawbacks
Integrated	• It reduces the management and operational costs. • It centralizes management tasks (single point of operation). • It provides overall view of the multi-layer network infrastructure.	• It requires big changes in the network structure and in current practices. • It is hard to adapt to meet future application demands. • It hardly deals with multi-vendor interoperability issues. • Its adoption disrupts the networks' regular activities. • It is difficult to deploy. • It requires to be integrated in all layers. • It has high deployment costs.
Coordinated	• It requires neither big changes in the network structure nor in current operational practices and business workflows. • It can be easily adapted to any type of environment to meet the future application demand. • It can easily deal with the multi-vendor interoperability issues. • Its adaption does not disrupt the networks regular activities. • Its deployment is easy and needs only to be interfaced with the IP and the transport NMSs. • It allows functionalities, which do not exist in the control plane frameworks. • Its functions are domain and layer independent.	• Cannot directly manage the networks nor it can make changes to the IP layer or the transport layer without the intervention of the NMSs at each layer. • Its normal workings depend on the responsiveness of third party systems (e.g., PCE) as well as the IP and the transport layer NMS.

practices. The ONE adapter is particularly useful for management actions such as coordinated self-healing, coordinated IP traffic offloading, and coordinated service provisioning. The ONE approach also allows coordination of network management functions in a multi-vendor environment, thus addressing the MVI problem as well. One of the key features in ONE is its ontology-driven nature, which enables syntactic adaptations based on shared semantic knowledge of different vendor spaces.

Table II summarizes the advantages and drawbacks of coordinated versus integrated multi-layer network management.

B. *Enabling Technologies for Coordinated Approaches*

In addition to the numerous advantages and benefits that a coordinated approach can provide to address the MLI and MVI problems in the context of network management, we have identified a number of emerging technologies that can assist in the implementation of truly coordinated platforms.

Beyond the scope of traditional mechanisms for network management, there are a number of technologies capable of enabling enhanced functionalities to this critical area of networking. MTOSI [17], NETCONF [16], semantic approaches and OpenFlow [18] are among the most relevant enablers for providing support to the field of multi-layer network management. Despite the fact that some of these technologies (e.g., semantic technologies and OpenFlow) were not initially designed for the purposes of network management, they have an interesting potential that can ease and address the management interoperability gap in multi-layer and multi-vendor settings. In this section, we will provide insights on the potential integration of these technologies in order to understand what makes them appealing for their applicability in the area of coordinated Multi-Layer Network Management (MLNM). It is worth highlighting that given the impact of OpenFlow, this technology will be further analyzed in Section VI-C as part of the Software Defined Networking (SDN) umbrella.

NETCONF: To fill the existing gap in the configuration of IP network equipment, in early 2003 the IETF created a working group to define and develop a *standard* configuration protocol. The result of this effort is the Network Configuration Protocol (NETCONF), specified in [16] as an IETF standard. NETCONF was defined to cope with the needs of providing configuration state maintenance, transactional-safe operations across multiple devices, separation of configuration from operational data, concurrency, consistency, and support to multiple configurations, in a standard and easy way of use. This set of requirements gather the most remarkable characteristics of CLI-based mechanisms along with the desired features of network providers in the scope of configuration management [98].

Some of the key features of NETCONF are: *i*) the ability to distinguish configuration data from operational data, i.e., variables that can be set by the administrator from statistics, alarms, notifications, etc.; *ii*) support to transactions, meaning that, it ensures completion of configuration tasks—not only on a device basis but even, on a network basis—otherwise, rollback operations are automatically performed; *iii*) transport protocol independence; *iv*) support to configuration locking; and *v*) filtering mechanisms that enable selected retrieval of configuration data [19]. Most importantly, NETCONF features automated ordering of operations, which means that the complexity of task sequence ordering is pushed from the operator's side into the device. Its design is flexible and extensible enough to be implemented and deployed by all vendors. Note that this is not an advantage over other protocols, such as SNMP, but is a *must* if NETCONF intends to become a widely adopted standard.

The complexities of SNMP and the proprietary nature of CLI-based mechanisms, have pushed toward the initial implementation of NETCONF in IP/MPLS vendor's equipment (e.g., Juniper and Cisco) as a means to guarantee the performance of the configuration procedure. The inclusion of NETCONF will enable operators to deal in a standard and reliable way with multi-vendor infrastructures, significantly decreasing the operational expenditures. However, as exposed earlier in Section II-B, the definition of network management information within NETCONF raises clear interoperability issues that still represent an important limitation to its wide acceptance and deployment. Most recently, YANG [41]—the IETF's proposal for a standard data model—has become the strongest candidate for the formal representation of network configuration management information. It provides well-defined abstractions of the network resources that can be configured or manipulated by a network administrator, including both devices and services. Currently, the IETF is working on the definition of standard YANG modules, to which vendors are expected to comply with in the future. To date, several Internet-drafts have been introduced for the definition of the interface, IP, routing, SNMP and system management data models [99]. However, there is still a long path before NETCONF and YANG become mature technologies and established as the default standard for IP network management configuration. Though, the future of NETCONF and YANG is promising and the interest of network device vendors is growing, almost eight years after its initial proposal, CLI-based mechanisms continue to be the preferred way for configuring network devices. For this reason, and based on the fact that a solution is required for current network settings, we envision semantic technologies as a promising enabler for the integration of dissimilar protocols in the scope of network management. We proceed to briefly describe the potential of these technologies in the scope of a coordinated platform dealing with heterogeneous protocols.

Semantic Adaptations: Semantic adaptations serve as a promising approach for enabling future coordination of multi-layer management. When combined with current available technologies (e.g., ontologies, data mining, artificial intelligence, natural language processing, etc.), semantic approaches can provide the means for achieving true interoperability in the configuration management of multi-vendor environments.

Semantic technologies can be envisioned as integrators across multi-vendor scenarios, providing the means for carrying out the mappings between data formats (e.g., CLI commands) of different device manufacturers based on the common semantics which define the configuration domain. In the context of IP device configuration, the *semantics* could be extracted, for example, from the "help set" provided to users in the form of text through the CLI environment or configuration manuals [97]. Regardless of the heterogeneity of device and configuration environments, configuration commands share common semantics (i.e., meaning) intrinsic to the domain of interest. Indeed, semantic approaches can significantly contribute to bridge the gap between heterogeneous devices by providing an agnostic view of configurable network resources.

The benefits that semantic approaches can provide go beyond the scope of seamless device configuration, and can be devised for any other scope in which the existence of diverse protocols or mechanisms lead to heterogeneous scenarios. They provide an evolutionary solution to current MVI problems through an intelligent, flexible, and extensible approach. Semantic adaptations can thus improve and enhance the experience of the final user, abstracting network managers from the particularities of each language or format, thereby removing the complexity that is left in the hands of operators (which is error-prone and highly restricts the level of automation of management tasks).

Semantic technologies can be combined with machine learning techniques [101] to develop software agents capable of semantically and syntactically adapting configurations for easing tasks in multi-layer and multi-vendor environments. In the literature, several research efforts can be found aligned with the use of semantic technologies to address the problems inherent to the network management domain [102]–[105]. For example, in [103], [104] H. Xui and D. Xiao consider the application of ontology languages to bring intelligence into the network management plane to enable automated configuration. Authors propose a general model in which three ontology-related languages are considered. They propose, firstly, the Ontology Web Language (OWL) [43] for modeling the domain knowledge, secondly, the Semantic Web Rule Language (SWRL) [106] to add behavior information—such as axioms and constraints—and finally, OWL-S [107]—a semantic markup language for Web Services—to automate the execution logic based on the use of Web-Services. In short, authors envision the use of Semantic Web Services for automation of network management and propose standardization of network management information on this basis. Moreover, in the work led by López *et al.* in [105], authors thoroughly analyze and compare several management information definition languages on the basis of their semantic expressiveness. The goal is to integrate different management models based on ontological mapping and merging techniques to create a global management ontology encompassing a huge set of information models (e.g., Structure of Management Information version 2—SMIv2, Managed Object Format/Common Information Model—MOF/CIM, etc.). Finally, Wong *et al.* [102] proposed a generic ontology-driven solution to the interoperability problem in network management. In this approach, ontology concepts are matched based on the similarity measure obtained through a novel function developed by the authors.

As seen, semantic technologies have already been considered in previous research studies to address the interoperability issues in network management as well as in many other fields (e.g., health care, product design, biomedicine, etc.). Nevertheless, there are still many open research lines that must be explored in order to exploit and properly use the resources offered by device manufacturers.

MTOSI: In the field of optical transport networks, MTOSI [17] has emerged with great force as a technology for enabling standard communication between multiple OSS (e.g., Element Management Systems, Network Management Systems, Service Activation Systems, Fault Management Systems, etc.), covering both service and resource management. This standard has been specified by the TeleManagement Forum (TMF) to provide a common interface to manage *multi-technology* networks. It is an XML/Web Service-based interface, that is independent from the underlying transport technology. MTOSI enables interoperability between the Service, Network and Element Management Layers of the Telecommunications Management Network (TMN) layering model.

The general specifications of the interface maintain that MTOSI will be used between OSSs within the same administration [100]. Hence, it covers the interoperability requirements of current Service Providers which use multiple management systems to manage complex multi-vendor and multi-technology networks.

To illustrate the MTOSI reference architecture let us consider the example shown in Fig. 11. This figure provides a view of the communication between different OSSs enabled through MTOSI at different levels. The interaction between the management systems is done over the Common Communication Vehicle (CCV). As depicted in the figure, in typical network settings (i.e., a multi-vendor scenario) a NMS—or other type of OSS—directly connected to the CCV can be at the same time managing underlying Element Management Systems (EMSs), which in turn manage network elements of a single vendor based on other management protocols (e.g., SNMP, TL1, CMIP, etc.). For this example, a Fault Management System providing an MTOSI-based interface can retrieve inventory from an Inventory OS to effectively fulfill its management functions.

During the last few years, MTOSI seemed to become the future standard for enabling interoperability between OSSs in the transport layer. This web-based interface was positioned as a rather appealing technology for overcoming the limitations in the scope of network management. However, a change in perspective in the field has made MTOSI lose momentum and instead, attention has turned most recently to Software Defined Networking (SDN), a new emerging technology with the power for taking the management solution to the next level.

SDN has become an increasingly popular concept whose potential certainly opens the field for research and innovation. For this reason, in the next section we will provide insights on SDNs capabilities and on the challenges from a management point of view.

C. *Software Defined Networks*

We could say that Software Defined Networking (SDN) is the current fulfillment of an old-time promise: providing the possibility of programmability of network functionalities, while offering a clear path for network management to follow the same direction of other Information Technology (IT) fields toward virtualization.

The idea of a flexible real-time control of network functions has been considered several times in the past, with proposals ranging from the use of "programming packets" to transmit the desired behavior to network boxes, up to the implementation of adaptive control both in software and hardware. However, the combination of radical decoupling and open interfaces that constitutes the kernel of SDN is a novel proposal that has gained a strong momentum, especially, with the advent of a protocol that demonstrated the feasibility of this approach, and allowed the deployment of real-scale SDN-based networks: OpenFlow [18].

The complexity and lack of flexibility of standard network devices has made network experimentation and innovation highly difficult at all scales for academic researchers. Any change to the software embedded in each device had to be coordinated between vendors in order to make the distributed control algorithms interoperable. Therefore, evolving at the pace required by research and experimentation was extremely difficult. In this context, OpenFlow was born as a cornerstone. The first step was to develop the ability to program switches from a remote controller. Realizing that this implied external software-based control of the data plane, bypassing traditional L2 and L3 protocols and associated configurations, was a natural consequence.

Software Defined Networking relies on two main assumptions. The first is a radical separation between the control

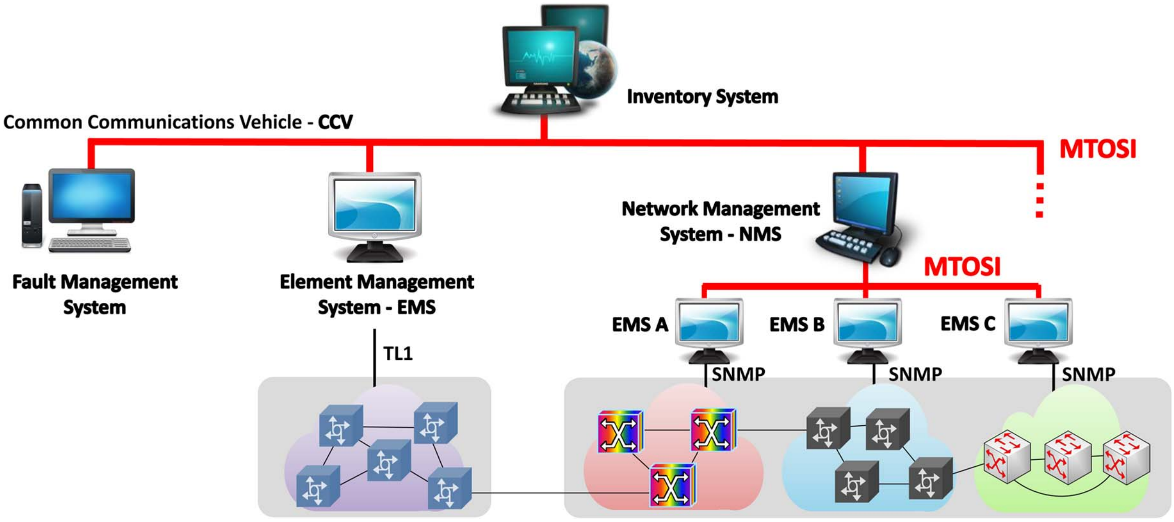

Fig. 11. MTOSI reference architecture example (adapted from "Framework DDP BA TMF518 FMW Version 1.2" [100]).

and the data planes, located in two (most often physically) independent entities: the controller, in charge of the control plane, and the switches, responsible for the functions in the data plane. The choice of singular and plural in the definition above is completely intentional: although not required by the model, the obvious deployment consists of a single controller taking care of several switches in a certain realm. The second assumption is the availability of an open protocol between controllers and switches, allowing for a free combination of elements from different vendors to provide network functions, and of an open interface to the control plane, so the controller can be uniformly accessed by other components participating in the network, such as sources of network intelligence or applications in general.

The most widely deployed SDN protocol, OpenFlow, is based on the definition of rules from the controller to be applied by the switches when receiving packets. Rules are fired by matching certain parts of the packets (or the path they arrive through), and contain actions to be applied to those packets, such as forwarding them to a certain path, making some changes to them, or even discarding them.

In summary, in SDN control decisions are taken by a central element, while switching decisions are actually applied by distributed elements. A common protocol allows the controller to communicate its decisions to the switches. Having this central element translates into the possibility of abstracting the network into a single element, as it becomes the one in charge of the whole network behavior. Furthermore, the common protocol acts in a similar way to a processor instruction set controlling its registries, processing units and peripherals, and therefore the network becomes a programmable entity, suitable to be controlled in the same way as any other element in the whole computing infrastructure.

A general architecture for SDN-based network management is proposed in [108] (shown in Fig. 12), where an *SDN Mediator* communicates with applications and services, and translates requests to the physical network components. This mediator relies on a database containing network topology and component information, and it is able to provide a fully virtualized view to applications and services. The mediator controls several processes:

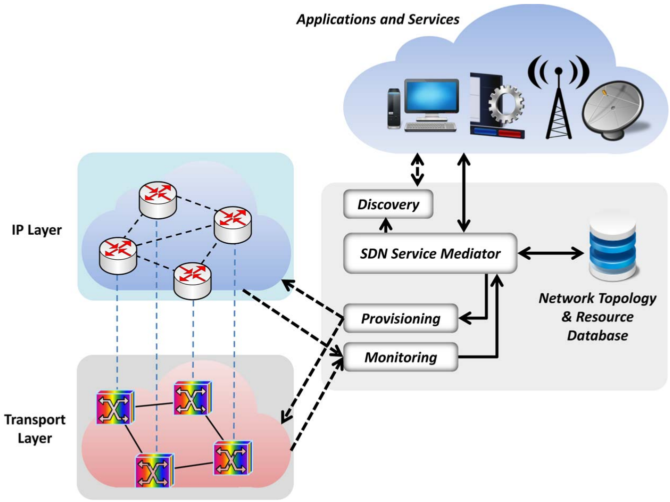

Fig. 12. Mediator architecture for SDN-based management.

- ***Discovery***. It enables the SDN users to discover and register to the Service Mediator. As a part of the discovery process, the SDN users may negotiate capabilities with the service mediator.
- ***Provisioning***. It allows the Service Mediator to provision the underlying network resources. While in principle the provisioning process should rely on OpenFlow, it is conceivable the use of other protocols to create or adjust traffic engineering connections.
- ***Monitoring***. This allows the Service Mediator to interface with the underlying network to gather topology information at an abstract level, and detect the network failures that may impact applications and services.

A more radical approach is taken by a group of the original OpenFlow proponents [111], who present a unified control for packet and transport networks, claiming that with separation of data and control, and the treatment of packets as flows, together

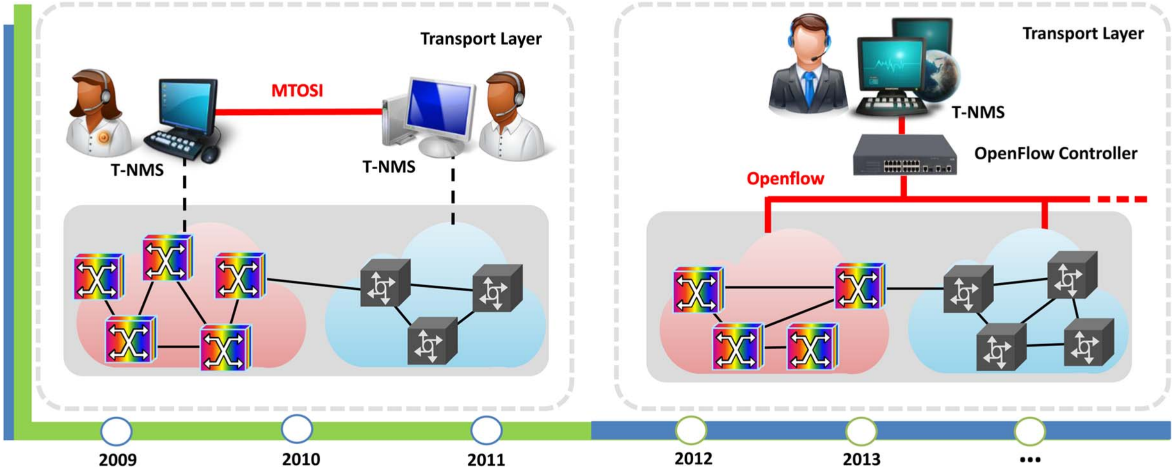

Fig. 13. Network management trend: SDN over MTOSI.

with the introduction of circuit-flow features in the OpenFlow protocol, a unified architecture becomes realizable for converged packet-circuit networks. OpenFlow abstracts each data-plane switch as a flow table. It allows the definition of a flow to be any combination of L2-L4 packet headers for packet flows, as well as L0-L1 circuit parameters for circuit flows.

Whether a mediator-based or a SDN-only approach is followed, it is important to remark four salient characteristics implied by the use of SDN for multi-layer network management:

- Since the network elements are controlled via a (few) uniform protocol(s), the management database can be greatly simplified.
- Management commands and/or configuration are always translated into pairs of the type $(\texttt{device}, \texttt{rule})$, and it is possible to override layer separations, device original functions, and other potential limitations in other models. A multi-layer management plane is a natural consequence of applying SDN, even if not a full integration is pursued.
- The northbound API can be adapted to provide different management views to the application services, not limited by individual elements, links or layers being managed. The network functions can be fully virtualized.
- This virtualization possibilities translate into an easy extensibility of the configuration programmatic interface, able to being updated according to the application/service needs, even in a real-time or *ad-hoc* manner.

Another important aspect is that with the advent of SDNs, the range of multi-layer capabilities has significantly increased, since open programmability enables that new applications can take control of network resources across all layers in the OSI stack (cf. Fig. 1). Observe that, in this paper, we have focused on multi-layer capabilities across the transport and network layers of a typical carrier-grade network, but SDNs also bring a plethora of possibilities to upper layers, allowing applications to intelligently combine network functions at different layers. Consider for instance some of the recent research advances combining the utilization of OpenFlow and the Multi-Path Transport Control Protocol (MPTCP). In this particular example, the goal is to intelligently and transparently assign traffic to multiple paths in order to improve the resilience, the stability, and the performance of different types of communications [112]–[116]. Another interesting approach can be found in [117], where a cross-layer cooperation module is defined between MPTCP and the Locator/Identifier Separation Protocol (LISP). In this example, the goal of the authors is to improve both the performance and the transfer time between the endpoints.

An example involving even a higher number of layers can be found in [118], wherein the authors propose a methodology to extend Open VSwitch (OVS)—an open-source OpenFlow switch—to support L4-L7 service awareness. Moreover, SDN for transport networks [119], [120]—in correspondence to our earlier discussions—has recently gained a lot of attention, and is considered one of the potential candidates for enabling packet/optical integration, and thereby, improve existing multi-layer path provisioning techniques [121]–[123]. Indeed, there are ongoing efforts within the Open Networking Foundation (ONF), for standardizing transport extensions to OpenFlow so as to enable SDN in optical networks. In the meanwhile, several approaches to SDN for the transport layer have already been developed. For example, ADVA, in a joint effort with IBM and the Marist College, have recently demonstrated an SDN solution for transport networks, mainly targeting the dynamic set up and tear down of wavelengths between data centers. Overall, SDN has become a revolutionary paradigm shift in the telecom field, and it is expected to have a significant impact on our conception of networking. The potential is remarkable, but the status of SDN-based applications enabling multi-layer functions in carrier-grade networks is still in a very early stage of development, so substantial research is needed before we can start witnessing the deployment of solutions in operational networks.

It is unquestionable that the advent of SDNs has weakened the power of MTOSI, which, only a few years ago, was positioned as the predominant trend for enabling transport network management interoperability. The paradigmatic differences between the two approaches has shifted the tendency toward SDNs. As shown in Fig. 13, this shift suggests that, in the future, the interest will no longer be focused on the communication between multiple OSS (i.e., the MTOSI

TABLE III
OBSTACLES AND PITFALLS, PATHS TOWARD SOLUTIONS, AND LESSONS LEARNED FOR MANAGING MULTI-LAYER AND MULTI-VENDOR SETTINGS

Obstacles and Pitfalls	Paths toward Solutions	Lessons Learned
Absence of standards and/or broadly accepted mechanisms to enable network management interoperability	• An early solution to the interoperability problem in network management was SNMP [33]. Despite being the de-facto protocol for network monitoring in IP-based networks, SNMP has failed to fulfill other scopes of network management, such as device configuration. • Most recently, NETCONF [16] is envisioned for device configuration and MTOSI [17] for OSS interoperability in transport networks. • OpenFlow has arised in the context of SDNs [18].	The absence of standard protocols prevents automation of cross-layer management operations, leading to manual management of current multi-layer infrastructures. Standard protocols for network monitoring (e.g., SNMP and most recently Web Services) and network device configuration (e.g., NETCONF or OpenFlow) are not sufficient to enable management interoperability across multi-layer platforms. For instance, Network Managers require means (i.e., mechanisms, platforms) to coordinate between both layers to optimize resource usage, avoid duplication of network functions and automate/execute cross-layer workflows.
Segmentation of Standardization Bodies	• For instance, MPLS-TP [58]	Solutions to multi-layer issues require of standardization bodies behind each domain (i.e., IP and Optical) to be aligned and to develop joint efforts to generate fully-compliant requirements and solutions to both technology layers. An example to this, is the MPLS-TP technology which begun as an ITU-T effort under the name of T-MPLS. However, IETF—the developers of MPLS standards—determined a set of inconsistencies between T-MPLS and native MPLS. They requested to extend the IETF's MPLS technologies to packet transport networks through the IETF Standards Process in a joint effort between both parties to consolidate a solution aligned to the IETF standards and fulfilling ITU-T requirements.
Poor Coordination across layers	• In-house developments are early attempts to coordinate multi-layer tasks in a static (i.e., pre-configured) way. • Most recently, the ONE Adapter [97] has approached multi-layer management in a coordinated fashion. • Coordinated systems based on SDN's (mediator models).	The lack of coordination between layers in multi-layer networks has led to duplication of network functions and long provisioning timescales. In-house developments have been for long time a way to flatten the issues in multi-layer management. However, the lack of flexibility makes them useful in scenarios where fixed solutions are sufficient. However, multi-layer management requires much more flexible, dynamic, programmable (i.e., configurable) solutions capable of overcoming the barriers of layer segmentation.
Lack of Cross-Layer Network Management Automation	• For instance, GMPLS control plane [9].	GMPLS is positioned as the unified control plane solution for dynamic path provisioning in multi-layer networks. However, neither these solutions are widely deployed nor control plane technologies are capable of addressing all the needs and requirements from a management perspective (e.g., proactive execution of policy-based workflows with cross-layer components, IP device configuration, etc.).
Limitations for Proactive Enforcement of Policy-based Management in Multi-Vendor settings	• In-house developments (i.e., umbrella NMSs).	Network programmability is a must in order to develop scalable solutions capable of adapting to the changing nature of network behavior. Network administrators require of flexible solutions that enable on-the-fly policy enforcement to bring dynamics to the multi-layer environment.
Overburden of multi-layer functions which add on the basis of their complexity (e.g., computation complexity) - (embedded complexity)	• Outsourcing of multi-layer functions, examples are the Path Computation Element (PCE) [29] and the Virtual Network Topology Manager (VNTM) [52]. • Virtualization and Network Functions Virtualization (NFV) [109].	The advent of third-party (i.e., external) management subsystems, represent a unique opportunity to be integrated into future solutions to help solving cross-layer issues. For example, a PCE for outsourcing computation of multi-layer paths. In this field, yet some issues still remain open. For instance, the communication protocol between entities for coordination of cross-layer functions (e.g., the communication between the NMS and the VNTM in a cooperative model for multi-layer path computation has not been yet defined).

paradigm), but instead, the new paradigm will be the one-to-multiple approach followed by SDNs for achieving true network programmability and virtualization through open and clear APIs.

VII. CONCLUSION AND LESSONS LEARNED

The multi-layer core infrastructures of large ISPs have evolved as administratively separated ecosystems. This business-driven separation has led to the operational and managerial isolation of both layers. The lack of mechanisms enabling communication from a management perspective has clearly derived in interoperability issues between layers. Several initiatives can be found in the fields of control plane and data plane technologies, though none of these is capable of addressing the needs and requirements that arise from the management point of view. In addition to this, the emergence of new trends in the field of IP over Optical transport (e.g., hybrid nodes, proprietary multi-layer NMSs, etc.) pose new challenges in the management of heterogeneous network environments.

The integration and coordination of network management solutions in the context of multi-layer networks are among the most predominant approaches for overcoming the isolation between the management ecosystems. These approaches can enable

TABLE III
(Continued.) OBSTACLES AND PITFALLS, PATHS TOWARD SOLUTIONS, AND LESSONS LEARNED FOR MANAGING MULTI-LAYER AND MULTI-VENDOR SETTINGS

Obstacles and Pitfalls	Paths toward Solutions	Lessons Learned
Inadequate discovery mechanisms of Inter-layer connections	• Manual Topological Databases.	Manual topological databases are error-prone, hard to maintain and present poor scalability features. Inter-layer discovery remains an open research challenge and requires of **automated** solutions capable of overcoming the restricted view (i.e., shared information) between layers.
Deficient mechanisms for seamless network device configuration (e.g., the preferred configuration mechanism in IP-based networks is CLI)	• NETCONF [16], a standard-based solution to the configuration issue in IP-based networks. • OpenFlow [18].	Standardization of network management protocols is not sufficient to overcome the configuration heterogeneity issue in multi-vendor environments. In this view, standardization of data models is equally relevant to the configuration domain to comply with a standard view of the network elements.
Organizational Barriers (i.e., Department segmentation)	• Integrated Network Management Solutions, e.g., Cyan's CyMS [50] or Juniper's PTX hybrid node [110].	Integrated solutions have important implications on current practices. On the one hand, the traditional separation between the IP and Optical Departments is reluctant to a game change from the operational, functional and business perspectives. To this end, emerging solutions should seek for non-disruptive approaches from the business model point of view. On the other hand, current integrated solutions are subject to single vendor scenarios, a non-desired feature by network operators.
High Operational and Capital Expenditures for managing Multi-Layer Settings	• Network Functions Virtualization (NFV) [109] and Software Defined Networking (SDN) [108]. • IPoDWDM solutions integrate transponders directly into the IP routers enabling IP equipment to transmit ITU-compatible coloured wavelengths directly to the optical gear.	IPoDWDM solutions claim to reduce costs generously due to simplification of the network, at the cost of moving lower layer complexities to the upper layer, since routers have never had to deal with wavelength issues. This is somehow debatable as an assertion of this type depends on many factors (e.g., is implementation-dependent). Anyway, newly emerging solutions require to lower OPEX and CAPEX while maintaining the simplicity of network operation. Moreover, featured virtualization functions are undoubtedly of huge interest for ISPs, and will potentially contribute to significantly lower costs (CAPEX), while the benefits that SDNs technologies bring along to the field of network management will impact on the OPEX.

interlayer interoperability, which can in turn significantly reduce the operational and capital expenses while facilitating a number of complex orchestrations required for management operations. Our research has identified that coordinated approaches seem to be the most suitable alternative, especially, for achieving automation of cross-layer operations, avoiding the redundancy of management functions, reducing operational and capital expenses, providing a smooth evolutionary practice, while offering higher flexibility. Examples such as the ONE Adapter in [97], as well as the mediation scheme for SDN-based management presented in Fig. 12, are indicative initiatives that envision the direction of a mediation model for truly accomplishing interoperability through the coordination of both layers.

In Table III we summarize the obstacles and pitfalls, the paths toward solutions, and the lessons learned in the management field of multi-layer networks. The aim is to provide a closer look into the main challenges, and summarize the issues that must be addressed by the research community in terms of future multi-layer management solutions. The future of network management for multi-layer network settings is not a clear panorama. However, the emergence of NETCONF, MTOSI, SDN supported through OpenFlow, as well as the consolidation of Web Services and many other new trends in the field of IP over Optical, are key indicators that a change of perspective is required to address the isolation of management ecosystems and improve multi-layer performance.

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