TeraFlowSDN White Paper

ETSI TERAFLOWSDN ALIGNMENT WITH TIP OOPT MUST REQUIREMENTS

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TeraFlowSDN

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Introduction

The collaboration amongst Network Operators within the Telecom Infra Project (TIP) Open Optical & Packet Transport (OOPT) group[1] has resulted in the selection and development of a shared set of network device management interfaces, along with the creation of the data models necessary to address their required use cases. The group's efforts have been documented in various white papers and documents, establishing the **M**andatory **U**se Case Requirements for **S**DN for **T**ransport (MUST).

This whitepaper aims to analyze the operators' requirements for SDN control of transport networks, as defined by the Telecom Infra Project, Open Optical & Packet Transport (OOPT) group. ETSI TeraFlowSDN, a novel Cloud-native SDN controller and SDN orchestrator (hierarchical SDN controller), has demonstrated its versatility by serving as an end-to-end SDN orchestrator on top of a large set of heterogeneous SDN data planes. With the release of Version 2.1 in July 2023[2], TeraFlowSDN has incorporated a significant list of features that (partially) comply with the operator's requirements in terms of network controllability, management, and support.

This assessment will not only benefit the TeraFlowSDN community by guiding the prioritization of feature evolutions to align with operators' needs, but it will also contribute to the TIP OOPT MUST community by providing recommendations for developments for potential requirements.

Ultimately, this white paper intends to promote network transformation and facilitate improved interoperability and compliance with operators' requirements within open-source communities. By aligning TeraFlowSDN with the specific needs of Network Operators, TeraFlowSDN aspires to become an open-source implementation that effectively fulfils and supports operators' requirements. This collaborative effort seeks to strengthen the integration of SDN technology into the transport network sector, and to contribute to the development of network infrastructure with a view to improved efficiency and boosted performance.

[1] https://telecominfraproject.com/oopt/
[2] https://tfs.etsi.org/news/20230720_teraflowsdn_release_21/

ETSI TeraFlowSDN

The ETSI open-source group TeraFlowSDN (OSG TFS) is developing TeraFlowSDN; a Cloud-native SDN controller enabling smart connectivity and services for future networks beyond 5G. OSG TFS fosters innovation through open-source software for open technologies, architectures, and interfaces within multiple network technological domains. TFS envisions a programable, open, and disaggregated network ecosystem to accelerate the adoption of SDN standards.

The TeraFlowSDN controller is a Cloud-native system based on a micro-services SW architecture, which allows for better resource allocation and accelerated development and deployment cycles. It offers IP control, management, and support for optical transport networks. This has been made possible through OpenConfig support for IP layer and interfaces with the optical layer using the Open Networking Foundation (ONF) Transport API (TAPI)[3]. This makes TFS unique, as there are currently no other open-source solutions that address End-to-End (E2E) SDN orchestration within the transport domain. TeraFlowSDN supports a wide range of use cases, as defined by several ETSI standardization groups, and aims for interoperability with ETSI Open Source MANO (OSM). It is compatible with integration into existing frameworks (i.e., NFV, MEC), and enables standardization groups and research initiatives to experiment with new features for flow aggregation, management (service layer), network equipment integration (infrastructure layer), AI/ML-based security, and forensic evidence for multi-tenancy.

The group liaises with the relevant standards bodies and projects, such as the Internet Engineering Task Force (IETF), ETSI ZSM, ETSI NFV, ETSI MEC, ETSI mWT, ETSI SAI, and P4.org. In addition to this, ETSI TeraFlowSDN is closely monitoring the Telecom Infra Project (TIP) MUST requirements, aligning with the proposed solutions. It is of interest to note that ETSI TeraFlowSDN is an initiative resulting from the H2020 TeraFlow project, which is funded by the European Community, and the group is therefore committed to delivering compliance with European cyber-security requirements.

TeraFlowSDN is an effort led by major network operators, technology vendors, and research institutions. The work is contribution-driven, with a constantly expanding community. Benefiting from ETSI's global outreach was one of the driving motivations behind the move. Participation in TeraFlowSDN is open to ETSI members, non-members, as well as individual developers and users. The current list of TFS members and participants is available[4].

ETSI TeraFlowSDN has been presented at multiple events, and demonstrations and tutorials are also available[5]. Bi-yearly Hackfests and community engagement activities are planned, such as the TeraFlowSDN Ecosystem Day, with everyone being welcome to join in with these activities. We are planning two releases per year, which will incorporate all of the latest features and bug fixes. Release 2.1, the latest stable release, was presented in July 2023. Should you want any further information, you

[3] https://wiki.opennetworking.org/display/OTCC/TAPI
[4] https://portal.etsi.org/TB-SiteMap/TFS/List-of-TFS-Members-and-Participants
[5] https://labs.etsi.org/rep/groups/tfs/-/wikis/TFS-Events

can keep up to date with all of the latest developments, integrations, and bug fixes in the *Develop* section[6].

The TeraFlowSDN Cloud-native architecture mostly consists of stateless micro-services which interact with each other to fulfil network management tasks, along with a few stateful micro-services, which are responsible for maintaining the network topology and state. TeraFlowSDN relies on Kubernetes[7] for handling the container orchestration supporting the micro-services. Kubernetes is a state-of-the-art container orchestrator that provides broad management capabilities, and is capable of operating geographically distributed infrastructures.

Figure 1 shows the TeraFlowSDN micro-service-based architecture. Following the design principles of cloud-native applications, each component is implemented as a micro-service that exports a set of Remote Procedure Call (RPC) services to other components. Each micro-service can be instantiated once or with multiple replicas, allowing for the application of load-balancing techniques. With the adoption of stateless micro-services, requests can be handled by any replica of the micro-service. Loads are balanced by establishing an endpoint to receive all service requests. The endpoint acts as a load balancer by delegating each request to one of the replicas of the service. The load balancer is also responsible for keeping track of the replicas, namely through tracking additions and deletions, and then updating its internal list of replicas. Depending on the RPC implementation, we may use the integrated Kubernetes load-balancer or adopt an external one. Each replica comprises a pod, which is a collection of containers that the Kubernetes platform manages as a single entity.

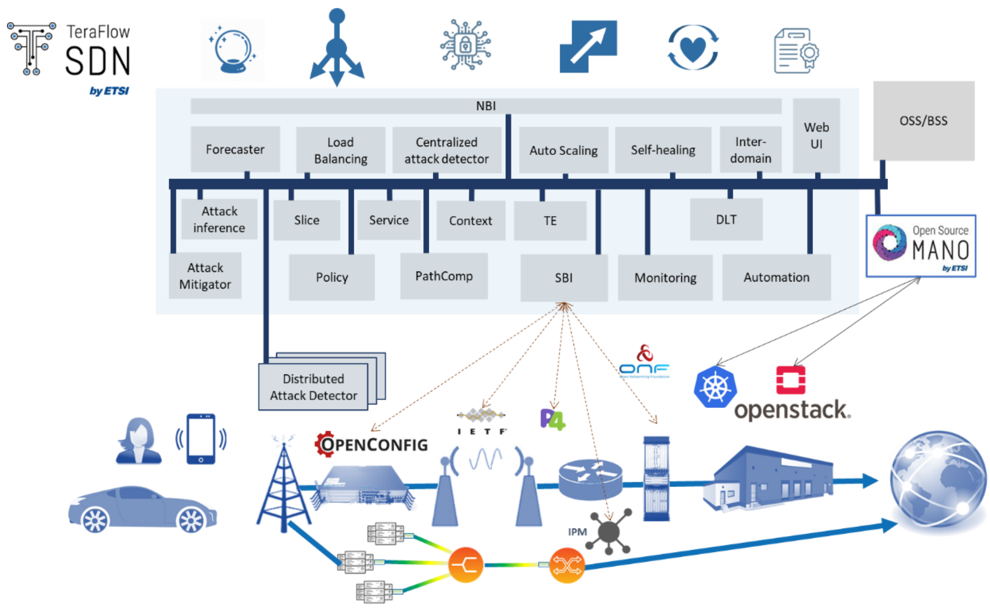

Figure 1 TeraFlowSDN architecture for release 2.1

[6] https://labs.etsi.org/rep/tfs/controller/-/tree/develop?ref_type=heads

[7] https://kubernetes.io/

Context is a stateful storage component. It stores the network configuration (e.g., topologies, devices, links, and services) and the status of all elements managed by TeraFlowSDN. Context leverages a database management system which is optimized for cloud-native scenarios, providing replication and high-availability deployments. The **Service** component oversees the configuration and deployment of the requested connectivity service through the South-Bound Interface (SBI) component. The Service component features a Service Handler API, making it simpler to add support for new service types. The appropriate Service Handler is selected for each connectivity service request and tasked with the set-up/teardown of the configuration rules through the SBI component. To this end, **SBI** interacts with the network equipment through pluggable drivers. In addition, the Driver API — part of the SBI — defined in Version 2.0 has been extended in Version 2.1 to add new network protocols and data models (e.g., gNMI), as well as to enhance its scalability. The **Automation** component enables the zero-touch onboarding of new devices under the realm of the TeraFlowSDN controller, while the **Policy** component implements Event-Condition-Action (ECA) loops that allow for the association of services with customized service-level agreements (SLAs). The **Monitoring** component manages the collection of various metrics configured for the network equipment and services, and it also stores tracking data for selected KPIs. It provides means through which other components can access the collected data. Internally, the Monitoring component relies on a database for the storage of the tracking data as time series, using its powerful research and aggregation mechanisms to retrieve collected data.

Within the context of TIP-OOPT, the TeraFlowSDN controller uses the North-Bound Interface (**NBI**) component to receive Layer 2 Virtual Private Network (L2VPN) requests and to then map them with the necessary connectivity service requests or Transport Network Slices for the Service and Slice components, respectively. The list of supported NBI is presented in Table 1. It will be updated in TFS wiki[8].

NBI	Service/Slice Type	Tested OSS/BSS/NFVO
IETF L2VPN Service Model (L2SM) [RFC8466]	L2-VPN	ETSI Open Source MANO v12.1+
IETF Network Slice Service YANG Model [draft-ietf-teas-ietf-network-slice-nbi-yang-02]	L2/L3 Slice	Standalone script

Table 1 Supported NBI services.

The NBI component consists of the interface from internal gRPC (Google Remote Procedure Call) and protocol buffers to external Representational State Transfer (REST)-like requests. It provides a REST-API–based NBI to external systems, such as Network Function Virtualization (NFV) and Multi-access Edge Computing (MEC) frameworks. We also include a Web-based User Interface (**WebUI**) that uses the gRPC-based interfaces made available by the TeraFlowSDN components to inspect the network state, and also to issue operational requests to the TeraFlowSDN components. The WebUI also provides a load generator that can be used to quickly set up services for performance assessment purposes.

[8] https://labs.etsi.org/rep/tfs/controller/-/wikis/6.-TFS-supported-NBI/6.1.-Introduction

TeraFlowSDN Release 2.1 provides extended and validated support for OpenConfig-based routers and interaction with optical SDN controllers through the Open Networking Foundation (ONF) Transport API (TAPI). In addition, TeraFlowSDN Release 2.1 includes full integration for microwave network elements (through the IETF network topology YANG model), and Point-to-Multipoint integration of XR optical transceivers and P4 white boxes. New features for P4 devices include the ability to load a P4 pipeline onto a given P4 switch; obtaining runtime information (i.e., flow tables) from the P4 switch; and the pushing of runtime entries into the P4 switch pipeline, thus allowing for fully-featured usage of P4 switches. A comprehensive list of supported and tested devices is described in Table 2. It will be updated regularly in TFS wiki[9].

Driver	Device Type	Configuration	Monitoring	Tested Devices
Emulated	Any	YES	YES (synthetic)	N/A
OpenConfig (NetConf)	Packet Router	L2/L3-VPN & ACLs	YES (ifaces, polling)	- Infinera DRX-30 with ADVA NOS-OPX-B-21.5.1 - Edgecore AS7315-30X with ADVA NOS-OPX-B-21.5.1
OpenConfig (gNMI)	Packet Router	IPv4 & Static routes	YES (ifaces, streaming)	- Nokia SR Linux v23.3.1
MicroWave	Intermediate Controller	L2 radio links	NO	- SIAE intermediate MW controller version SM-DC 8.3.2 managing SIAE AGS20 radio terminals
Transport API	Intermediate Controller	L0 optical links	NO	- CTTC Open Line System controller
IETF L2VPN	Intermediate Controller	L2/L3 slices	NO	- TeraFlowSDN as child IP controller
P4	Intermediate Controller	L2 packet connections	NO	- CTTC Open Line System controller
XR	Intermediate Controller	L0 optical links	NO	- Infinera Pluggable Manager (IPM) controller

Table 2 Control and Management of Network Elements

Since Release 1, Service Level Agreement (SLA) validation has been re-engineered across all of the workflows, from device monitoring to service and slice life-cycle management. Thus, the Slice, Service, Policy, SBI and Monitoring components have all been updated to support the necessary network automation workflows. Furthermore, the Slice and the **Path Computation** components have also been introduced. The Slice component enables the management of Transport Network Slices and features slice-grouping capacities to reduce the number of configuration rules required.

[9] https://labs.etsi.org/rep/tfs/controller/-/wikis/5.-Control-and-management-of-network-elements/5.1.-Introduction

The **Cybersecurity** mechanisms were also updated, now including new components for **attack detection** (either distributed or centralized), **attack inference**, and **attack mitigation**. Component scalability has also been improved. In addition, several new use cases are now supported, such as the optical layer attack detection, which uses either supervised or unsupervised learning. The Distributed Ledger Technology (**DLT**) component has also been extended to interact with the **Inter-domain** component, and to use the deployed Hyperledger Fabric.

TIP OOPT MUST

The Open Optical & Packet Transport group is a project within Telecom Infra Project focusing on defining open technologies, architectures, and interfaces in Optical and IP Networking. This group is led by major operators, technology vendors, and research institutions. Its main purpose is to consider and review various aspects of the Transport network architecture, including optical transponders, line systems, IP access devices, and open APIs, along with network simulation and planning tools.

Within OOPT, one of the MUST group's main initiatives is the acceleration of the adoption of SDN standards for IP/MPLS, Optical, and Microwave transport technologies. To achieve this, it is defining a common SDN architecture, along with open and standard interfaces between the control and the management layer of the network devices.

MUST is actively developing a common set of interfaces for device management and data model creation for the use cases required by operators. Initially focusing on mobile aggregation and backhauling, such as L3 VPN and discovery, MUST is now expanding its scope beyond those specific areas.

Despite disruptions caused by the COVID-19 pandemic, the group managed to conduct several live trials and pilots, which started in 2020. Some commercial deployments have already been launched in South Africa and Romania, demonstrating progress in real-world networks. Additionally, the ecosystem has seen an increase in networking vendor engagement.

Recently, the group has been actively working on the production of new updates and test release requirements, which involves collaborative work with vendors on API development. These efforts demonstrate the continuous positive progression and commitment of the Open Optical & Packet Transport group in its aim to drive and boost innovation and standardization in the field of optical and IP networking.

Analysis of TIP OOPT MUST requirements

Within TeraFlowSDN, the primary areas of focus for analysis are the requirements for an E2E SDN orchestrator and an IP SDN controller. Both of these functionalities have been successfully demonstrated using TeraFlowSDN. While various partners are still working to extend TeraFlowSDN into an Optical or wireless backhaul SDN controller (or multiple controllers), the feature definitions in TeraFlowSDN are still work in progress, and the compliance analysis has not yet been completed and rationalized at this stage.

In the following sections, a comprehensive summary of the multiple requirements proposed by the TIP OOPT MUST group will be provided. These requirements will serve as a reference point, facilitating a thorough analysis of TeraFlowSDN's capabilities and its alignment with industry standards and best practices. The aim is to assess TeraFlowSDN's adherence to these requirements and its suitability as an E2E SDN orchestrator and IP SDN controller. Thanks to this analysis, we can gain valuable insights into its effectiveness and potential for meeting the demands of modern networking environments.

Architecture requirements

Generic Architecture requirements

[ARCH-01] Hierarchical architecture: The preferred open transport SDN architecture within a single operator network is based on a hierarchical controller, along with several technology-specific SDN controllers. It should be noted that, in TIP OOPT MUST, multi-operator networks are not within the scope, the assumption being that all technology domains belong to the same operator.

[ARCH-02] Technological SDN domains: In the case whereby a transport segment is divided among multiple administrative domains, multiple SDN domain controllers for the relevant transport segment may be included in the hierarchy.

[ARCH-03] Microwave, IP and Optical SDN controllers: The open transport SDN architecture has anticipated the control separation between technologies by introducing a dedicated domain controller for each specific technological segment, i.e., microwave, IP, and optical transport. Each domain controller manages a set of Network Elements (NEs) through a standardized, technology-dependent SBI that is also vendor-independent.

[ARCH-04] Controller NBI: Each controller also has an NBI for communication with the hierarchical controller.

[ARCH-05] E2E SDN orchestrator NBI: In addition to the SDN domain layer, the hierarchical controller aggregates demand from the management and service layer, including Operational Support System (OSS) and orchestration. It exposes a unified NBI, providing resource configuration abstraction and technology-agnostic service definitions for consumption.

Generic technological SDN controller requirements

[ARCH-TECH-01] Real-time network database: The controller will oversee the collection of data from the NEs (physical and logical), making this data available to be queried via NBI for inventory purposes. The set of transport services and the Traffic Engineering (TE) information in each domain is also maintained and made available for query.

[ARCH-TECH-02] Transport connectivity services implementation: Configuration/modification/ deletion of transport service endpoints and their parameters based on requests through the NBI. The level of abstraction provided will depend on the technologies and use cases in scope.

[ARCH-TECH-03] Path computation element (PCE): Within the IP domain, Stateful PCE will be used to manage all intra-domain transport connectivity (Label Switched Path - LSP) in order to calculate new LSP paths upon service creation, or when traffic optimization is triggered by the operator — with or without TE constraints. The controller also monitors all network LSP statuses. Protection switching is still triggered on a network-wide level by the corresponding transport protocols (e.g., RSVP-TE) to ensure the appropriate survivability.

[ARCH-TECH-04] SBI plug-ins: Protocols needed for communication to the NEs. For example: NETCONF/YANG for configuration manipulation executed by any SDN domain controller, or BGP-LS for collecting TE network topology information.

[ARCH-TECH-05] NBI RESTCONF/YANG: Controllers will provide an interface for transport service creation/modification/deletion triggered by the hierarchical controller, but also for notifications of any network changes coming from the SDN domain controller to the hierarchical controller.

[ARCH-TECH-06] Alarm/Event management: Alarm and event information can be collected through the NETCONF/YANG directly from the NEs, enabling the controller to perform closed-loop actions against the network (e.g., a specific alarm/event can trigger a PCE calculation for a new, more optimized LSP). Alarms and events can be queried to other fault and performance management systems.

[ARCH-TECH-07] Telemetry collection: Information collected directly from NEs through NETCONF /YANG — or by streaming telemetry (gRPC) populating the event manager — can trigger network optimization based on operator-defined threshold crossing alerts (TCAs). Telemetry data is made available to controllers and external systems, so that they can perform additional closed-loop automations and big data analysis.

[ARCH-TECH-08] Real topology view: Each SDN controller, using standard network protocols such as BGP-LS, IGPs and LLDP, can maintain a multi-vendor topology view of each domain that can be exposed to the hierarchical controller and network planning applications.

Reference documents

- TIP OOPT, How TIP's Open Optical Group is driving disaggregated transport network solutions.
- TIP OOPT, Open Transport SDN Architecture Whitepaper, 2020

E2E SDN orchestrator requirements

Generic requirements for an E2E SDN orchestrator

[E2E-01] Multi-domain and multi-technology topology: The hierarchical controller coordinates the information and interfaces of the transport network domain SDN controllers, allowing for more advanced use cases.

[E2E-02] Topology export: With E2E visibility of all transport network segments, it exposes an abstracted topology view of resources and the set of services available to clients through its northbound APIs.

[E2E-03] Abstraction: The abstraction level exposed by the controller may vary according to the needs of the northbound client (e.g., OSS, service orchestrators). Depending on the use (e.g., alarms, performance data, detailed domain inventory), the OSS can directly interface with the domain controllers, thereby maintaining architecture scalability.

[E2E-04] E2E SDN orchestrator SBI functionalities: On the hierarchical controller SBI, each SDN controller will expose vendor-agnostic, network-level programmability, and resource discovery functionalities. Amongst other purposes, the SBI is designed to 1) provide access to a device's configuration data, 2) expose topology and network inventory information for each OSI layer, and 3) offer active monitoring of device configuration changes and network status data (i.e., traffic statistics). The function of alarm and device inventory information, for Fault Management (FM) and Resource Inventory Management (RIM), has been developed to be managed at the SDN domain controllers in the first phase, although exposure level through the hierarchical controller will also be evaluated.

[E2E-05] E2E SDN orchestrator components: The hierarchical controller's internal architecture may be split into three conceptual building blocks: E2E transport network control, Multi-layer PCE, and Service binding to transport resources.

[E2E-06] E2E transport network control: The functional component within the hierarchical controller is responsible for providing E2E control by coordinating the disparate technologies through its corresponding SDN domain controllers (OTN/WDM optical network, IP/MPLS core/backhaul, and MW/MBH network). This controller will provide for each layer E2E visualization (i.e., per-layer topology composition) and stateful control of provisioned network services. This includes cross-layer resource relationships, i.e., the mapping between optical channels (OCh) created in L0 and Optical Transport Network (OTN) services available in the L1, or (analogously) between L2 links and underlying transport services.

[E2E-07] Multi-layer PCE: Computations completed on the domain controller level take into account resources existing on the technological layer and the respective domain. However, the multi-layer, active stateful PCE module has the role of computing paths across multiple technologies (IP/MPLS, optical, and MW) based on multi-layer topology information (see, multi-layer topology composition), as well as with collaboration of the IP/MPLS path computation element, optical controller, and MW controller.

[E2E-08] Service binding to transport resources: By means of the PCE function, this enables the hierarchical controller to obtain the best connections for a given transport connectivity service. For example, the set of LSPs is computed for a VPN with bandwidth or latency constraints. With a multi-layer view, it can correctly compute disjointed constraints (that could otherwise lead to inaccurate information). It allows the hierarchical controller to assign specific network transport resources to VPN services.

[E2E-09] RESTCONF: RESTCONF is proposed as the transport protocol for all defined management operations in the SDN architecture NBIs.

[E2E-10] YANG discovery: RESTCONF allows clients to discover the YANG module conformance information for the server, should the client want to use it.

[E2E-11] RESTCONF JSON encoding: The solution adhering to this specification MUST support media type "application/yang-data+json". This must be indicated in the HTTP header fields "Accept" or "Content-Type" of the corresponding HTTP Request/Response messages. The JSON representation is defined in "JSON Encoding of Data Modeled with YANG"(RFC7951[10]).

[E2E-12] RESTCONF streams: The solution implementing the RESTCONF server must expose its supported notification streams by populating the "restconf-state/streams" container definition in the "ietf-restconf-monitoring" module. The RESTCONF standard defines the Server Sent Events (SSE) as the standard protocol for the RESTCONF stream notification service. The MUST specification for RESCONF NBI notification support is restricted exclusively to SSE.

E2E SDN orchestrator SBI requirements

[E2E-SBI-01] SBI towards Optical SDN controller: Due to its maturity and availability within the industry, the ONF Transport API (TAPI) is the information model considered by most vendors as the NBI of the optical domain controller. The T-API models include a set of technology specification models which are designed to enhance the previously described service models by including technology-specific information from each transport layer. The transport layers covered by the T-API are as follows: DSR/Ethernet; OTN/ODU; and Photonic Media. The MUST reference is TAPI v2.1.3 Reference Implementation Agreement for the set of use cases.

[E2E-SBI-02] SBI towards IP SDN controller: The interface between the End-to-End (E2E) SDN orchestrator and the IP SDN controller has been designed to utilize RESTCONF and support the provision of L3/L2 VPN Network Model Support. The E2E SDN orchestrator is required to consume network topology information, and, for this purpose, it will be dependent on the IETF Network Topology YANG models. These models provide a standardized representation of the network's physical and logical elements, enabling the orchestrator to effectively comprehend and manage the underlying infrastructure. In regard to Traffic Engineering requirements, the selected data models are IETF TE Tunnels and Interfaces. These specific models have been tailored to take into account Traffic Engineering considerations, facilitating the creation and management of traffic-engineered tunnels and interfaces in order to optimize network performances and resource utilization.

[E2E-SBI-03] SBI towards Microwave transport SDN controller: E2E SDN orchestrator will be able to provide topology discovery functions, service and connectivity provisioning, network activation and configuration, fault management, performance analysis, and network inventory. Two possible implementations have been proposed for the majority of use cases, based on ONF TR-532 MW model and IETF RFC 8561 "A YANG Data Model for Microwave Radio Link".

Reference documents

- TIP OOPT, Open Transport SDN Architecture Whitepaper, 2020
- TIP OOPT, MUST Optical SDN Controller NBI Technical Requirements Document TIP OOPT PG - Version: 1.1

[10] https://datatracker.ietf.org/doc/html/rfc7951

- TIP OOPT, MUST IP SDN Controller NBI Technical Requirements OOPT Date May 14, 2021 Document version: v1.0
- TIP OOPT, MUST Use Cases and Technical Requirements for Wireless Backhaul SDN Domain Controller & Network Equipment TIP OOPT PG – Version: 2.0

IP SDN controller

IP SDN controller NBI requirements

[IP-NBI-01] Supported YANG models for L2/L3VPN: The service models that need to be supported in MUST specification are: L3NM, VPN2 common, Routing-Policy, Access Control List, BGP-Policy-Extension, and L2NM. The L3VPN creates a virtual routing network instance (VRF) in each of the nodes engaged in the service deployment. This routing instance enables the routing information's propagation between the sites implicated in the service.

[IP-NBI-02] Exported topological models: The topology models that need to be supported in current specification are: IETF Network Topology, IETF L3 Network Topology, IETF L2 Network Topology, IETF UNI Topology, and IETF TE Topology.

[IP-NBI-03] Inventory: The model that needs to be supported for inventory purposes in the MUST specification is the IETF Network Topology (RFC8345[11]).

[IP-NBI-04] Traffic Engineering: The traffic engineering models that need to be supported in the MUST specification are IETF Traffic Engineering Tunnels and Interfaces, IETF Traffic Engineering Common YANG Types, and YANG Data Model for requesting Path Computation.

IP SDN controller SBI requirements

[IP-SBI-01] NETCONF support: The SDN solution for the IP segment is based on a single, multi-vendor IP SDN domain controller in charge of configuring the IP Network Elements. The target SBI for vendor-agnostic device configuration must comply with NETCONF (RFC6241[12]) standard protocol and meet common specific requirements (e.g., a subset of NETCONF capabilities) that bind the reference implementation of the interface. IP/MPLS networks are formed by multiple IGP domains and therefore the SDN controller will manage multiple Interior Gateway Protocol (IGP) domains to provide a unified network view. The IP SDN domain controller will be the main point of entry into the Net, in order to avoid overloading them. It will also provide a coherent view of the IP network, and will have a set of standard NBI and SBI plug-ins to receive and process requests for the creation of new transport connectivity services, such as L2 and L3 VPNs. The controller will handle the translation of the request to low-level device configurations, before transferring it to network devices. The data model will support L3 and L2 network models for service provisioning.

[11] https://datatracker.ietf.org/doc/html/rfc8345
[12] https://datatracker.ietf.org/doc/html/rfc6241

[IP-SBI-02] Topology: The controller should collect real-time IP topology through the use of specific protocols, such as BGP-LS and LLDP. Additionally, it will have a real-time database containing physical and logical information for each network IP device.

[IP-SBI-03] TE support: In regard to TE use cases, the IP SDN controller will be able to create TE tunnels (with RSVP-TE or segment routing) and optimize the set of tunnels deployed on the network. The controller must support complex scenarios, such as multi-IGP environments.

[IP-SBI-04] Path computation support: Some of the functions, such as PCE, may be provided by a standalone controller module. Whenever a function is unpaired from the controller, it must be implemented using the standard controller NBI and SBI, such as PCEP or ONF Transport API.

[IP-SBI-05] Inventory support: NETCONF retrieves the information regarding all of the logical or virtual interfaces of a specific equipment, such as sub-interfaces, VLAN interfaces, tunnel interfaces and other non-physical interfaces.

[IP-SBI-06] Telemetry and statistics: gRPC[13], NETCONF.

Reference documents

- TIP OOPT, Open Transport SDN Architecture Whitepaper, 2020
- TIP OOPT, MUST IP SDN Controller NBI Technical Requirements OOPT Date May 14, 2021 Document version: v1.0
- TIP OOPT, MUST IP – SDN Controller SBI / Router NBI Technical Requirements Version 1.1

[13] https://grpc.io/

ETSI TeraFlowSDN compliance of TIP OOPT MUST requirements

This section analyses the previously summarized requirements, following a clearly defined methodology. The ETSI TeraFlowSDN compliance status will allow for further developments to be prioritized for future releases.

Compliance methodology

The compliance methodology outlined below aims to assess the alignment of a system, product, or solution with the requirements established in the MUST reference documents. The goal is to determine the level of compliance with each requirement, and three possible compliance values are proposed:

Aligned

When a system is marked as "Aligned" in regard to a specific requirement, this means that the system meets and adheres to that particular requirement. In other words, the system's implementation or features precisely match those specified in the MUST reference document for that particular requirement. This demonstrates a high level of compliance, and indicates that the system supports and is compatible with the intended functionality or standard.

Partially aligned

A system marked as "Partially aligned" presents a certain level of compliance with a given requirement, but it does not fully meet all aspects of the requirement, as specified in the MUST reference document. There may deviations, gaps or discrepancies in the system's implementation when compared with the standard. While it partially satisfies the requirement, there may still be room for improvement in order to achieve full compliance.

Requires alignment

When a system is marked as "Requires alignment" in relation to a particular requirement, this indicates that the system does not currently meet the requirement, and that significant adjustments or enhancements are necessary. The system falls short of the expected level of compliance, and substantial changes are required in order to bring it in line with the MUST reference document.

Overall, this compliance methodology allows stakeholders to assess the degree to which a system adheres to the requirements established in the MUST reference documents. It provides a clear indication of areas where the system is compliant, where it partially complies, and where improvements are required for in order to achieve compliance. The use of these compliance values allows for a more structured and transparent evaluation process, in turn enabling better decision-making and facilitating the implementation of standardized technologies and practices.

Architecture requirements

[ARCH-01] Hierarchical architecture	Aligned	TFS can be configured and instantiated to support multiple underlying network domains, i.e., running as E2E SDN orchestrator, or directly interacting with specific technological network elements, such as running as SDN controller.
[ARCH-02] Technological SDN domains	Aligned	The Service component oversees the selection of the appropriate handlers for the requested connectivity services, and using these handlers to configure and deploy the requested connectivity service through the Southbound Interface (SBI). For this purpose, the SBI component interacts with the network equipment through pluggable drivers. In addition, a Driver Application Programming Interface (API) and a Service Handler API have been defined to facilitate the addition of new network protocols and data models to the SBI component and service types to the Service component, respectively.
[ARCH-03] Microwave, IP and Optical SDN controllers	Aligned	TeraFlowSDN Release 2 provides extended and validated support for: • OpenConfig-based routers. • Interaction with optical SDN controllers through the Open Networking Foundation (ONF) Transport API (TAPI). • Integration for microwave network elements (through the Internet Engineering Task Force - IETF - network topology YANG model). • Point-to-Multipoint integration of XR optical transceivers. • Support for P4 white boxes, including loading a P4 pipeline on a given P4whitebox; obtaining runtime information (i.e., flow tables) from the P4 white box; and pushing runtime entries into the P4 white box pipeline, thus allowing for total usage of P4 white boxes.
[ARCH-04] Controller NBI	Aligned	The TeraFlowSDN controller uses its North-Bound Interface (NBI) component to receive:

		• Layer 2 Virtual Private Network (L2VPN) requests and convert them to necessary Service component connectivity services. • Transport Network Slices, and to set them up through the Slice and Service components.
[ARCH-05] E2E SDN orchestrator NBI	Partially aligned	Transport Network Slice NBI provides technology agnostic service definitions. Multiple tenants are provided with full visibility over network resources. Per-tenant Resource abstraction is not available.
[ARCH-TECH-01] Real-time network database	Aligned	Support for the CockroachDB database has been integrated, ensuring robust data storage and management. Additionally, the component now incorporates compatibility with the NATS message broker, enabling efficient and reliable communication between distributed systems. Furthermore, it has been equipped with the ability to persist slices, allowing complex data structures to be stored for future use. In addition to this, specific constraints, configuration rules, and policy rules can now be persisted, facilitating the preservation and retrieval of critical application settings and guidelines.
[ARCH-TECH-02] Transport connectivity services implementation	Aligned	As previously detailed, NBI supports: • Layer 2 Virtual Private Network (L2VPN) requests and convert them to necessary connectivity services. • Transport Network Slices via the Slice and Service components.
[ARCH-TECH-03] Path computation element (PCE)	Partially aligned	The PathComp component has undergone a significant overhaul, resulting in a newly implemented and path computation module with a high degree of scalability. This upgraded component now offers a range of powerful algorithms to efficiently compute paths in various scenarios. Firstly, the basic Shortest Path algorithm has been incorporated, enabling the determination of the shortest route between two points in a network. Secondly, the k-Shortest Path algorithm has been integrated, providing the ability to identify multiple feasible paths, in order of their lengths, offering increased flexibility and redundancy. Additionally,

		the component now exposes the implementation of a k-Disjoint Paths algorithm, which allows for the identification of multiple non-overlapping paths, in turn enhancing network robustness and resilience. These developments collectively grant the PathComp component enhanced capabilities, making it a crucial and indispensable tool for path computation in various applications. The Traffic Engineering component provides basic support for PCEP establishment and modification of Label Switched Paths. PCEP is being extended and Release 3.0 will support SRv6 TE.
[ARCH-TECH-04] SBI plug-ins	Partially aligned	NETCONF/YANG and gNMI Network Element configuration support is provided. The BGP-LS feature for collecting TE network topology information is currently under development, and is expected to be delivered with TeraFlowSDN Release 3.0.
[ARCH-TECH-05] NBI RESTCONF/YANG	Aligned	TeraFlowSDN provides multiple REST API implementations based on well-known YANG data models.
[ARCH-TECH-06] Alarm/Event management	Partially aligned	Internal alarm/event information can be easily subscribed through Monitoring component. However, telemetry data is not yet made available to controllers and external systems in order to perform additional closed-loop automations and big data analysis.
[ARCH-TECH-07] Telemetry collection	Aligned	The Monitoring component provides support for subscriptions and alarms, enabling efficient and automated monitoring of critical events and system states. This gives users the ability to stay up-to-date and to adopt a proactive approach in addressing potential issues promptly. Additionally, a substantial upgrade has been made by migrating over to the scalable QuestDB time-series database. This migration allows for the seamless storage and retrieval of time-stamped data, enabling real-time analysis and visualization of monitoring metrics. The integration of QuestDB enhances the component's performance and scalability, making it a reliable and

		powerful tool for monitoring and analyzing large-scale systems.
[ARCH-TECH-08] Real topology view	Partially aligned	TeraFlowSDN does not provide BGP-LS, IGPs, and LLDP for a multi-vendor topology view. The BGP-LS topological updates and export features are currently under development, and are expected for Release 3.0. This module will expose the topology in a dynamic manner, with the IETF format. Currently network topology exposed using TeraFlowSDN NBI is a direct translation of the TeraFlowSDN topological database to JSON. In further releases, model translation should be provided so each domain that can be exposed to the hierarchical controller and network planning applications.

E2E SDN orchestrator requirements

[E2E-01] Multi-domain and multi-technology topology	Aligned	TeraFlowSDN Context component contains multiple underlying topologies. It also contains multi-layer topology, covering how they are related.
[E2E-02] Topology export	Partially aligned	External applications are able to retrieve topological data, but it is described using internal data model.
[E2E-03] Abstraction	Requires alignment	An abstraction mechanism is required to provide multiple abstractions of network resources through the E2E SDN orchestrator NBI.
[E2E-04] E2E SDN orchestrator SBI functionalities	Partially aligned	TeraFlowSDN E2E SDN orchestrator focuses on network programmability through connectivity services, topology, and monitoring functionalities. Support for direct network element configuration through underlying SDN controllers is not provided.
[E2E-05] E2E SDN orchestrator components	Aligned	E2E transport network control, Multi-layer PCE, Service binding for transport resources.
[E2E-06] E2E transport network control	Partially aligned	TeraFlowSDN Service component includes a task scheduler to support dependencies in multi-layer scenarios.

[E2E-07] Multi-layer PCE	Partially aligned	TeraFlowSDN PCE component computes the inter-domain routes without interaction with the underlying SDN controller PCE components.
[E2E-08] Service binding to transport resources	Partially aligned	Only basic support of TE is provided through the TE component. Extensions are required for the RSVP protocol. A new module is currently being developed to improve the TE information.
[E2E-09] RESTCONF	Aligned	TeraFlowSDN offers a REST-like interface, conforming with the RESTCONF protocol.
[E2E-10] YANG discover	Requires alignment	TeraFlowSDN does not allow for the automatic identification of supported YANG data models.
[E2E-11] RESTCONF JSON encoding	Requires alignment	TeraFlowSDN will advertise the necessary RESTCONF JSON encoding.
[E2E-12] RESTCONF streams	Requires alignment	TeraFlowSDN will support SSE event streams.
[E2E-SBI-01] Optical SDN controller SBI	Aligned	TeraFlowSDN provides an SBI plugin to interact with an Optical SDN controller that provides ONF Transport API.
[E2E-SBI-02] IP SDN controller SBI	Partially aligned	TeraFlowSDN provides an SBI plugin based on RESTCONF and IETF L2VPN service model. However, the topology from the underlying IP SDN controller is identified using the internal network model.
[E2E-SBI-03] MW transport SDN controller SBI	Partially aligned	TeraFlowSDN provides an SBI plugin based on RESTCONF and IETF network models and eth-tran-services.

IP SDN controller requirements

[IP-NBI-01] Supported YANG models for L2/L3VPN	Requires alignment	TeraFlowSDN provides support for only L2VPN provisioning, using the IETF L2VPN service model. The L3VPN service model is required. Furthermore, L2/L3VPN network models are also desirable into the aim of aligning with MUST.
[IP-NBI-02] Exported topological models	Partially aligned	TeraFlowSDN support for topological information export is based on its internal data model. Work is currently underway on a module that will expose the topology dynamically with the IETF format. Expanded to support L2/L3 network topology.

[IP-NBI-03] Inventory	Partially aligned	TeraFlowSDN does not provide inventory support, but there is an ongoing feature to provide it in upcoming TeraFlowSDN release. The information will be provided in the IETF format.
[IP-NBI-04] Traffic Engineering	Partially aligned	Only basic support of TE is provided through TE component. Extensions are needed for RSVP protocol. Working on improving the TE component.
[IP-SBI-01] NETCONF support	Aligned	TeraFlowSDN provides support for NETCONF as SBI. Specifically, for the router, it provides support for L2VPN OpenConfig data models.
[IP-SBI-02] Topology	Partially aligned	BGP-LS feature is under development and will be provided in the upcoming TeraFlowSDN release.
[IP-SBI-03] TE support	Partially aligned	[IP-SBI-03] TeraFlowSDN provides TE support through PCEP component. The establishment and teardown of LSP is available, although lacking in updates.
[IP-SBI-04] Path computation support	Requires alignment	IP SDN controller provides a path computation component, but it does not provide support for external path computation requests.
[IP-SBI-05] Inventory support	Partially aligned	TeraFlowSDN does not provide inventory support, but there is a feature in development which aims to provide it in upcoming TeraFlowSDN release.
[IP-SBI-06] Telemetry and statistics	Aligned	TeraFlowSDN can export telemetry and statistics through its Prometheus micro-service.

Prioritization of work in ETSI TeraFlowSDN

As TeraFlowSDN is focusing on contributions to fill in the gaps in open-source software ecosystem, ETSI TeraFlowSDN priorities will primarily cover E2E SDN orchestration and IP SDN controller-related requirements.

Prioritization methodology

In order to prioritize work in ETSI TeraFlowSDN, we have created a prioritization matrix which takes into account both categories of urgency and importance. This matrix will help us to visualize and assess tasks or requirements based on their urgency and levels of importance.

Urgency: Categorizing each task or requirement into one of the following urgency categories:

- Urgent: Requires immediate attention and must be addressed as soon as possible.
- Required in the short term: Requirements that are not particularly urgent but should be taken care of in the near future.
- Required in the long term: Requirements that are not currently urgent but will become essential in the future.

Levels of importance: Categorizing each task or requirement into one of the following importance categories:

- Essential: Tasks that are critical and must be included in the Minimum Viable Product (MVP).
- Necessary: Important tasks that should be part of the MVP but are not as critical as the "Essential" ones.
- Not necessary for MVP: Tasks that are valuable but not essential for the initial MVP release.

Architecture requirements

[ARCH-05] E2E SDN orchestrator NBI	Partially aligned	Required in the short term	Necessary
[ARCH-TECH-03] Path computation element (PCE) – TE support	Partially aligned	Required in the short term	Essential
[ARCH-TECH-04] SBI plug-ins – BGP-LS	Partially aligned	Urgent	Essential
[ARCH-TECH-06] Alarm/Event management	Partially aligned	Required in the short term	Essential
[ARCH-TECH-08] Real topology view	Partially aligned	Required in the short term	Necessary

E2E SDN orchestrator requirements

[E2E-02] Topology export	Partially aligned	Required in the short term	Necessary
[E2E-03] Abstraction	Requires alignment	Required in the short term	Necessary
[E2E-04] E2E SDN orchestrator SBI functionalities – Direct interaction with network elements	Partially aligned	Required in the long term	Not necessary for MVP
[E2E-06] E2E transport network control – Enhanced support of multi-layer dependencies	Partially aligned	Required in the short term	Not necessary for MVP
[E2E-07] Multi-layer PCE	Partially aligned	Required in the long term	Not necessary for MVP
[E2E-08] Service binding to transport resources	Partially aligned	Required in the short term	Essential
[E2E-10] YANG discover	Requires alignment	Required in the long term	Not necessary for MVP
[E2E-11] RESTCONF JSON encoding	Requires alignment	Required in the long term	Not necessary for MVP
[E2E-12] RESTCONF streams	Requires alignment	Required in the short term	Essential
[E2E-SBI-02] IP SDN controller SBI – Support for L3VPN Service model.	Partially aligned	Urgent	Essential
[E2E-SBI-02] IP SDN controller SBI – Support for LxVPN network models	Partially aligned	Required in the short term	Essential
[E2E-SBI-03] MW transport SDN controller SBI	Partially aligned	Required in the long term	Not necessary for MVP

IP SDN controller requirements

[IP-NBI-01] Supported YANG models for L2/L3VPN	Requires alignment	Required in the short term	Essential
[IP-NBI-02] Exported topological models	Partially aligned	Required in the short term	Necessary

[IP-NBI-03] Inventory	Partially aligned	Required in the long term	Not necessary for MVP
[IP-NBI-04] Traffic Engineering	Partially aligned	Required in the short term	Essential
[IP-SBI-02] Topology	Partially aligned	Required in the long term	Not necessary for MVP
[IP-SBI-03] TE support	Partially aligned	Required in the short term	Essential
[IP-SBI-04] Path computation support	Requires alignment	Required in the long term	Not necessary for MVP
[IP-SBI-05] Inventory support	Partially aligned	Required in the long term	Not necessary for MVP

Requirement Priority matrix

[ARCH-05] E2E SDN orchestrator NBI	Required in the short term	Necessary
[ARCH-TECH-03] Path computation element (PCE) – TE support	Required in the short term	Essential
[ARCH-TECH-04] SBI plug-ins – BGP-LS	Urgent	Essential
[ARCH-TECH-06] Alarm/Event management	Required in the short term	Essential
[ARCH-TECH-08] Real topology view	Required in the short term	Necessary
[E2E-02] Topology export	Required in the short term	Necessary
[E2E-03] Abstraction	Required in the short term	Necessary
[E2E-04] E2E SDN orchestrator SBI functionalities – Direct interaction with network elements	Required in the long term	Not necessary for MVP

[E2E-06] E2E transport network control – Enhanced support of multi-layer dependencies	Required in the short term	Not necessary for MVP
[E2E-07] Multi-layer PCE	Required in the long term	Not necessary for MVP
[E2E-08] Service binding to transport resources	Required in the short term	Essential
[E2E-10] YANG discover	Required in the long term	Not necessary for MVP
[E2E-11] RESTCONF JSON encoding	Required in the long term	Not necessary for MVP
[E2E-12] RESTCONF streams	Required in the short term	Essential
[E2E-SBI-02] IP SDN controller SBI – Support for L3VPN Service model.	Urgent	Essential
[E2E-SBI-02] IP SDN controller SBI – Support for LxVPN network models	Required in the short term	Essential
[E2E-SBI-03] MW transport SDN controller SBI	Required in the long term	Not necessary for MVP
[IP-NBI-01] Supported YANG models for L2/L3VPN	Required in the short term	Essential
[IP-NBI-02] Exported topological models	Required in the short term	Needed
[IP-NBI-03] Inventory	Required in the long term	Not necessary for MVP
[IP-NBI-04] Traffic Engineering	Required in the short term	Essential
[IP-SBI-02] Topology	Required in the long term	Not necessary for MVP
[IP-SBI-03] TE support	Required in the short term	Essential
[IP-SBI-04] Path computation support	Required in the long term	Not necessary for MVP

[IP-SBI-05] Inventory support	Required in the long term	Not necessary for MVP

Prioritization of work in ETSI TeraFlowSDN

1	[E2E-SBI-02] IP SDN controller SBI – Support for L3VPN Service model.	Urgent	Essential
2	[ARCH-TECH-04] SBI plug-ins – BGP-LS	Urgent	Essential
3	[ARCH-TECH-03] Path computation element (PCE) – TE support	Required in the short term	Essential
4	[ARCH-TECH-06] Alarm/Event management	Required in the short term	Essential
5	[E2E-08] Service binding to transport resources	Required in the short term	Essential
6	[E2E-12] RESTCONF streams	Required in the short term	Essential
7	[E2E-SBI-02] IP SDN controller SBI – Support for LxVPN network models	Required in the short term	Essential
8	[IP-NBI-01] Supported YANG models for L2/L3VPN	Required in the short term	Essential
9	[IP-NBI-04] Traffic Engineering	Required in the short term	Essential
10	[IP-SBI-03] TE support	Required in the short term	Essential

11	[ARCH-05] E2E SDN orchestrator NBI	Required in the short term	Necessary
12	[ARCH-TECH-08] Real topology view	Required in the short term	Necessary
13	[E2E-02] Topology export	Required in the short term	Necessary
14	[E2E-03] Abstraction	Required in the short term	Necessary
15	[IP-NBI-02] Exported topological models	Required in the short term	Necessary
16	[E2E-06] E2E transport network control – Enhanced support of multi-layer dependencies	Required in the short term	Not necessary for MVP
17	[E2E-04] E2E SDN orchestrator SBI functionalities – Direct interaction with network elements	Required in the long term	Not necessary for MVP
18	[E2E-07] Multi-layer PCE	Required in the long term	Not necessary for MVP
19	[E2E-10] YANG discover	Required in the long term	Not necessary for MVP
20	[E2E-11] RESTCONF JSON encoding	Required in the long term	Not necessary for MVP
21	[E2E-SBI-03] MW transport SDN controller SBI	Required in the long term	Not necessary for MVP
22	[IP-NBI-03] Inventory	Required in the long term	Not necessary for MVP
23	[IP-SBI-02] Topology	Required in the long term	Not necessary for MVP
24	[IP-SBI-04] Path computation support	Required in the long term	Not necessary for MVP

25	[IP-SBI-05] Inventory support	Required in the long term	Not necessary for MVP

Recommendations for TIP OOPT MUST

TIP OOPT MUST requirements serve as a robust foundation for establishing a comprehensive set of use cases and requirements for Transport Network Control and Management. As these requirements are constantly evolving, we offer valuable recommendations for enhancing future TIP OOPT deliverables. Given the dynamic nature of the industry and the need for continuous improvement, we propose key areas to be explored and further defined in future versions of the deliverables.

For the E2E SDN Orchestrator, it would be beneficial to analyze and propose a NBI for E2E SDN Orchestrator in a new specification (there is no MUST document providing details for E2E SDN Orchestrator NBI). Additionally, data models and protocols for topology and telemetry export can greatly enhance network monitoring capabilities. Moreover, the exploration of inter-domain interfaces between multiple E2E SDN orchestrators can unlock opportunities for cohesive multi-domain network management. Emphasizing alignment with emerging data models, such as CAMARA Quality on Demand (QoD), can further boost interoperability, as well as future-proofing the system. In regard to the E2E SDN orchestrator's SouthBound Interface (SBI), we also encourage consideration of the inclusion of L2VPN/L3VPN service models. This approach empowers underlying IP SDN controllers with a certain degree of autonomy while also ensuring flexibility and modularity. Additionally, of the introduction of optional gNMI support for OpenConfig YANG data models, as is already available in TeraFlowSDN, may enhance the system's manageability and programmability.

As for the IP SDN controller, in the IP NBI deliverable, we recommend that the autonomic technology-based controllers are further explored, leveraging their self-managing capabilities to streamline network operations. This would implicate the concept that a higher degree of abstracted NBI, possibly utilizing L2VPN /L3VPN service models, may simplify interactions with the IP SDN controller and enhance its integration with the E2E SDN Orchestrator. This could be introduced as an optional feature for the IP SDN controller. Furthermore, specifying standardized data models for telemetry and statistics from the IP SDN controller would provide essential insights to ensure effective monitoring and troubleshooting. From an IP SBI perspective, in order to achieve seamless management, of the optional use of gNMI support for OpenConfig YANG data models should be considered.

By taking these considerations into account and aligning with industry best practices, ETSI TeraFlowSDN can further strengthen its position as an innovative and adaptive solution, poised to meet the ever-changing demands and needs of modern Transport Network Control and Management, including supporting a more abundant and more developed set of transport and connectivity technologies and network systems.

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