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Secured autonomic traffic management for a Tera of SDN flows

TeraFlow

# D1.4: Final Project Periodic Report

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*Abstract*

This Deliverable provides a summary of the progress of technical activities and management aspects in the second period of the TeraFlow project, i.e., from January 2022 to June 2023.

Besides reporting on the technical work, this Deliverable also summarises management-related aspects and the status of effort consumption.

[End of abstract]

Revision History

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# EXECUTIVE SUMMARY

This Deliverable presents the second project periodic report for the TeraFlow project, which was prepared during P2. Firstly, we have proceeded to answer and describe how the reviewer's comments have been addressed during P2. All recommendations have been followed, and specific attention has been given to the reviewer's comments.

Later, we present a summary of the project achievements and realized technical work. We start by summarising the progress towards the project objectives, and later we summarise the technical work realized per work package and task. We have included a short paragraph indicating how each involved partner has contributed to the task's success. At the Work Package level, we have also analysed how COVID-19 has affected the work package.

Dedicated attention is given to the WP6 objective to maximise the project's impact, facilitating the adoption of its results. We have highlighted this by including a complete section that summarizes D6.4.

Later in this Deliverable, an overview is provided of the project management-related tasks and the administrative issues attended to during Period 2. This overview includes the recommendations of the Advisory Board, Grant agreement amendments, resources and spending, updated risk management, gender balance activities, project deviations, and virtual project meetings.

The preparation of Deliverables has been monitored, and quality checks have been made. All project Deliverables and Milestones due in the reporting period have been reached. Details are given in the final section of this report.

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# Abbreviations

| | |
|---|---|
| **5G PPP** | 5G Infrastructure Public Private Partnership |
| **API** | Application Programming Interface |
| **AI** | Artificial Intelligence |
| **B5G** | Beyond 5G |
| **CI/CD** | Continuous Integration / Continuous Delivery |
| **DLT** | Distributed Ledger Technology |
| **DOA** | Decentralized Autonomous Organizations |
| **DWDM** | Dense Wavelength Division Multiplexing |
| **ECA** | Event Condition Action |
| **ETSI** | European Telecommunications Standards Institute |
| **gRPC** | Google Remote Procedure Call |
| **IDC** | Inter-Domain Component |
| **IETF** | Internet Engineering Task Force |
| **IP** | Internet Protocol |
| **ITU** | International Telecommunications Union |
| **KPI** | Key Performance Indicator |
| **L2** | Layer 2 |
| **L2VPN** | Layer 2 Virtual Private Network |
| **L3** | Layer 3 |
| **L3VPN** | Layer 3 Virtual Private Network |
| **MANO** | Management and Orchestration |
| **MEC** | Multi-access Edge Computing |
| **M** | Month (as M12) |
| **ML** | Machine Learning |
| **MS** | Milestone (as MS4.1) |
| **MW** | Microwave |
| **NBI** | Northbound Interface |
| **NFV** | Network Functions Virtualisation |
| **NOS** | Network Operating System |
| **OLS** | Optical Line System |
| **ONF** | Open Networking Foundation |
| **OS** | Operating System |
| **OSM** | OpenSource MANO |
| **OSS/BSS** | Operation Support System/Business Support System |
| **P4** | Programmable Protocol-independent Packet Processor |
| **PC** | Project Coordinator |
| **PCE** | Path Computation Element |
| **PCEP** | Path Computation Element communication Protocol |
| **PM** | Person-Month |
| **RPC** | Remote Procedure Call |
| **SBI** | Southbound Interface |
| **SDN** | Software Defined Network |
| **SDO** | Standards Development Organisation |
| **SLA** | Service Level Agreement |
| **SR** | Segment Routing |
| **T** | Task (as T3.1) |
| **TE** | Traffic Engineering |

| | |
|---|---|
| **TED** | Traffic Engineering Database |
| **TIP** | Telecomm Infra Project |
| **TM** | Technical Project Manager |
| **TNS** | Transport Network Slice |
| **VIM** | Virtualised Infrastructure Manager |
| **WIM** | WAN Infrastructure Manager |
| **WP** | Work Package (as WP6) |
| **Y** | Year (as Y2) |
| **ZTP** | Zero-Touch Provisioning |

 

# 1 Comments to reviewers

In this section we detail how all reviewer's comments have been taken into consideration during P2 of TeraFlow.

## 1.1 General comments

The TeraFlow project aims at delivering a new OS, including a controller and applications which embraces a microservices approach (disaggregation ready, cloud based), is secure and sets the basis for the next generation of SDN controlled networks.

Based on the deliverables and milestones there are two sets of technological achievements considered. First, the development of the software itself. Regarding this aspect, the progress is very good and promising. TeraFlow is achieving excellent progress on building a community of users and open sourcing the project results.

Second, the TeraFlow project aims to extend the SotA on different aspects and algorithms. Considering the DoA, there are several aspects that the reviewers expect to see (at least work on them):

- SLAs on aggregated slices
- Optimal slice grouping
- Complexity reduction of DLTs
- Algorithms for latency budgets as function of the application requirements
- Energy reduction.

The work in this reporting period has resulted in a significant number of scientific publications exceeding the targeted KPI.

The dissemination efforts towards non-scientific audience are of high quality and are likely to increase the visibility of the project and contribute to the uptake of the project result.

The impact of the project results can be very high in telcos, and all the different companies providing services to them. The project has performed a detailed business analysis.

### 1.1.1 Answer to reviewer's general comments

We are grateful for the reviewers' valuable comments and feedback and acknowledge and agree with their general comments. However, we would like to highlight that delivering a complete SDN solution has required significant effort beyond our original expectations. As a result, our focus has been more on SDN controller development than the proposed solution's algorithms aspects. Nonetheless, we would like to emphasize that we have not neglected the proposed actions and objectives outlined in the Description of the Action.

To address the reviewers' concerns, we have dedicated substantial effort to extend our work on the suggested topics during Y2 and Y3, in addition to many other areas. We hope this information provides a clear picture of the steps we have taken to address the reviewers' suggestions, and we are happy to provide more details if needed.

### 1.1.1.1 SLAs on aggregated slices

This topic has been widely evaluated and demonstrated from both WP4 and WP5 perspectives. D4.2 [D42] provides the technical insides of research contributions related to different aspects of QoS-enabled inter-domain connectivity (in section 5.3.4.2 QoS-Enabled Inter-Domain Connectivity) and also D5.2 [D52] and D5.3 [D53] present and evaluate the scenario 2 workflow: Inter-domain Provisioning using Transport Network Slices with SLA. There we present the workflow demonstrated at [OECC22].

### 1.1.1.2 Optimal slice grouping

We define in [D32] a slice group as an entity consisting of one or multiple slices with a unique group identifier. One slice belongs to one and only one slice group. Slice grouping requires a mechanism to map a slice into its slice group, also known as a slice template or slice blueprint. An initial evaluation has been presented in [D52], and results are provided in [D53]. Moreover, a demonstration at [OFC23] was presented as a live demonstration of the concept.

Below, Figure 1 plots the received transport slice requests and the clusters to which they are related.

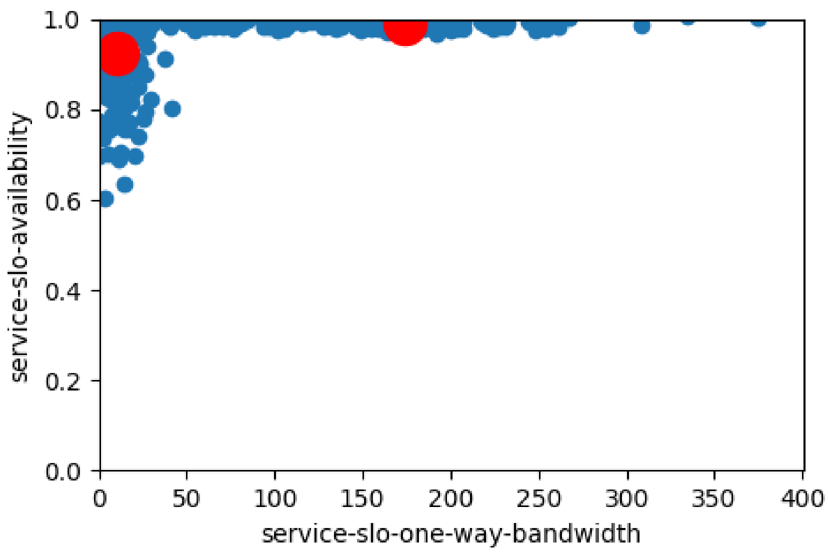


*Figure 1 Example of slices grouped in two clusters*

### 1.1.1.3 Complexity reduction of DLTs

Existing blockchain technologies suffer from multiple shortcomings, such as a lack of security for smart contracts that led to hundreds of millions of US Dollars-worth of tokens being stolen over recent years, limited scalability that hinders adoption for decentralised applications (Dapps) and the ever-growing size of the blockchain storage, due to nodes having to store all the transactions that ever happened on the blockchain.

In [D42], we summarise our research contributions to blockchain technologies. More details are available in the following publications:

1) “On the Storage Overhead of Proof-of-Work Blockchains” [NEC22]

2) “Mitosis: Practically Scaling Permissioned Blockchains” [NEC22]

3) “Practical Mitigation of Smart Contract Bugs [NEC21]

Moreover, in [D52] and [D53], we have presented an experimental evaluation of topology abstraction mechanisms that allow simplifying and abstracting the topological information shared between multiple domains [NFVSDN22].

#### 1.1.1.4 Algorithms for latency budgets as function of the application requirements

The Path Computation Component (PathComp) is designed and implemented to offer a dedicated and standalone computing entity and select the network resources when creating or modifying new/existing network connectivity services. In [D32] Path Computation component is detailed, including latency budgets. This component has been used in many workflows in [D53].

Moreover, detailed work with simulated results is included in [D53] Scenario 2 on Latency budgets as a function of the application requirements. [NTNU23] extends the results presented on the requested topic.

#### 1.1.1.5 Energy reduction.

Before tackling the implemented EAR algorithm, the transport network topology, and the experimental scenario/assumptions to generate the network connectivity requests, it is worth briefly overviewing the adopted energy network model, which was thoroughly discussed in [D42].

In [D53], Scenario 1 - Energy-Efficient Path Computation is validated and evaluated, including the performance of the Path Computation component when dynamically handling network connectivity services relying on a devised energy-aware routing (EAR) algorithm. Moreover, in [D53] Scenario 2 - Path Computation within the Green Economy [TNOR23], the concept of Decarbonization Level Agreements (DLAs) is introduced to include green intents in the service ordering process, and specifically applied to path computation for inter-domain connectivity services.

Energy reduction of Machine Learning components has also been considered in TeraFlow WP4. Specifically, addressing the pressing challenge of energy consumption in the telecom industry, we harness the full potential of state-of-the-art Green Artificial Intelligence techniques to optimize the size and complexity of Machine-Learning models to reduce their energy usage while maintaining their ability to detect potential cyber threats accurately. Existing energy optimization techniques were examined and compiled into a novel set of 11 optimization strategies to reduce the energy consumption of deep neural networks. These novel strategies were applied to the TeraFlowSDN ML-based attack detectors without negatively impacting the models’ performance. This reduced the average energy consumption by up to 83.30% with minimum performance degradation. Two papers describing the solutions adopted and the proposed open-source framework were submitted [MOZ23a], [MOZ23b].

## 1.2 Recommendations concerning future work

We have listed the reviewer’s recommendations for future work and clearly provided how we have addressed them during the P2.

### 1.2.1 Ensure that any delays and deviations are fully documented in the periodic reports

In order to accomplish this request, we have included a new column in all tables of Section 5. It includes commentaries regarding any delay and deviation the milestones and deliverables. Moreover, we have included access to all milestones through a permanent link:

TeraFlow Milestones

(https://cttcbarcelona-my.sharepoint.com/:f:/g/personal/rvilalta_cttc_es/Ev0Mk3URjnxLrzd8CI8k_IQB5RKo6gWBNa-okC7kUfTFdQ?e=DGizm0)

### 1.2.2 Make better use of the opportunities provided by advisory board members

We strongly believe that the role of advisory board members should undergo a significant transformation, shifting from mere periodic meetings to active and direct involvement in driving project impact. In pursuit of this goal, we have initiated a series of one-to-one meetings to foster synergies and gather valuable inputs to enhance TeraFlow's activities. In Section 4.2, we have compiled a comprehensive list of notable accomplishments attributed to each member of our esteemed Advisory Board. We express our sincere gratitude to our advisory board members for their invaluable insights, which have played a crucial role in maximizing the overall impact of TeraFlow.

### 1.2.3 Make sure the open access requirements are followed

We have listed all publications in D6.4. They have been included also in the Continuous Reporting tool and available at our website with links to persistent repositories:

https://www.teraflow-h2020.eu/publications

We have uploaded machine-readable electronic copies of the published versions or final peer-reviewed manuscripts accepted for publication to Zenodo, ArXiv, or the institution repositories for scientific publications from our partners – except in those cases of Gold Open Access, in which the original link to the publication is provided).

At the moment of the composition of this deliverable, we have 42 publications in open access (33 conferences and 9 journals).

### 1.2.4 Include in your DMP a deadline in time for publishing the datasets used for your research, even if they are not accessible

We understand the need to improve the description of used datasets project-wide. To this end, we have updated D1.5, the Data Management Plan (DMP), to improve project-wide descriptions of used datasets. The addition of two new concepts, availability and Deadline for open access, will provide valuable information to stakeholders.

The concept of availability, with categories such as Open/Upon request/Unavailable, will help communicate how the proposed dataset can be accessed. This will clarify to users and potential collaborators about the accessibility of the dataset.

The inclusion of a Deadline for open Access is also a useful addition. This provides an expected deadline indicating when the dataset will be publicly available. This information is crucial for planning purposes and ensures that interested parties know when they can expect to access the dataset.

Furthermore, updating D1.5 with the datasets identified during project execution is an important step in maintaining a comprehensive record. This list will serve as a reference for researchers, project members, and other stakeholders, allowing them to understand the datasets utilized throughout the project's lifecycle.

### 1.2.5 Add to the next periodic report the numbers on the use of resources, to understand the project progress and also add a table showing the activities of each partner on each task, to be able to evaluate how each beneficiary contributed to the project activities

We understand the request and have fully provided a specific section that includes detailed information on partner resource's usage (Section 4.4), as well as each task description has included a new subsection with specific information of each partner's contributions.

### 1.2.6 Also in the next periodic report, please add a section on the innovations of the project, including a snapshot of the TeraFlow IP registry and summary on how each innovation is going to be exploited and which companies are going to do it (Similar to D6.2 section on exploitation per partner, which is very good, but summarized)

We understand the request, and thus, we have extended Section 3.3.1 to provide the requested information. Now it includes the TeraFlow IP registry and summary on how each innovation is going to be exploited and which companies are going to do it.

### 1.2.7 There should be a clearer explanation on how Milestones have been achieved. This should be included in the documentation presented for review. Please include a link to any material needed for review in the comments for each milestone

All Milestones are documented through internal documents. They follow a lighter review and editorship process than the deliverables, but they ensure a certain milestone is reached and document it. We have included access to all internal milestone documents through a permanent link:

TeraFlow Milestones (https://bit.ly/teraflow_milestones)

### 1.2.8 Address the success of Objective 1 “Adoption of SDN by telecom operators“ clearly in the deliverables for the next review, taking into account that this is a very vague and potentially difficult to measure objective

We acknowledge the reviewer's valid concern regarding the vagueness and measurability of Objective 1. To address this issue, we have actively monitored this objective from multiple perspectives, outlined as follows:

a) Increasing the adoption of open and vendor-agnostic SDN:

TeraFlow has strategically aligned its impact activities to promote multi-vendor interoperability and open standards. By introducing standard interfaces at both the device level (SBI) and service level (NBI), we have successfully showcased TeraFlowSDN's capabilities across various technological domains such as IP routers, microwave, XR optics, and transport networks. Moreover, multi-vendor demonstrations have included collaborations with industry leaders like ADVA and Infinera.

b) Ensuring TeraFlow results are integrated into telecom operators' roadmaps:

We have established an independent and sustainable ecosystem centered around ETSI TeraFlowSDN to achieve this objective. This innovative approach has significantly amplified the impact of TeraFlow by fostering a thriving community around the proposed open-source, cloud-native SDN controller. We have rebranded TeraFlow OS to TeraFlowSDN controller (TFS) and released version 2.0 directly at ETSI OSG TFS. Furthermore, we have engaged with up to eight SNS projects and one CELTIC-NEXT flagship project, directing them towards utilizing TFS for their impact activities. Our plans for future features extend up to R5, scheduled for completion by the end of 2025.

c) Encouraging the adoption of TeraFlow architectural principles by operators:

This objective involves persuading operators to incorporate TeraFlow's proposed architectures and requirements into their roadmaps through elicitation processes. Notably, TeraFlow-related operators like TID and TNOR have successfully aligned their interests and internal roadmaps, such as Telefónica's iFusion project, with Telecom Infra Project (TIP) Open Optical & Packet Transport (OOPT) Mandatory Use Case Requirements for SDN for Transport (MUST). This alignment ensures that TeraFlow's architectural principles and interfaces seamlessly match the architecture and requirements of TIP MUST, positioning ETSI TeraFlowSDN as a reference implementation of the proposed TIP framework.

Overall, these concerted efforts and collaborations demonstrate our commitment to addressing the concerns raised and actively pursuing concrete measures to achieve the objectives outlined in TeraFlow.

### 1.2.9 Update the gender balance information in the Sygma system and embark on significant documented efforts to improve the gender balance where it has not been achieved

We have urged all partners to provide the required information in Sygma. Moreover, we have dedicated a section in this deliverable D1.4 to document the efforts to improve gender balance.

# 2 Progress of Technical Work and Achievements

In this section, we present a summary of the progress of the technical work and the project achievements. We start by summarising the progress towards the project objectives, and later we summarise the progress individually per work package breakdown.

## 2.1 Summary and Progress Towards Project Objectives

**Objective 1 "Adoption of SDN by telecom operators":** a) Accelerate innovation in transport (optical and microwave) and IP networks and ultimately help operators provide better connectivity for communities all around the world; b) Beyond 5G integration with L3VPN/L2VPN up to the network edge; and c) Automated service management for transport network slices.

This objective is mainly in the scope of WP2, reported in D2.1 and D2.2, but has also significantly progressed within WP3, WP4, and WP5 with the following key results over the reporting period:

- Use cases have been proposed for the TeraFlow SDN controller. Figure 2 shows the complete set of use cases for TeraFlow, as detailed in D2.2.

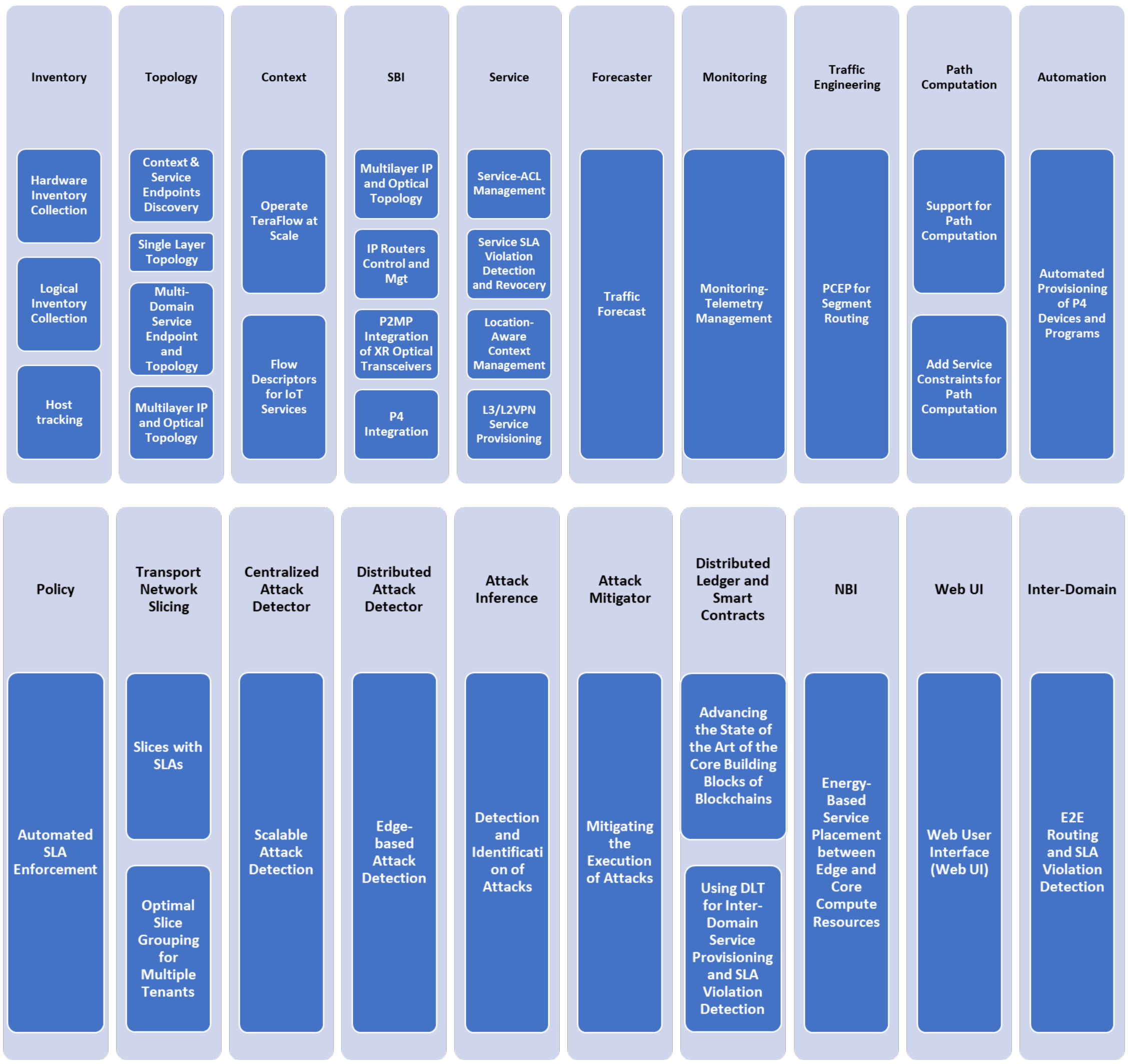


*Figure 2 Complete set of use cases for TeraFlow*

- A complete set of requirements for the TeraFlow SDN Controller has been introduced. They have been classified as functional and non-functional and cover the proposed use cases.
- We have presented an architecture for the TeraFlow SDN controller. First, we have provided an overall view of the architecture. Secondly, we have presented each detailed component architecture, focusing on RPC and data models. Finally, we have presented several workflows that involve multiple component interaction.
- The TeraFlowSDN has been implemented following the cloud-native architecture concept. The software is divided into micro-services that execute specific tasks and collaborate through messages to achieve the end goal for which the software is designed. In TeraFlowSDN, the communication between components is based on gRPC. We defined different RPC methods and messages and grouped them by micro-service. Deliverables D3.2 and D4.2 describe the architectural details of each component, the interface they expose, and some preliminary experimental results validating their stand-alone functionalities. Release 1.0 was presented in February 2022. Release 2.0 was presented in February 2023. At the time of writing, we are finalizing release 2.1.
- The TeraFlowSDN can process a request for an L3VPN and L2VPN service over a DWDM network or microwave network and deploy the necessary underlying network resources using the Transport API or inter-mediate microwave controller, as well as to configure the necessary routers using OpenConfig and NetConf protocols. More details are provided in D3.2 and D5.3.

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| **Objective 2 "Provide a novel SDN controller for Beyond 5G networks that evolves network flow management to cloud-scale requirements in order to support a 10x increase of connectivity services":** a) Design, development, and demonstration of a novel revolutionary cloud-native Network Operating System; b) Introduction of a new architecture to support massive IoT and new mobility paradigms; and c) Adoption of novel protocols for inventory, alarms, telemetry, and provisioning. |

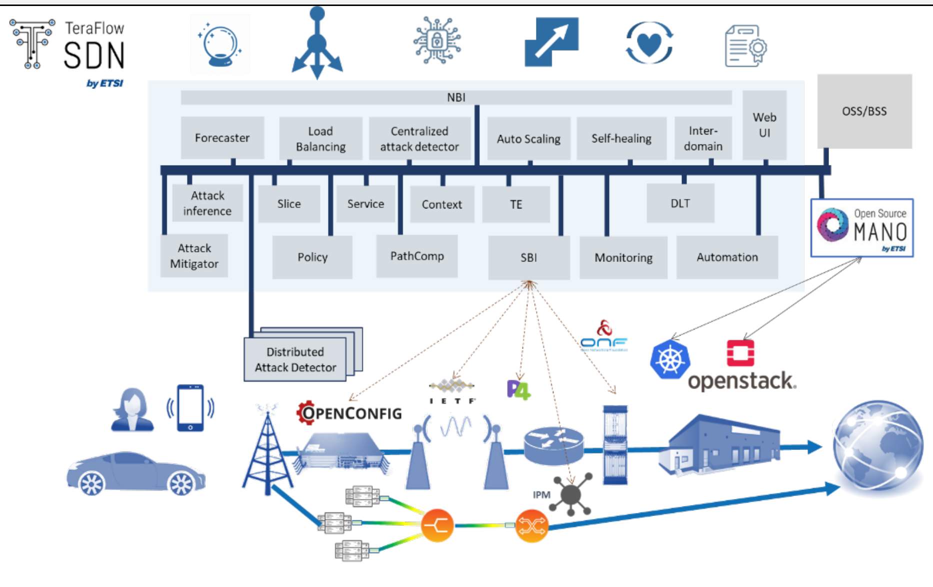


*Figure 3 ETSI TeraFlowSDN release 2.0 architecture*

This objective is mainly in the scope of WP3, reported in D3.2, but has also significantly progressed within WP2 and WP4 with the following key results over the reporting period:

- ETSI TeraFlowSDN components are designed and (partially) implemented following state-of-the-art software development and packaging techniques in independent cloud micro-services. These micro-services are managed via Kubernetes. Currently, the following SDN device types are supported: emulated, OLS ONF Transport API, ONF TR-532 microwave, NETCONF/OpenConfig, P4 whiteboxes, and gNMI/OpenConfig. Please refer to Figure 3 for the architecture of our SDN controller.

- These micro-services communicate with each other via a well-defined gRPC-based message bus, while exposing additional APIs (e.g., REST) to external entities or services. D2.2 provides details on all the updated protocol buffers.
- TeraFlow leverages the scalability merits of Kubernetes to provide independent, per-component scaling and load-balancing features, roll-back software recovery, and on-the-fly software package upgrades. D3.2 provides an analysis of each component, and scalability as a whole is evaluated in D5.3. Figure 4 provides an example of scalability measurement for setup of L2NM services.

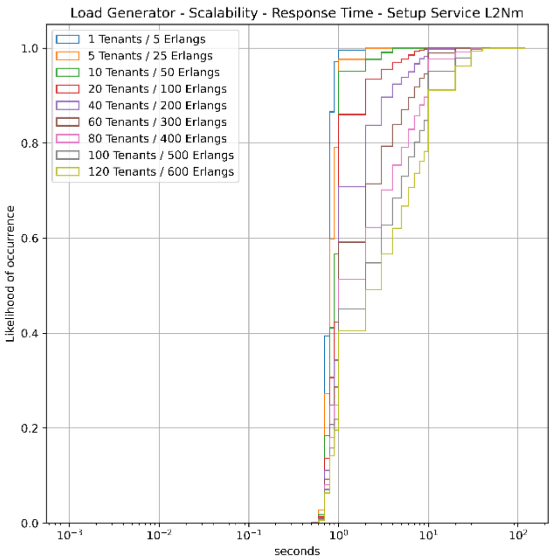


*Figure 4 Scalability – Setup L2 Service – Response Time*

- The introduction of location-awareness in end-to-end connectivity services and in network topologies is indispensable. D5.3 considers provisioning and updating of end-to-end connectivity service, considering that location-aware connectivity services might need service endpoint migration due to the dynamic nature of joint edge-cloud continuum and the provisioning of services to moving end users.
- TeraFlowSDN offers a built-in metrics collection framework that can benchmark and monitor the performance of the internal components. Unlike the Monitoring component, which collects KPI data from the infrastructure, the metrics collection framework is concerned with KPI data coming from the TeraFlowSDN components. This framework has provided some of the results from D5.3.

**Objective 3 "Easily integrate the TeraFlowSDN with distributed computing (including Multi-access Edge Computing) enable multi-tenancy and inter-domain connectivity through Transport Network Slices":** a) Integration with telco cloud and MEC; b) Provisioning of multi-tenant transport network slices; and c) Inter-domain provisioning of connectivity services.

This objective is mainly in the scope of WP3 and WP4, with the following key results over the reporting period:

- The integration of TeraFlowSDN with telco-cloud is shown in Figure 5. It shows two geographically-distant data centers (acting as Virtual Infrastructure Manager - VIM) that must be interconnected through a transport network slice using a WAN Infrastructure Manager

(WIM). Each DC has network connectivity access through Customer Edge (CE) equipment connected to Provider Edge (PE) equipment, each located at a network operator's Point of Presence (PoP). For instance, DC1 has its CE connected to data net and DC2. A transport network slice is deployed over a network connectivity service to satisfy the communication requirements between the two data centres.

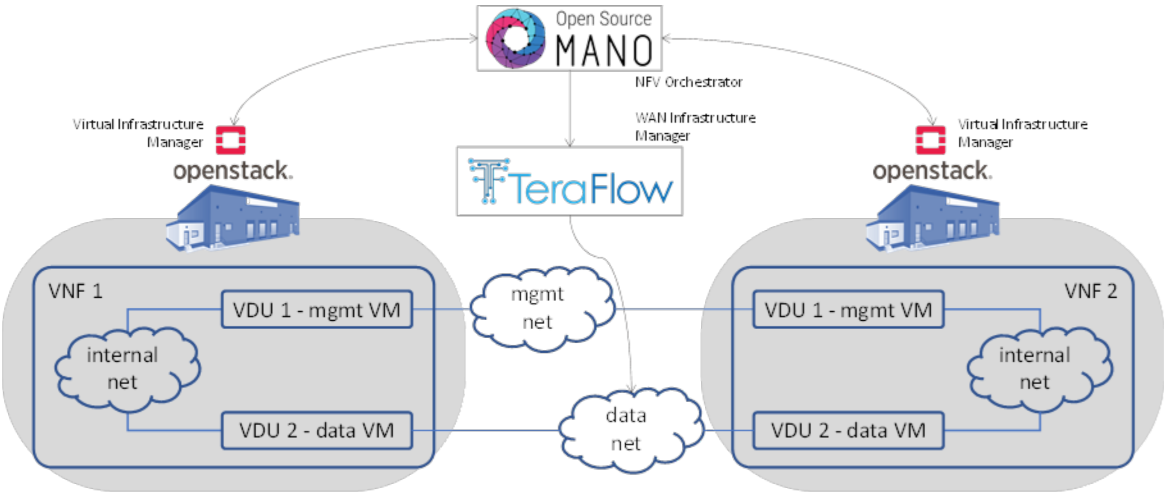


*Figure 5 Integration of NFV-O and Transport SDN Controller*

- TeraFlow has implemented a transport network slice (TNS) preliminary YANG data model for deploying TNS using ETSI TeraFlowSDN[2]. In D3.2, details about the TFS Slice component are provided, and the concept of slice grouping is introduced. Moreover, TNS has been demonstrated in OFC22 and OFC23 demonstrations. In D5.3, performance evaluation is provided for TNS provisioning.
- Moreover, in D6.4 contributions to ETSI OpenSourceMANO are detailed regarding the necessary new features and bug fixes for a complete and working integration with ETSI TeraFlowSDN.
- D4.2 and D5.3 present the inter-domain connectivity model designed for TFS. D4.2 presents the final architecture for Inter-Domain Component (IDC). Figure 6 illustrates the final design of the Inter-Domain Component (IDC). The main changes to the previous version are as follows. First, information exchange between domains is now performed via the DLT Component rather than a direct interaction between local and remote IDCs. Furthermore, the new PathComp Component is used to compute end-to-end SLA-enabled paths through multiple domains. For this, each local IDC additionally computes and maintains an abstracted version of its domain which can be shared with peer domains.

[2] X. Liu, et al., "IETF Network Slice YANG Data Model", IETF draft TEAS Working Group, March 2023. Work in progress. Available from https://datatracker.ietf.org/doc/draft-liu-teas-transport-network-slice-yang/

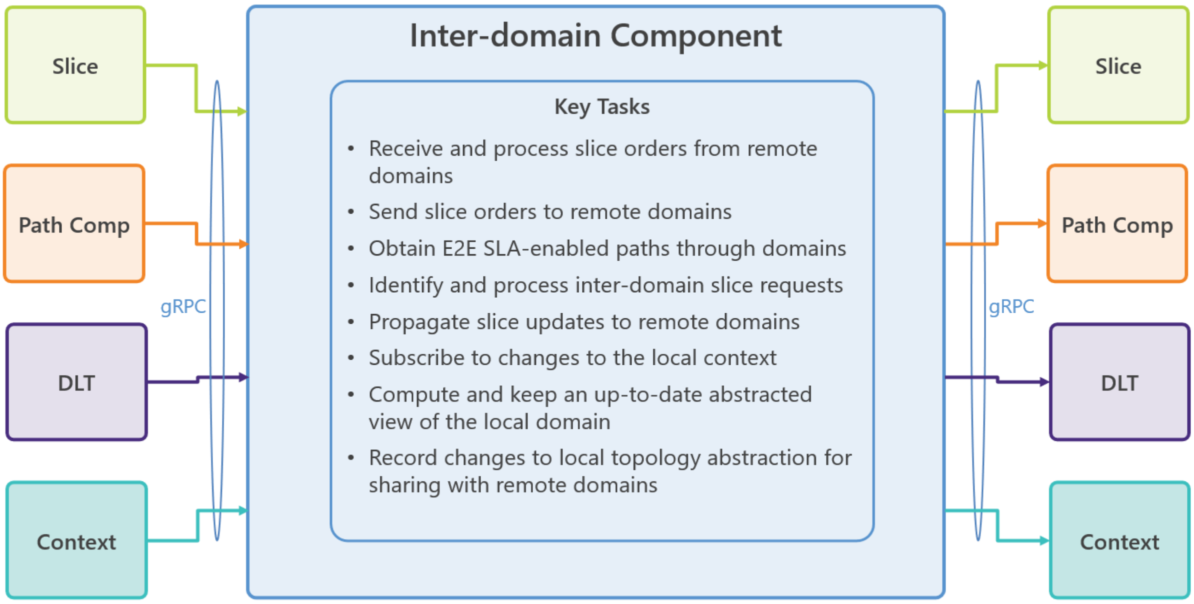


*Figure 6 Final Design of the Inter-Domain Component (IDC)*

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| **Objective 4 "Secure operator network":** a) Cyberthreat analysis and protection; b) Distributed ledger technologies. |

This objective is mainly in scope of WP4, reported in D4.2 and D5.3, with the following key results over the reporting period:

- TeraFlow has designed and implemented an advanced cybersecurity solution based on cyberthreat analysis and protection. This solution is crucial for protecting TFS's network infrastructure in the Software-Defined Networking (SDN) domain against sophisticated attacks at the optical, network, and transport layers. Given the complexity of this task, it is performed over multiple services and specifically designed components address the individual requirements. Broadly speaking, the work is split across four components: The Centralised Attack Detector, the Distributed Attack Detector, the Attack Mitigator, and the Attack Inference. The Centralised Attack Detector is a component that receives traffic data from the optical layer or the Distributed Attack Detector and detects various threats using a machine-learning (ML) based engine. When attacks are detected, the information is sent to the Attack Mitigator to enforce mitigation strategies (e.g., to drop a malign connection). In T4.1, three research activities were conducted in the context of the Centralised Attack Detector. First, we developed a methodological framework for transforming neural-network-based detectors into more efficient models concerning energy consumption. Second, we designed a new method for generating high-quality adversarial examples to transform ML-based detectors into equivalent models resilient to such adversarial attacks. In addition, we developed a Generative Adversarial Network (GAN) architecture to generate synthetic data that can fully substitute for real data in training ML-based detectors, and therefore avoid the generation of privacy breaches that might arise if real data were used to train the detectors.
- T4.2 describes the design and development of a Distributed Ledger Technology (DLT) Component focusing on distributed ledgers and smart contracts to secure 5G networks. The key features of DLT, and Blockchains in particular, namely, decentralisation, immutability, and transparency, make their use appealing for managing resources and services in multi-tenant networks. Blockchains replace centralised network management with replicated databases,

which leads to a resilient and trustworthy platform for storing and processing sensitive data. In the TeraFlow project, DLT is used in the multi-domain scenario to record actions by the internal components and manage TFS configurations. Additionally, the DLT serves as the data backbone for collaboration among multiple TFS nodes by sharing the SDN resources available in their transport network infrastructures. D4.2 describes the implementation of the DLT module based on the modular architecture of Hyperledger Fabric. We also present the technical improvement made to the DLT Component published at IEEE Blockchain and ACSAC. In addition, we describe in detail the role of the DLT Component in TFS, the general architecture of the DLT Component, and how it is used to share, in a trustworthy manner, updates about the infrastructure of the different TFS domains. Another result achieved was the demonstration in D5.3, presenting a Blockchain-based architecture to provide SDN actions to configure connectivity services in transport domains.

**Objective 5 "Generate impact and standardisation of project results. Support the 5G PPP programme":** a) Advertise the TeraFlowSDN, make it available as open source, and foster industry adoption of its features; b) Communication and dissemination of TeraFlow results to appropriate stakeholders; and c) Promote and actively drive standardisation and multi-vendor interoperability events.

This objective is mainly in the scope of WP6, reported in D6.4, with the following key results over the reporting period:

- The website (https://www.teraflow-h2020.eu/) has been conveniently updated throughout the whole reporting period. Events, scientific papers, news, videos, and blog posts by Consortium experts have been regularly produced and uploaded to their sections. The events also include links to their related presentations, papers or open access proceedings, and pictures of the event when available. The website has also uploaded marketing materials like posters, roll-ups, leaflets, and biannual newsletters. In this project's last phase, the scenarios' definition and implementation have been further developed, and the website have been updated accordingly. Besides, a new section called TeraFlowSDN has been created, connected to the TeraFlowSDN community in ETSI.
- Social media has become the primary channel for delivering news and information to stakeholders and the public. Updates and relevant news were regularly posted to get further engagement with the targeted audience. TeraFlow project created accounts on Twitter (@TeraFlow_h2020, 354 followers at project closure) and LinkedIn (TeraFlow H2020, 302 followers at project closure). The TeraFlowSDN group also set their own Twitter (@TeraFlowSDN) and LinkedIn (TeraFlowSDN) accounts managed by the ETSI communication team. The audiences are slightly different, but all the accounts are interrelated. From March 2022, the dissemination team implemented a targeted post strategy, specifically tagging relevant profiles like partner chairs, co-chairs and speakers in events and other interested parties. Tagging relevant people, projects, or organisations has significantly increased the number of followers and audience engagement. It became an effective way to gain exposure and benefit from extra exposure when they reciprocally tag the project, widening the reach of posts.
- Twenty-six videos are available on our website, including one general-purpose video created to promote the project - with more than 1300 views. Twelve of them have been produced during this reporting period.

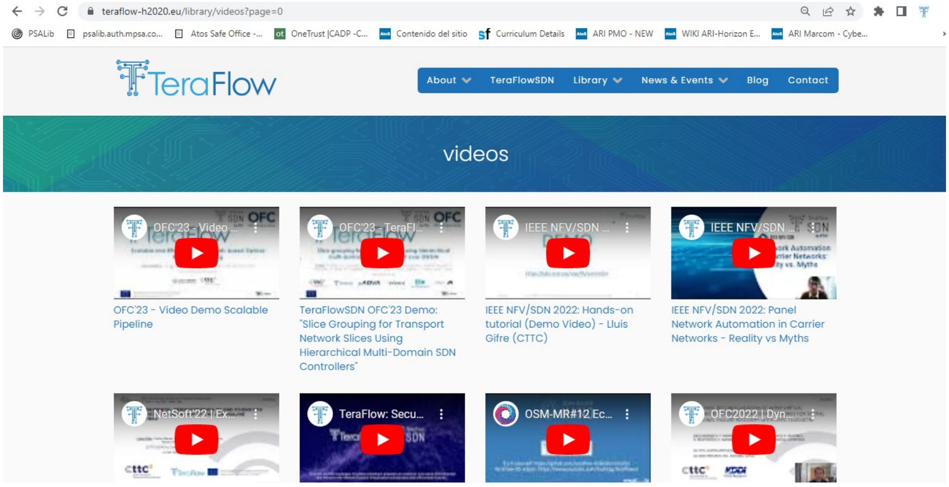



*Figure 7 Video section in TeraFlow project website.*

- Design and production of different types of communication material (posters, social media banners, brochures, newsletters), which have been used at events to increase project visibility.
- Publication of press releases and news on partner's own websites and other related projects or initiatives (TeraFlowSDN, OSM, 5G PPP), as well as specialised websites/magazines and media.
- The Consortium has produced 51 publications, with 44 open-access publications (34 conferences and 10 journals). The distribution by reported period is as follows: 2021 (M1-M12): 21 in open access (19 conferences and 2 Journals); 2022-2023 (M13-M30): 23 in open access (15 conferences and 8 Journals); 7 not in open access yet, some of them under review (6 conferences and 1 journal).
- TeraFlow has been presented in a total of 61 events. TeraFlow was presented in 40 events with 5 booths during this reporting period. After the pandemic, 2022 and 2023 have been very active years, with increasing attendance to face-to-face events. Participation in external events and organisation of own events/workshops in collaboration with other initiatives and projects (TeraFlowSDN, OSM, 5G PPP webinars, for example) or co-located within bigger and renowned venues, reaching over 2800 persons with different roles and from different backgrounds such as researchers, academics, industry, and standardisation bodies. D6.4 highlights the most significant events of the period (OFC22 and OFC23, Layer 123 2022, NetworkX 2022, IETF 115 and 116, FIRA'22 Workshop at SIGCOMM 2022, ETSI Research Conference 2023, EUCNC 2023, ICC 2023, AI-NET Annual Event 2023, and IEEE NetSoft 2023.
- To ensure the sustainability of the project results and uptake by third parties, TeraFlow partners have created ETSI TeraFlowSDN Open Source Group (TFS OSG). This strategy has captured interest in the community and provided new contributors through multiple upcoming SNS projects.
- TeraFlowSDN partners are closely discussing with ETSI OSM developers to accomplish a functional integration between the OSM latest release and the TeraFlowSDN architecture. Other open-source projects that TeraFlow is aligning with are ONF and HyperLedger, so that their users can leverage TFS for research and innovation activities.
- TeraFlow is taking part in relevant working groups in SDOs (ETSI, ONF, OpenConfig, IETF and TIP), and other industry fora, contributing with related documentation to help form strategies and ensure that TeraFlow objectives are met.

- A significant presence of TeraFlow has been provided to the 5GPPP community through the organization and participation of working group meetings, joint whitepapers, special sessions and booths.

## 2.2 WP2 - Use Cases, Requirements, Architecture, Business Model Analysis, and Data Models

WP2 sets the necessary foundations for the TeraFlowSDN and it is organised into four distinct areas through the WP2 tasks:

- Task 2.1: Use case definitions and requirements.
- Task 2.2: Architecture.
- Task 2.3: Business model analysis.
- Task 2.4: TeraFlowSDN data models.

### 2.2.1 Task 2.1: Use Case Definitions and Requirements

D2.2 has presented the final version of the use cases proposed for the TeraFlow SDN controller. They are classified into the following topics: inventory, topology, context, SBI, service, forecaster, monitoring, traffic engineering, path computation, automation, policy enforcement transport network slicing, ML-based security, distributed ledger and smart contracts, compute integration, NBI, Web UI, and inter-domain. Figure 2 provides the classification typology.

These use cases refer to multiple network technologies covering IP, Optical, and Microwave. Optical and Microwave are deployed as transport networks, while IP is intended to provision L3VPN services.

Table 1 shows the relationship between the proposed use cases and the D5.2 scenarios. This matrix will ease specific demonstrations in the scope of WP5. Please refer to D5.2 for a clear description of the proposed scenarios:

- Scenario 1: Autonomous Network Beyond 5G.
- Scenario 2: Inter-domain.
- Scenario 3: Cybersecurity.

*Table 1 Scenario – Use case matrix*

| | Autonomous Network Beyond 5G | Inter-domain | Cybersecurity |
|---|---|---|---|
| **Inventory** | X | X | |
| **Topology** | X | X | X |
| **Service** | X | X | X |
| **Transport network slicing** | X | X | |
| **Monitoring** | | | X |
| **Traffic Engineering** | X | | |
| **Automation** | X | | |
| **Policy** | X | | |
| **ML-based security** | | | X |
| **Distributed ledger and smart contracts** | | X | |

| | | | |
|---|---|---|---|
| **Compute** | X | | |
| **Inter-domain** | | X | |

Moreover, different requirements for the TeraFlow SDN Controller have been introduced. They have been classified as:

- Functional Requirements: refer to the system's necessary actions or limitations, which can be articulated in input responses. These requirements are categorized based on the same use case topics.
- Non-functional Requirements: refer to standards against which system performance can be evaluated, rather than specific behaviours. Unlike functional requirements, which detail specific actions, non-functional requirements include performance, usability, scalability, security, reliability, and portability.

#### 2.2.1.1 Partner's contributions

●**CHAL** has contributed to the definition of the ML-based security use case, in particular, focusing on the security aspects related to optical networks. CHAL also contributed to the initial definition of the Web UI scenario.

●**CTTC** has contributed to the definitions of multiple use cases, such as Compute, Transport Network Slicing and Interdomain. Moreover, Inter-domain scenario has been lead to perform requirement elicitation.

●**TID** has contributed with the definitions of the use cases "Inventory", "Topology", "Services", "SBI", "NBI", and their requirements. To have realistic input to the definition of the use cases, information has been compiled from other OBs.

●**INF** has contributed requirements for L3 network element control and management and Open XR optics integration through device driver layer through TAPI layer.

●**SIAE** has contributed to the implementation of the uses "Inventory", "Topology", "Services" working on MW device driver managing the MW portion of the transport network.

●**NEC** has contributed to the integration of the DLT component in the use-case, in particular focusing on the security, privacy and usability aspect of using DLT as a data-sharing platform.

●**ATOS** has participated in the elaboration of the requirements for the high-performance and automation controller. ATOS has defined the Monitoring-Telemetry Management use case in MS2.2 and updated monitoring requirements. It has also participated in the elaboration of D2.2, where all these contributions have been included.

●**TNOR** has contributed to the definition of the Inter-domain component, the network slicing component and the accompanying use cases, and their requirements.

●**UPM** has contributed to the definition of the ML-based security use case, focusing on the security aspects related to packet layer networks. In addition, a distributed use case was defined to enhance the scalability of the cybersecurity components.

●**VOL** provided support during Y1 for use cases related to automatically configuring network elements via SBI.

●**NTNU** has contributed to the scenario and use-case inter-domain and the design of the related components.

●**UBI** has provided technical requirements related to the P4 activities of the project.

●**STR** has contributed to the design of the initial Traffic Engineering communication module.

●**ODC** provided support in alignment with IETF use cases such as those described in Abstraction and Control of TE Networks (ACTN).

### 2.2.2 Task 2.2: Architecture

A detailed architecture description for TeraFlowSDN release 2.0 is provided in D2.2. In this section, we briefly describe the overall architecture to make the deliverable self-contained by introducing the main design of TeraFlowSDN.

The SDN controller cloud-native architecture consists of stateless micro-services interacting with each other to fulfil network management tasks, in addition to a few stateful micro-services responsible for keeping the state of the network. TeraFlowSDN relies on Kubernetes to handle the containers supporting the micro-services. Kubernetes is a state-of-the-art container orchestrator that provides broad management capabilities and can operate geographically distributed infrastructures.

Figure 8 shows the proposed micro-service-based architecture. Following the design principles from cloud-native applications, each component is implemented as a micro-service that is able to export a set of Remote Procedure Call (RPC) services to other components. Each micro-service can be instantiated once or with multiple replicas, allowing load-balancing techniques to be applied. By adopting stateless micro-services, requests can be handled by any replica of the micro-service. Load balancing works by establishing an endpoint that will receive all the requests for service. 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, i.e., tracking the addition and deletion of replicas and updating its internal list of replicas. Depending on the RPC implementation adopted, we may use the built-in Kubernetes load balancer, or adopt an external one. Each replica comprises a Pod, i.e., a collection of containers that Kubernetes manage as a single entity.

Context component stores the network configuration (e.g., topologies, devices, links, services) and its status as managed by the TeraFlowSDN components in a No-SQL database to optimize concurrent access. Internally, it implements a Database API enabling to switch between different backends. The TeraFlowSDN controller uses its North-Bound Interface (NBI) component (previously known as Compute) to receive Layer 2 Virtual Private Network (L2VPN) requests and convert them to necessary connectivity services or Transport Network Slices via the Slice and Service components. The Service component selects, configures, and deploys the requested connectivity service through the South-Bound Interface (SBI). To this end, the SBI component interacts with the network equipment and/or underlain network controller through pluggable drivers. In addition, a Driver Application Programming Interface (API) has been defined to facilitate the addition of new network protocols and data models to the SBI component. The Automation component implements several Event-Condition-Action (ECA) loops defining the automation procedures in the network. Monitoring manages the different metrics configured for the network equipment and services, and stores monitoring data related to selected Key Performance Indicators (KPI). It provides means for other components to access the collected data. Internally, the Monitoring component relies on a database to store the monitoring data as time series, exploiting its powerful querying and aggregation mechanisms for retrieving the collected data.

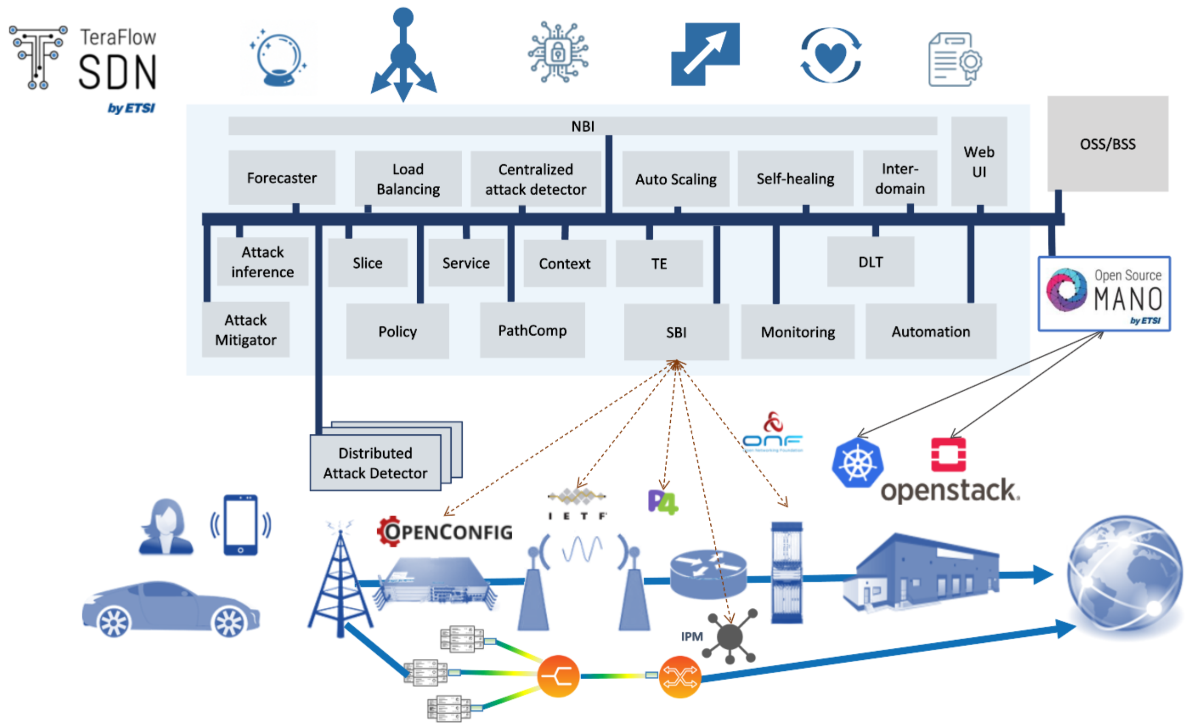



*Figure 8 TeraFlowSDN architecture*

North-Bound Interface (NBI) component serves as the interface from internal gRPC (gRPC Remote Procedure Call) and protocol buffers towards external Representational State Transfer (REST)-like requests. It provides a Representational State Transfer API (REST-API)–based on NBI 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 issue operational requests to the TeraFlowSDN components.

TeraFlowSDN Release 2 provides extended and validated support for OpenConfig-based routers and interaction with optical SDN controllers through the Open Networking Foundation (ONF) Transport API (TAPI). Moreover, TeraFlowSDN release 2 includes complete integration for microwave network elements (through the Internet Engineering Task Force - IETF - network topology YANG model), and Point-to-Multipoint integration of XR optical transceivers and P4 routers. New features for P4 routers include loading a P4 pipeline on a given P4 switch; getting runtime information (i.e., flow tables) from the P4 switch; and pushing runtime entries into the P4 switch pipeline, thus allowing total usage of P4 switches.

Service Level Agreement (SLA) validation has been re-engineered through all the workflows, from Device monitoring to Service and Slice life cycle management. Thus, the Slice, Service, Policy, Device and Monitoring Components have been updated to support the necessary network automation workflows. Moreover, Slice grouping has also been introduced, along with the Path Computation Component. This component allows new use cases, such as energy-aware service placement.

Cybersecurity mechanisms have been updated, including novel components for attack detection (either distributed or centralized), attack inference, and attack mitigation. In addition, several novel use cases are supported. Distributed Ledger Technology (DLT) has also been extended to interact with the Inter-domain Component and use the deployed Hyperledger Fabric.

Several workflows have been analyzed, such as L3VPN Establishment with SLA, L3VPN Establishment, L2VPN Establishment, Inventory, Multi-Layer Topology Discovery, Service ACL, Service Location-Awareness, Traffic Engineering, Slice SLA Enforcement, Slice Grouping, Forecaster, Inter-Domain Slice SLA Enforcement, DLT Record Exchange Between DLT Connector and DLT Gateway, Inter-Domain DLT, Energy-Aware Network Service Placement.

#### 2.2.2.1 Partner's contributions

●**TID** has contributed to the architectural definition. Also, with the creation of the workflows for "L3VPN Establishment", "L2VPN Establishment", "Inventory" and "Service ACL".

●**CTTC** has contributed to multiple components definitions, such as Forecaster, Slice, SBI, PathComp, and Service, as well as aligned multiple workflows, such as Service Location-Awareness, Slice SLA Enforcement, Slice Grouping, Forecaster, Inter-Domain DLT, and Energy-Aware Network Service Placement.

●**INF** contiributed L3 related component architecture and introduce the necessary network automation workflows, provided Open XR device driver component for TeraFlowSDN architecture as interface to Infinera IPM (Intelligent Pluggable Manager) controller to create L1 service connections for XR Optics.

●**SIAE** contributed to identify and implement appropriate standard model to address inventory recovery and service creation over MW portion of the transport network. Provided device and service drivers as interface to SIAE intermediate controller towards MW equipment.

●**NEC** contributed to the general architecture and the APIs for interacting with the distributed ledger component.

●**ATOS** has participated in the development of the architecture and in the workflow definition. In this period, ATOS has upgraded the architecture of the monitoring component, the design and workflow. ATOS has participated in conversations with CTTC about how to cover scalability goals in the component. There has been also a second iteration of the monitoring component architecture (operations and functional structure) defined in MS2.2. All this work has been the basis for ATOS contribution to D2.2.

●**TNOR** has contributed to the task by addressing the system integration and migration contexts, and how the information model evolutions might affect the relevant challenges. Architectural considerations driven by the service information models has been considered.

●**CHAL** contributed to the design and specification of the TeraFlow architecture and participate in the definition of the workflows.

●**UPM** contributed to the definition of the general architecture and in particular, the distributed cybersecurity solution for protecting TeraFlow's infrastructure at the packet layer.

●**VOL** provided support during Y1 defining the architecture of TeraFlowSDN and their NBI and SBI.

●**UBI** has contributed 4 blocks in the TeraFlowSDN architecture, namely the ZTP, Policy Management, P4 SBI driver, and P4 service handler.

●**ODC** helped derive the functional components required and overall TeraFlow architecture and interfaces, to address the use cases. They disseminated the TFS architecture in international standards commutiees.

●**ADVA** has contributed to TFS architecture design discussions with contributions towards NBI and Slice components.

### 2.2.3 Task 2.3: Business Model Analysis

In Task 2.3, we have conducted ecosystem and business model analyses of the TeraFlowSDN system, collaborating with Task 6.3. In our analyses we have relied on frameworks sourced from theories on platform ecosystems and technological innovation systems, and development of business model canvases for roles. Together, this provided new insight into emerging roles and reinforcing of others in a growing ecosystem. The data input to our analyses have been two rounds with partner interviews, two virtual and one physical workshops, partner surveys, TeraFlow partners' exploitation plans, and published literature. We especially appreciated the input from open-ended interviews with partners. Over the project's lifetime, the insight has been introduced and iterated in several cycles converging toward a shared view.

Our analyses suggested roles and type of relationships in the TeraFlowSDN ecosystem, uncertainties, and enabling and blocking mechanisms for the further evolution of the ecosystem, as well as gaps between business models as-is and to-be. In the final phase, we used approaches from complex adaptive systems to further elaborate on the ecosystem roles, and the dynamics and causal direction between roles, in particular feedback loops and network effects. The final analysis reinforced relevant business models already suggested, and introduced the Specialized System Integrator which represents a more adaptive, forward-leaning approach. The value proposed is increased flexibility, scalability and innovation adapted to continuously changing needs of the markets. These results provided insight on potentially stable and more sustainable evolution paths for the TeraFlowSDN ecosystem. The results are documented in D2.1, D2.2, and D6.4.

#### 2.2.3.1 Partner's contributions

●**TNOR** has contributed to the task needed to address the task objectives. TNOR has driven and contributed to the analyses of TeraFlowSDN ecosystem and buisness models. Furthermore, TNOR contributed to the analysis of the service concepts (see WP3) and how the business relationships might evolve along with relevant scenarios and roadmaps.

●**TID** has contributed to the partner identification and analysis of business models for the TeraFlow solution. Additionally, TID has presented the project's initial results internally and provided feedback from the operational businesses. TID has also elaborated a business model and exploitation plan jointly with TELENOR and ATOS.

●**NTNU** will contribute to the stakeholder and ecosystem analysis. NTNU lead the work on System Dynamics Modeling for analyzing the TeraFlowSDN Ecosystem and identified potential stable and sustainable evolution paths for the TeraFlow SDN ecosystem together with TNOR and ATOS.

### 2.2.4 Task 2.4: TeraFlowSDN Data Models

In this task, we have identified the selected data models to be used as both external (including Northbound and Southbound) and internal interfaces (between TeraFlowSDN components).

The external interfaces are the ones offered to be consumed from external components of TeraFlow and typically use NETCONF or RESTCONF protocols, and we have separated in NBI interfaces and SBI interfaces.

Several interfaces are proposed to be used as NBIs, being summarised in L3/L2 network models, Traffic Engineering (TE) tunnels, and IETF Transport Network Slices. The SBIs focus on device communication and more information about them is provided in D3.2 – SBI component architecture description. Release 2.0 supports the following SBIs: OpenConfig, ONF Transport API, ETSI mWT (Microwave), P4, XR Optics IPM, and emulated OpenConfig devices.

Google Remote Procedure Calls (gRPC)[3] is a protocol based on HTTP/2 as a transport protocol and it uses protocol buffer encodings for transported messages and data models. As it is based on HTTP/2 and uses byte-oriented encoding, it introduces low latency. gRPC has been used in highly scalable and distributed systems. It has been decided to use gRPC as the internal protocol in the TeraFlow SDN Controller. All defined internal protocol buffers are part of the TeraFlow SDN source code, and they are available at https://gitlab.com/teraflow-h2020/controller/-/tree/develop/proto

#### 2.2.4.1 Partner's contributions

●**ATOS** has contributed to the selection, development and integration of the data models. More concretely, ATOS has performed the evolution of the data model of the monitoring component, for which, parallel meetings with CTTC and UBI have been needed to define the functionalities and fields. During this period, there has been a second iteration of the data model of the monitoring component presented in MS2.2 and contribution to D2.2.

●**CTTC** has contributed to the initial protocol buffer examples for service, and later several internal data models have been contributed. Also has contributed punctually to external NBI and SBI interfaces.

●**SIAE** contributed to define internal data models for microwave network elements and their transport resources, in order to provide different levels of abstractions as best suited for each OS module and internal API.

●**NEC** contributed on the requirements and limitations of the data that must be exchanged with and stored by the distributed ledger component.

●**CHAL** has contributed to the definition and specification of the data models related to the security components in the TeraFlowSDN architecture.

●**TID** has participated in the definition and specification of data models pertaining to Openconfig driver services (L2VPN, L3VPN and ACL), inventory, topology, and gNMI in the TeraFlow architecture.

### 2.2.5 Impact of COVID-19 on WP Activities

COVID-19 has not had any significant impact on WP2 during the project duration. Milestones and deliverables have been delivered reached and delivered on time, or with insignificant delays.

[3] E. Breverman et al., Optical Zero Touch Networking—A Large Operator Perspective, OFC 2019.

## 2.3 WP3 - Life-cycle Automation and High-Performance SDN Components

WP3 bridges key gaps in state-of-the-art SDN controllers in four distinct areas organised as WP3 tasks:

- T3.1: High-performance control plane operations through a revolutionary cloud-native network operating system (NOS) design, based on distributed and fully disaggregated micro-services.
- T3.2: Native support for key transport technologies, such as Internet Protocol (IP), optical, and microwave (MW), as well as emerging next-generation SDN technologies, such as the programmable protocol-independent packet processors (P4).
- T3.3: Automated, zero-touch provisioning (ZTP) of network services and NOS lifecycle operations.
- T3.4: Multi-tenant network slicing as a service coupled with SLA requirements.

### 2.3.1 Task 3.1: High-Performance SDN Framework

This task is devoted to design, develop, and test acceleration techniques that enable the TeraFlowSDN controller to provide high-performance flow management from a control plane perspective. This workspace is bundled into four main cloud-native components implemented as fully disaggregated micro-services belonging to the TeraFlowSDN controller: i.e., the Context Management, Monitoring, Traffic Engineering, and Path Computation Components. More details on this task are provided in D3.2.

The **context** component is the primary entry point for accessing and managing elements within the TeraFlowSDN controller database. It facilitates operations related to reading, updating, and removing objects such as topologies, devices, links, services, and connections. The various TeraFlowSDN components rely on the context component to access these objects and perform their functionalities. A comprehensive internal redesign has enhanced the component's performance and scalability. This redesign incorporates self-replication capabilities and scalability of the component's database. Moreover, novel features have been introduced, including utilising a NewSQL database, specifically CockroachDb, to support the distribution and replication of the internal database. The second release of the TeraFlowSDN context component introduces several key enhancements. One significant addition is the introduction of component replication, which allows for the distribution of the internal database. This feature ensures that data is replicated across multiple nodes, such that if one node becomes unavailable, another copy of the data is available for serving read and write operations. Additionally, protocol buffers definitions have been reviewed and extended to accommodate the requirements of other components within the system. This includes support for constraints in Service and SBI Components, service constraints in path computation, support for Inventory, permanent storage of policies from the Policy component, and ACL (Access Control List) support in Service. The context micro-service, housing the NewSQL database, is pivotal in the TeraFlow architecture. It employs a distributed architecture that employs a concept of continuous range-based sharding. Key spaces of the tables are divided into continuous ranges, or shards, which are then replicated across multiple nodes. This design ensures data redundancy and fault tolerance. In order to maintain consistency across all database shards, a consensus algorithm is utilized. The consensus algorithm facilitates the synchronization of changes and ensures that updates are propagated across nodes before the final commit. The two commonly used consensus algorithms in distributed databases, Paxos and Raft, are employed. These algorithms elect leaders for each shard, and changes within the shard must be processed by the leader with acknowledgement from the followers before being committed. In case of leader failure, the remaining nodes in the shard must reach a quorum to elect a new leader.

The **monitoring** component plays a crucial role in the TeraFlowSDN (TFS) system as it manages, stores, and provides access to metrics in the form of Key Performance Indicators (KPIs). It offers a gRPC API that allows other components or agents within the TeraFlow SDN controller to leverage its functionalities. The monitoring component operates based on a monitoring model driven by KPIs, enabling external actors to define their generic, ad-hoc, and vendor-independent KPIs and associated alarms and subscriptions. Its primary objectives include generating and managing multiple metrics and KPIs, enabling external subscriptions to serve real-time monitoring data, managing ad-hoc alarms, and integrating with external time-series visualization tools. The evolution of the monitoring component has focused on three main aspects: expanding its functionalities to meet monitoring requirements, improving overall stability and performance, and enhancing horizontal scalability to handle highly loaded scenarios. Several features and extensions have been incorporated to achieve these goals. The monitoring protobuf data model has been updated to support subscriptions and alarms, and new RPC methods have been added to export the updated functionalities. A new distributed and scalable time-series database called QuestDB has been integrated to store monitoring data to enhance performance. Furthermore, subsystems for subscriptions and alarms have been defined and implemented, and the management database structure has been expanded to support these subsystems effectively. The final design of the monitoring component revolves around KPIs, alarms, and subscriptions. External actors can define their vendor-agnostic KPIs and associated alarms and subscriptions, which are managed through an internal management database. Monitoring data related to the KPIs can be ingested from external sources into a high-performance time-series database through the monitoring component. Additionally, the monitoring component allows integration with various third-party data visualization tools such as Grafana. The architecture consists of two main blocks: the Monitoring Core and the MetricsDB. These blocks can be deployed in separate containers but are interconnected within the same monitoring component, facilitating efficient and modular deployment.

D3.2 details significant efforts to evaluate multiple databases and possible architectures to improve the latency of the monitoring component. Figure 9 provides an example of the performance analysis for the component.

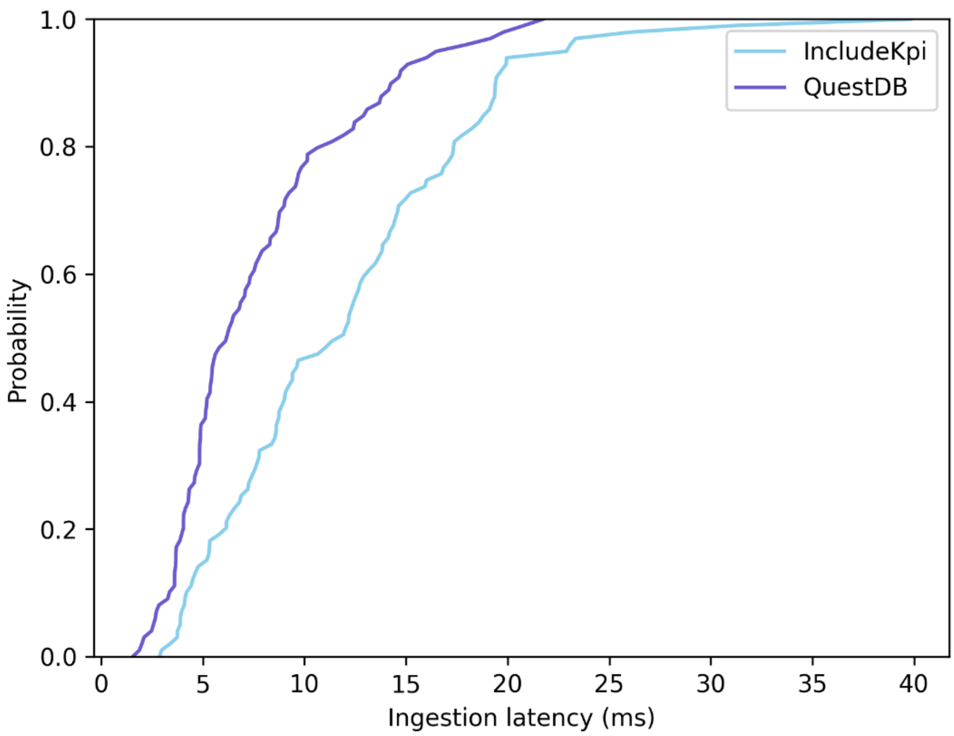



*Figure 9 evaluation of the ingestion latency of the IncludeKpi gRPC method*

The **Traffic Engineering** Component (TE) provides path computation for Segment Routing (SR) over the compatible infrastructure provided by the Device component. It utilizes the information exposed by the Context component to consolidate devices in a Traffic Engineering Database (TED). The TE component is responsible for maintaining and synchronizing the SR Label Switched Paths (LSPs) received from devices and creating new LSPs requested by the Service Components. Communication between the TE component and other TeraFlow components, including Service, Context, and Device, is facilitated through gRPC. The communication channel with devices is established using the Path Computation Element Protocol (PCEP), with the TE component acting as the server and the devices as clients. In the new release of the TE component (version 2.0), a complete reengineering effort has taken place to ensure seamless integration and support for traffic engineering using the Path Computation Element Protocol (PCEP). This new release introduces several significant features and extensions.

First and foremost, integration with the Service, Device, and Context components has been established, allowing for efficient collaboration and information exchange. Additionally, a TE workflow demonstration has been developed, utilizing emulated routers to showcase the capabilities and functionality of the TE component. One notable enhancement is the creation of Segment Routing paths using PCE-initiated LSPs, further expanding the possibilities and flexibility of the traffic engineering capabilities within the TeraFlow system.

The **Path Computation** Component (PathComp) is responsible for computing and selecting network resources when creating or modifying network connectivity services. It relies on various inputs, including the Context information encompassing topology and domain details, existing services, attributes, and targeted network service connectivity characteristics, such as endpoints and specific requirements like bandwidth and latency. The PathComp also considers a performance objective, which can involve optimizing resource usage or minimizing network power consumption. The PathComp is designed to handle both single and multiple network connectivity services. In the case of multiple services, it becomes useful for restoring diverse services affected by network anomalies or reoptimizing allocated resources. When a successful computation is achieved, the output of the PathComp includes information about the devices and links forming the computed path, as well as specific configuration parameters related to switching or technology. However, if the PathComp cannot find a feasible path or resources that fulfil the service requirements, it sends a response indicating the unavailability. Regarding new features and extensions, the PathComp focuses on concentrating path computation and resource selection functions within a specialized component. It operates as a server that can host various algorithms targeting different objective functions, such as K-Shortest Path, Shortest Path, and Energy-Aware Routing. The PathComp exposes a defined interface and workflow to other TeraFlow OS components, with the Service component being the primary component interacting with it. However, other components like Automation, Slice, or Inter-Domain may also utilize the functionalities of the PathComp based on their specific requirements.

#### 2.3.1.1 Partner's contributions

●**ATOS** has been T3.1 leader. During this period, ATOS has performed the refinements in the development of monitoring component for the software releases of this component. ATOS has also upgraded the set of unit tests and preliminary integration tests with device and context components and has analysed potential options to upgrade management and time series databases in the monitoring component. Aligned with WP2, ATOS has implemented a new data model of the monitoring component for subscriptions and alarms. ATOS has also implemented and tested the QuestDB management database of the monitoring component. It has performed the performance evaluation of QuestDB, InfluxDB and the monitoring component overall. With all this work, ATOS has contributed to MS3.2 and D3.2.

●**UBI** has contributed storage APIs to the Context component, related to the Automation (ZTP) and Policy Management components as well as bug fixes in the Monitoring component during its integration with the Policy component.

●**CTTC** has contributed to the design of the Context component and their exposed APIs to interact with other components, the architecture of the Path Computation component along with the supported routing algorithms.

●**SIAE** has contributed studying how can be extended MW driver to support Monitoring and Topology discovery functionalities using standard models.

●**STR** has contributed with TE component and provided demonstration of PCEP support with Free Range Routers (FRR) virtual routers. STR has also contributed with toolboxes to create microservices in Erlang environments.

### 2.3.2 Task 3.2: Hardware and L0/L3 Multi-layer Integration

This task has focused on the design of the northbound and southbound interfaces, and preliminary results of the core TeraFlowSDN components: the Device Component, Service Component, and Forecaster component.

The **SBI Component** interacts with the underlying network equipment. Different protocols and data models might be needed to manage the network equipment. For this reason, the Device Component provides a Driver API that enables developers to implement new drivers and integrate them into the

TeraFlowSDN. The component consists of a gRPC-based NBI exposed to the rest of the TeraFlowSDN components, and a set of SBIs that interact with different network equipment using appropriate protocols and data models. In between, the Device Servicer block dispatches the incoming requests and interacts with the SBI Driver API to choose the appropriate driver for each network device. The SBI Driver API enables the Device Component to be extended to use different protocols and data models to communicate with various types of programmable devices. The available driver plugins are listed below:

- An emulated driver plugin for testing purposes.
- An OLS ONF Transport API driver plugin.
- An ONF TR-532 microwave driver plugin.
- A NETCONF/OpenConfig driver plugin for packet routers.
- A P4 driver plugin for next-generation whitebox switches.
- An XR Constellation driver plugin.

In D3.2, we report performance results for all the aforementioned SBI driver plugins.

The **Service Component** is in charge of managing the life-cycle of the connectivity services established in the network. Different service types could be requested and different protocols and data models might be used to configure the network equipment. For this reason, the Service Component implements a Service Handler API that enables network operators to precisely define the service types they need to support and the behaviour for each of them. The component consists of a gRPC-based NBI exposed to the rest of the TeraFlowSDN components, and a Service Servicer block that dispatches the incoming requests and interacts with the Service Handler API to choose the appropriate handler for each service type requested. Given that the Service component needs to know about the state and details of the existing connectivity services and the devices supporting them, it makes use of the Context Management component to store and retrieve up-to-date details about the devices and the services using the Context Management gRPC interface. The Service Handler interface enables network operators to extend the Service component to support different service types and use different protocols and data models to configure the devices. In D3.2, we report five service handlers, namely L2VPN, L3VPN, P4-based, Microwave, and REST-based service handlers, with a detailed performance evaluation of each one.

**Forecaster** is a novel TFS component that can perform proactive SDN traffic prediction (i.e., forecasts) using ML algorithms. For example, it is able to collect real-time Key Performance Indicators (KPI), such as link occupancy, and use ML algorithms to forecast where and when a problem (e.g., link resource unavailable) is likely to occur, to reroute traffic before it happens. Multiple traffic forecasting libraries can be introduced to provide the component with multiple engines. One of the possibilities mentioned above is the Prophet library, which already includes a seasonal model for data forecasts. Another possibility could be the introduction of AutoML. AutoML does not require training; thus, no previous data modelling is required.

#### 2.3.2.1 Partner's contributions

●**INF** developed XR Constellation driver plugin and TeraFlowSDN WebGui enhancement to create service cross-connection, as well as related development/test environment support work, including XR module docker emulator setup and feature development used through IPM and TeraflowSDN controller, XR optics integration/verfication to the Edgecore DCS-240/AS9732-32DB SONiC with SONiC CMIS extensions, physical HW interoperability (serdes), and verification/testing XR module with 1x400G and 4x100G breakout modes

●**TID** has participated in the SBI component in the Netconf/Openconfig driver plugin and the configuration of the Service component to process Netconf/Openconfig services. Also, in creating a new driver to support gNMI in the SBI component.

●**SIAE** has contributed in developing MW driver and service handler.

●**UBI** has contributed the P4 SBI driver plugin and a P4 service handler.

●**ODC** has provided guidance on standards alignment and workflow support.

●**ADVA** has contributed to SBI component interface interoperability with OpenConfig and ADVA NOS. Moreover, has contributed to design of Forecaster component.

●**CTTC** has contributed to Forecaster component, as well as contributed to Service NBI.

### 2.3.3 Task 3.3: SDN Automation

T3.3 is in charge of two core TeraFlowSDN components, i.e., the Zero-Touch Provisioning (ZTP) and Policy Management Components, both of which aim at automating crucial tasks of the TeraFlowSDN controller.

The **ZTP** component, also titled the Automation Component, provides the means, in the form of RPCs, to automatically (i) onboard a new device (i.e., ztpAdd RPC), (ii) reconfigure an already onboarded device (i.e., ztpUpdate RPC), and (iii) remove an onboarded device (i.e., ztpDelete RPC) or all of the onboarded devices (i.e., ztpDeleteAll RPC). In addition to those key functions, the Automation Component also exposes two read-only RPCs that allow other TeraFlowSDN components to access the current state of devices and the roles associated to the various devices. Apart from the main automation services, the Automation Component exploits a publish-subscribe TeraFlowSDN mechanism to dynamically associate components with relevant events that require immediate actions, through a dedicated Events API. D3.2 demonstrates detailed workflows showing how the Automation Component reacts to certain events to provision device onboarding, update, and deletion operations automatically. Moreover, D3.2 evaluates the basic ZTP RPCs with an increasing number of concurrent requests to the Automation component. Figure 10 shows the time required for the Automation component to provide an exponentially increasing number of emulated devices. The number of devices is shown in the $x$-axis, while the $y$-axis displays the total time to realize zero-touch provisioning for this increasing number of devices. The clock ticks when K6 issues the first RPC and stops when the last RPC is concluded, which implies that all devices are in ZTPDeviceState=CREATED.

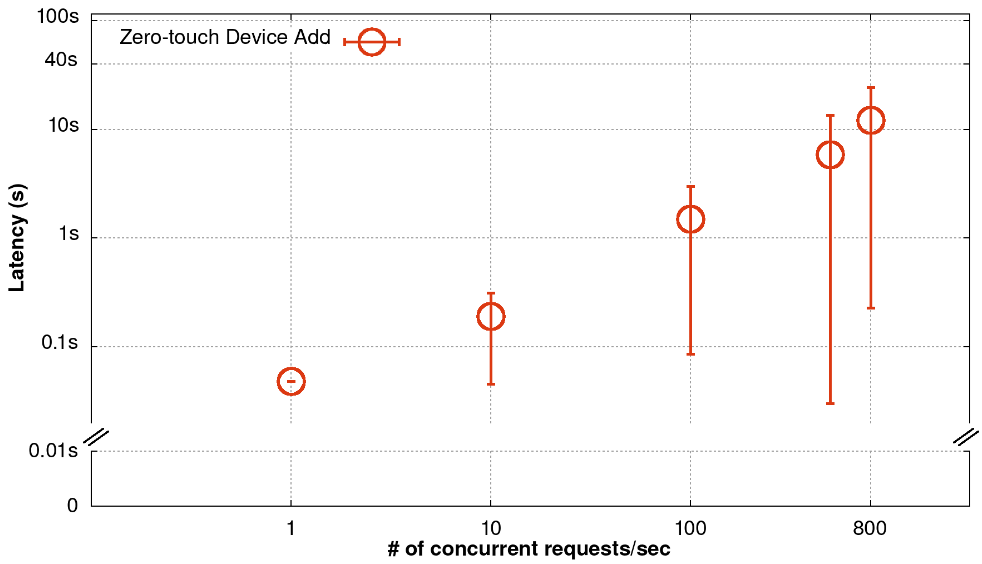



*Figure 10 Zero-Touch add benchmark using an exponentially increasing number of emulated devices.*

The **Policy Management** component utilises an emerging technique called "Event Condition Action" (ECA) to provide event-driven policy management. ECA policy enables actions to be automatically triggered based on when certain events in the network occur while certain conditions hold. Using the ECA policy model, the Policy Management component translates a network operator's high-level network policy statements into a correct set of low-level instructions that realise this policy across the various network elements. To meet this objective, the Policy component offers RPC methods that allow a client to (i) express and add a new policy (i.e., policyAdd RPC), (ii) update an already applied policy (i.e., policyUpdate RPC), and (iii) revoke an applied policy (i.e., policyDelete RPC). Policies can be expressed at the level of an end-to-end service or at the level of an individual device. In addition to those key functions, the Policy Management Component also exposes three read-only RPCs that allow other TeraFlowSDN components to access the current state of policies associated to the various devices or services. Specifically, the Policy component allows a client to query a single policy rule using a policy rule ID (GetPolicy), or to query a list of policy rules by device ID (i.e., GetPolicyByDeviceId) or service ID (i.e., GetPolicyByServiceId). Apart from the main Policy services, the Policy Management Component exploits a publish-subscribe TeraFlowSDN mechanism to associate components with relevant events that require immediate actions dynamically. This is the role of the "Events API". D3.2 demonstrates detailed workflows that visualize the interactions of the Policy Management component with other relevant TeraFlowSDN components, such as Context, Service, Monitoring, and Device. D3.2 also evaluates the basic Policy Management RPCs with an increasing number of concurrent requests to the Policy component.

#### 2.3.3.1 Partner's contributions

●**UBI** has fully developed both Automation and Policy Management components.

●**CTTC** has provided support for integration of both components with other internal TFS components, extending, when necessary, the offered interfaces. For example, PathComp component has introduced multiple extensions necessary to support Policy workflows.

●**TID** has provided guidance in interface definition of both components, while providing multiple use cases and policy definitions.

●**SIAE** has contributed to service and device component extensions to support the automation of microwave elements support.

●**ATOS** has worked in defining the alarm subsystem of the monitoring component during this period. There have been several meetings to perform integration work between automation/policy component and monitoring, adjusting the workflow to cover the automation/policy component needs and requirements from the monitoring side.

●**TNOR** has worked on the use cases of the automation component and contributed to the zero-touch automation framework based on intents, which is of interest to mobile operators from the customer-facing service perspective. Contributions were accepted by an ETSI ZSM work item.

●**CHAL** has contributed to the definition of the interfaces of the monitoring component, specifically the ones related to the query of KPIs.

●**NTNU** has shifted all of its efforts to T4.3 due to focus on integration and analysis.

●**STR** has shifted all of its efforts to T3.1 with TE component.

●**ODC** provided input on the use of ECA and the current standards activity for policy.

### 2.3.4 Task 3.4: Transport Network Slicing and Multi-tenancy

Network Slices provide the necessary connectivity with a set of specific commitments of network resources between several endpoints over a shared underlay network. In this context, transport network slices are provided to support connectivity with a dedicated Service Level Agreement (SLA), which shall be mapped as an abstract technology intent, regardless of the underlying implementation (e.g., L2VPN or L3VPN). Thus, transport network slices once deployed shall be monitored and enforced, in terms of the established SLA constraints/requirements. The current IETF Network Slice Service YANG Model allows the request for the necessary connectivity constraints.

We define a slice group as the entity consisting of one or multiple slices with a unique group identifier. One slice belongs to one and only one slice group. Slice grouping requires a mechanism to map a slice into its slice group, also known as slice template or slice blueprint. From our transport network perspective, slice grouping can be based on mapping slice SLA requirements to the existing set of slice groups. Thus, slice grouping introduces the need for a clustering algorithm to find service optimization while preserving the slice SLA.

D3.2 evaluates the implemented slice component, which has been demonstrated in [OFC23] (see Figure 11).

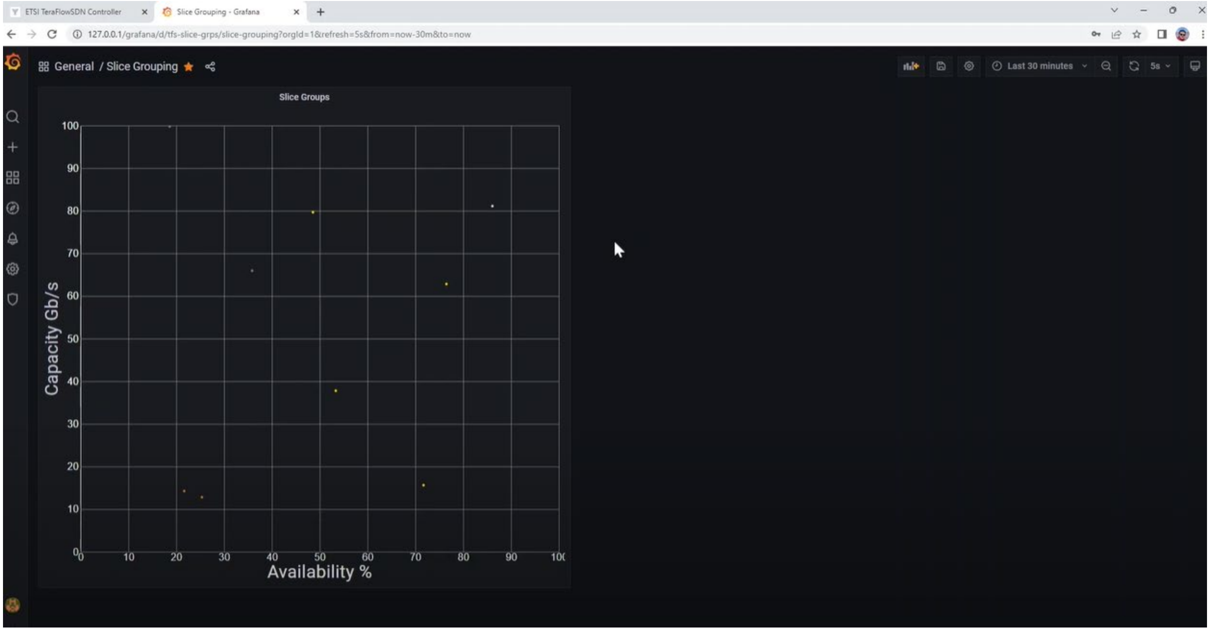



*Figure 11 Demonstration of Slice Grouping using ETSI TeraFlowSDN [OFC23]*

#### 2.3.4.1 Partner's contributions

●**ADVA** has lead T3.4 and contributed to IETF Network Slice NBI interface and Slice component.

●**CTTC** has researched on slice grouping and algorithms for mapping requested slices to slice templates, including contribution to several demonstrations.

●**TID** has contributed to the relationship between IETF Network Slice models for requesting the IETF Network Slices and Network Model.

●**SIAE** has shifted their efforts in T3.1, T3.2, and T3.3 thus no significant contribution is made in T3.4.

●**ATOS** has supported partners in this task by actively participating in the technical meetings.

●**TNOR** has worked on the definition and requirements of the network slicing component. Specifically, TNOR collaborates with NTNU to investigate the impact of isolation in network slicing and available solutions to enable proper isolation for the SLA assurance.

●**VOL** contributed to prototyping Network Slicing component during Year 1 through the definitions of the interfaces.

●**NTNU** participated in the workflow and component design. Most of the efforts, however, were shifted to T4.3.

●**UBI** has shifted all of their efforts in T3.1, T3.2, and T3.3, thus no significant contribution is made in T3.4.

●**ODC** synched the discussions on the network slicing SBI with their work on the IETF network slicing framework document.

### 2.3.5 Impact of COVID-19 on WP3 Activities

No major impact due to COVID-19. All WP3 activities were conducted in time and both deliverables were submitted in time.

## 2.4 WP4 - Network Security and Interworking Across B5G Networks

WP4 is responsible for the design and development of the TeraFlowSDN Security and Integration Components. While WP3 focuses on the **core** TeraFlowSDN components, WP4 focuses on the **security and integration** related TeraFlowSDN components. To tackle the security and integration aspects, WP4 has been structured into three tasks namely T4.1, T4.2, and T4.3.

- The first task (i.e., T4.1) concerns cyberthreat analysis and protection and is targeted towards designing and implementing an advanced cybersecurity solution.
- The second task (i.e., T4.2) describes the design and development of a Distributed Ledger Technology (DLT) focusing on distributed ledgers and smart contracts to secure 5G networks.
- The third task (i.e., T4.3) provides the means for integrating the TeraFlowSDN into beyond 5G (B5G) networks.

### 2.4.1 Task 4.1: Cyberthreat Analysis and Protection (UPM/CHAL)

Providing Cyberthreat Analysis and Protection (CAP) is an essential requirement for SDN controllers. TFS includes a dedicated app designed to fulfil this function. Nevertheless, two factors contribute to the complexity of this task. Firstly, the various layers of the network stack (such as network and physical layers) necessitate distinct approaches due to their inherent disparities. Secondly, the network may consist of multiple services, each with its unique cybersecurity requirements. Consequently, the CAP functionality must be tailored to address the specific needs of these individual services.

TFS effectively tackles these challenges by adopting a comprehensive approach that specifically targets two key layers of the network stack: the network layer and the optical layer. To address security concerns in the optical layer, TFS employs the Centralised Attack Detector (CAD), which continuously evaluates the security status of optical channels. Meanwhile, at the packet layer, attacks are detected by the CAD based on connection statistics transmitted by the Distributed Attack Detector (DAD). The DAD's primary responsibility lies in monitoring services at the packet layer. It achieves this by analyzing the exchanged packets and aggregating them into a collection of statistics per connection. These statistics are then forwarded to the CAD for further analysis using a machine learning-based component. Given the computational complexity involved in packet analysis and the anticipated high volume of packets requiring scrutiny, the DAD can be situated alongside the monitored devices. This architectural decision minimizes network overhead, enables more scalable deployments of the DAD and facilitates prompt responses to threats identified by the CAD.

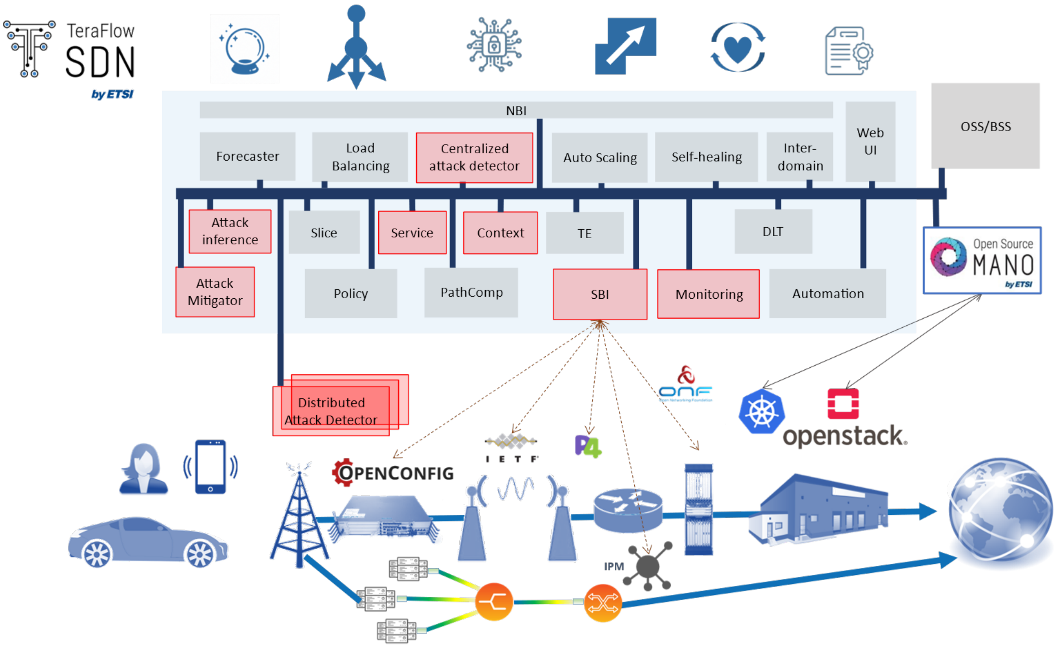



*Figure 12 TFS Architecture Highlighting the Components Involved in Cyberthreat Analysis and Protection.*

In the second version of the CAP integrated into TFS (release 2.0 code freeze in MS4.2), the original components (Centralised and Distributed Cyberthreat Components) were decomposed into four components that serve specific functions within the CAP framework. These four components, namely Centralised Attack Detector (CAD), Distributed Attack Detector (DAD), Attack Mitigator (AM), and Attack Inference (AI), were designed to enhance the existing workflow developed in the previous version (D4.1) and integrate it with the other components of TFS. Figure 12 visually presents the updated TFS architecture, highlighting the four newly introduced components associated with the CAP.

The CAD component operates in two layers: the optical layer and the packet layer. The optical layer receives monitoring data from various devices and utilizes machine learning algorithms to detect and identify attacks. In the packet layer, it receives traffic data from the DAD component. It applies a machine learning-based engine to classify the traffic, distinguishing between different types, such as cryptomining attacks and normal traffic. The CAD component then forwards this information to the AM component and ensures it is recorded in the Monitoring Component.

The DAD component monitors the network data plane to identify malicious network flows. It is strategically positioned at the network edge to enhance scalability and response time during the attack detection process, enabling real-time identification of malicious traffic. In order to achieve this, a feature extractor is deployed at the network edge to gather and generate statistical summaries of network flows. This involves aggregating packets into flow-level statistics, where each flow consists of packets associated with the same packet flow, characterized by the same source IP address, source port, destination IP address, and destination port. This aggregation process occurs continuously within a specific time window, which can be configured accordingly. Consequently, each set of aggregated flow statistics is transmitted to the CAD component to detect malicious traffic.

The CAP function relies on ML-based attack detection and identification, which may require the utilization of various ML models and techniques. To accommodate this requirement, we have introduced the Attack Inference (AI) component as a separate module in the second version of TFS architecture. This component is a dedicated host for ML models and offers gRPC interfaces, enabling other components, particularly those within the CAP, to conduct inferences seamlessly.

In the earlier version, the Attack Mitigator (AM) component functioned as a placeholder, solely receiving messages from the CAD containing essential flow attributes such as source and destination IP addresses, ports, and the inference results categorizing the flow as either cryptomining or standard traffic. However, in the current version, significant enhancements have been made to this component, enabling it to process this information to select and enforce the actions associated with the applicable policy.

In addition to the CAP components, the integration efforts aimed at establishing direct communication with the Service, Context, and Monitoring Components to achieve a fully integrated workflow. Furthermore, the SBI (Security Behavior Intelligence) indirectly contributes to attack mitigation by utilising the Service Component.

In Figure 13, the integration of CAD, DAD, and Attack Mitigator components with the rest of the TFS components is showcased in the context of packet layer cybersecurity. This scenario exemplifies how TFS leverages innovative ML techniques to effectively handle emerging cyber threats, including the detection of malicious encrypted traffic like cryptomining malware.

A distributed solution has been devised to address the challenge of detecting and identifying malware network flows in the data plane, which a centralized ML-based component cannot efficiently achieve due to scalability limitations and slow response times. This solution deploys a feature extractor at the network edge to collect and summarize packets, generating connection statistics. These flow statistics, aggregated by the feature extractor, are then transmitted to an ML classifier running in CAD. Using real-time analysis, the ML model identifies malicious flows and communicates with the Attack Mitigator. The Attack Mitigator, in turn, takes appropriate mitigation actions, such as dropping the malicious connection. The enforcement of these actions is carried out by the core components of the TFS Controller, allowing security assessments to be conducted at scale.

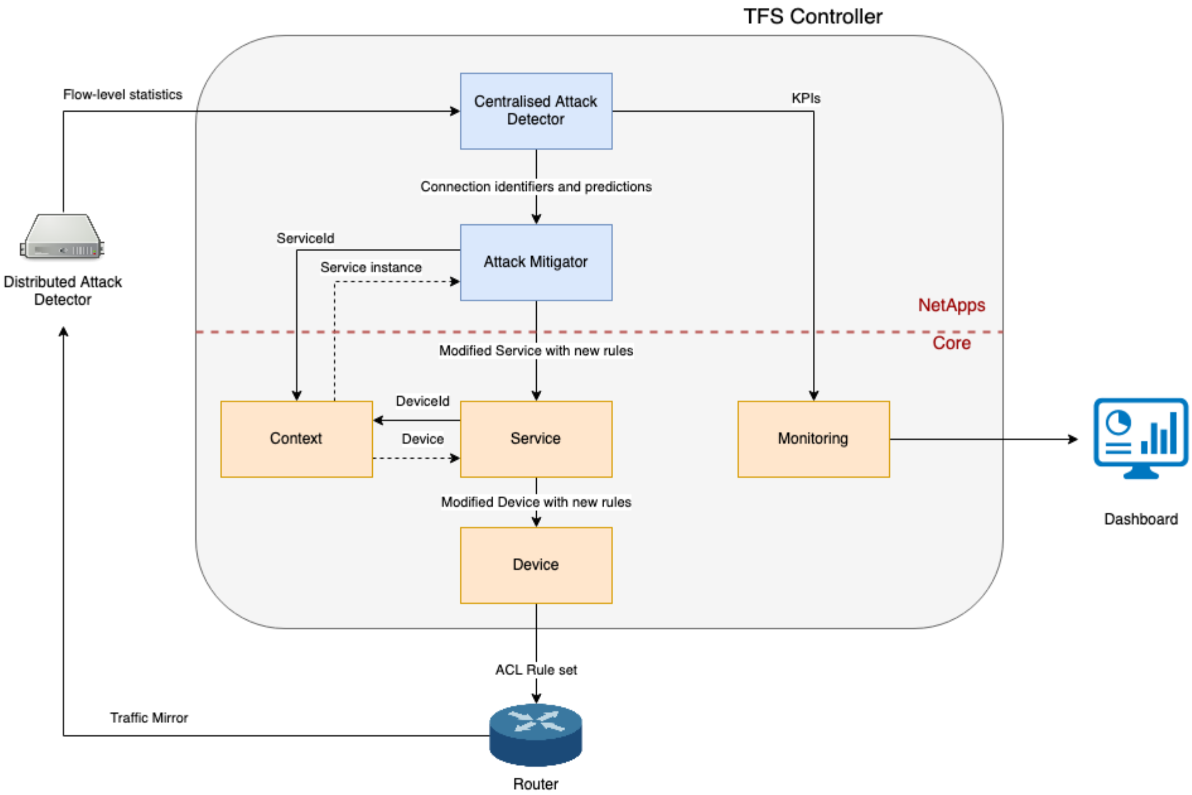



*Figure 13 Final Design of Packet Layer Cybersecurity components.*

Figure 14 demonstrates how the optical layer components are integrated within the Cybersecurity scenario. The main objective of this scenario is to showcase how Optical Performance Monitoring (OPM) and machine learning techniques enable TeraFlowSDN to detect, identify effectively, and counter threats that target the physical layer of optical networks. In this particular case, periodic data from optical devices is transmitted via an Optical Line System (OLS) to the monitoring component. The optical physical layer monitoring loop is activated regularly to gather a list of active optical services in the network. For each service, the attack detector acquires OPM data from the monitoring device and utilizes the Attack Inference method to detect and potentially identify the attack, depending on the adopted machine learning technique. The syndrome and service identifiers are forwarded to the Attack Mitigator if an attack is detected. Before implementing a mitigation strategy, such as relocating the optical service to a different spectrum, the Attack Mitigator may request additional context from the Context component. The Service component assists in executing the mitigation strategy.

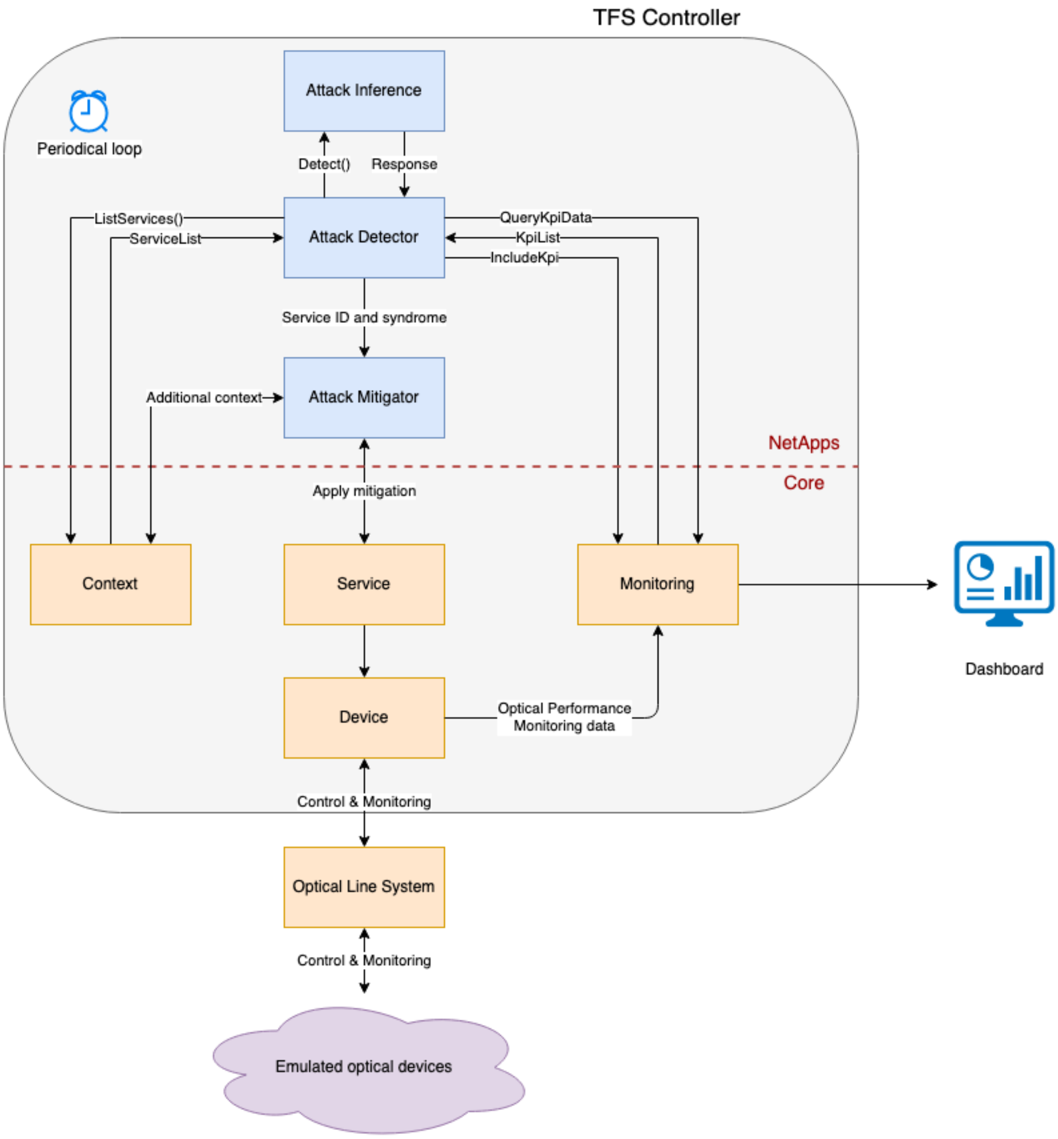



*Figure 14 Final Design of Optical Layer Cybersecurity components.*

### 2.4.1.1 Partner's contributions

●**UPM** has contributed to designing the Distributed solution for the attack detection and mitigation at the packet layer. In particular, UPM designed In addition, UPM trained specific machine learning models to detect cryptomining attacks as a paradigmatic use case and integrated them in the CAD component. Finally, UPM investigate two innovative solutions (i) to reduce the energy consumption of the machine learning models deployed in the CAD and (ii) to fortify these models against the recently appeared adversarial attacks. A comprehensive description of all the work carried out can be found in D4.2, providing detailed information and documentation.

●**TID** has contributed to the design and development of the detection of attacks in IP layer in use case 3, including the generation of attacks and associated datasets, interface specification, as well as the support for the integration of the different internal modules for cyberthreat detection (CAD, DAD, and Attack mitigator).

●**CHAL** has implemented the initial idea of the project as a ML-based diagnosis module for optical networks. The module has been validated for the optical cybersecurity use case. The module encompasses four components (described in detail in D4.2) that perform the cybersecurity assessment in a scalable and timely fashion.

### 2.4.2 Task 4.2: Distributed Ledger and Smart Contracts

DLT allows a set of nodes to become a distributed database by sharing information in a verifiable and transparent manner and recording the data to be stored using a consensus mechanism. Blockchain is the best-known example of a DLT. Blockchain is not only a distributed data base, but it also allows the execution of code (i.e., smart contracts) allowing the peers to work together without the need of a central element commanding any action. Blockchain is being used in multiple research SDN aspects, such as the security of flow management and the recovery of SDN nodes after a failure. The use of Blockchains replaces centralised network management consisting of conventional database management systems. Major advantages are the elimination of trusted third parties that maintain the databases with single points of failure, and data provenance, including data immutability and traceability.

The new TeraFlowSDN DLT component includes the following new features: Record management and Event subscription.

Regarding record management, the DLT Component enables any TFS instance to add, update, or delete records on the DLT in order to share real-time information on the infrastructure's status. The underlying DLT then automatically propagates the transaction through all the DLT nodes. Records can be of any of the following type: context, topology, device, link, service, or slice.

DLT component also provides event subscription, so that TFS components can subscribe to record updates in order to be notified of real-time changes happening to the network architecture. The component has been evaluated in [D42]. Figure 15 shows the CDF of the DLT latency for the 100 requests. We observe that the delay in general is close to 10 seconds. The main contribution of this delay is due to the cost of uploading the record into the blockchain due to the consensus and ordering constraints that need to be fulfilled.

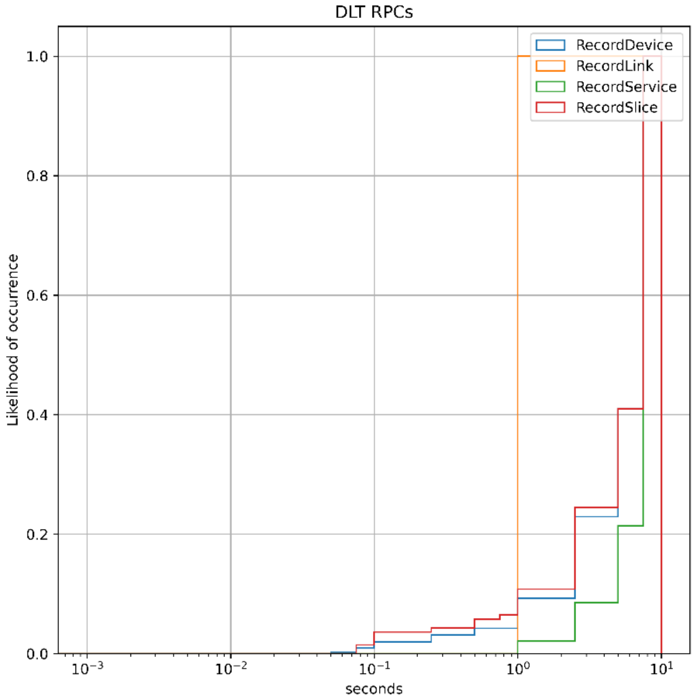



*Figure 15 CDF for the DLT Delay.*

Apart from contributing to TeraFlowSDN, blockchain research has followed three objectives: Securing Smart Contracts, Improving Blockchain Scalability through Effective and Dynamic Sharding, and Optimizing Blockchain Storage.

Developing secure smart contracts poses a significant challenge due to the complexity and potential vulnerabilities associated with these contracts. Existing approaches either lack support for real-world contracts or rely on developers to fix bugs, which is impractical. Several high-profile attacks on the Ethereum blockchain, such as the decentralized autonomous organizations (DAO) attack and the Parity Multisig Wallet attack, have highlighted the need for improved smart contract security. However, current proposed solutions suffer from usability issues, false positives/negatives, and high manual effort requirements. Security concerns remain a key barrier to widespread adoption of public blockchains like Ethereum. To address these challenges, a practical smart contract compiler has been developed that automatically inserts security hardening checks at the source-code level.

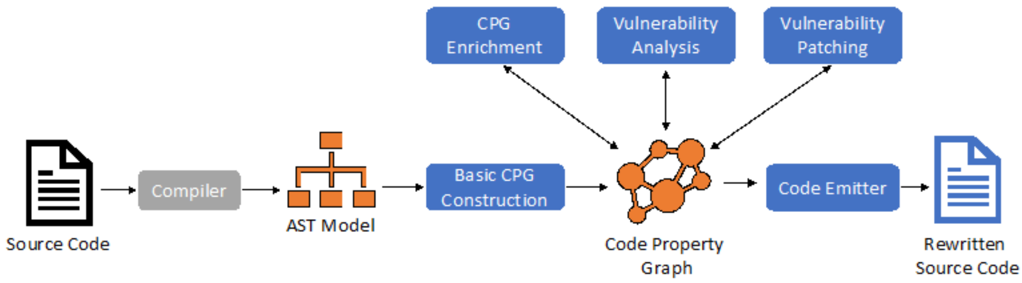



*Figure 16 Overview of our Source-Code Hardening Tool*

Figure 16 shows the tool, which uses a code property graph (CPG) to model control-flows and data-flows, enabling the detection of vulnerabilities. It is platform-agnostic and can be extended to different platforms and programming languages. The evaluation of the tool on real-world contracts demonstrates its effectiveness in preventing verified attack transactions.

Scalability is a major hurdle for large-scale blockchain deployments. Permissionless systems like Bitcoin suffer from high latency and confirmation times, while permissioned blockchains face scalability limitations. Blockchain sharding has emerged as a promising solution to achieve low latency and high scalability. However, existing sharding methods are often tailored to specific models and deployments and rely on static sets of blockchain nodes. Real-world blockchain deployments require the ability for nodes to join and leave the system dynamically. MITOSIS, a novel approach to improve scalability in permissioned blockchains, has been designed to address this challenge. MITOSIS enables the dynamic creation of new blockchains as participants join, similar to the process of cell division. It allows parallel processing and maintains high throughput while preserving low latency. The solution offers autonomy to newly created chains, enabling them to choose their consensus protocol while facilitating interoperability with other chains. MITOSIS can be integrated into existing permissioned blockchains such as Hyperledger Fabric with minimal modifications and manageable overhead.

Finally, Blockchain systems like Bitcoin are criticized for their high computational and storage overhead. While energy consumption has received attention, storage overhead has been largely overlooked. Full nodes in these blockchains are required to store and verify all transactions, resulting in a significant storage burden. To address this issue, research has explored methods to reduce the storage footprint of Proof-of-Work-based blockchains. Through empirical measurements and analysis, it has been demonstrated that full nodes can locally reduce their storage requirements by approximately 96% without modifying the underlying blockchain protocol. Client-side strategies have also been investigated to decrease storage further while incurring minimal computational overhead. These findings provided insights into effectively reducing the storage overhead of Proof-of-Work-based blockchains and were published at the IEEE International Conference on Blockchain in 2022.

#### 2.4.2.1 Partner's contributions

●**NEC** designed and developed the DLT component based on the requirements on data sharing to share information between TeraFlowSDN instances in the multi-domain network services. NEC further worked on how to improve the DLT technologies, by reducing the data storage overhead, improving the scalability as well as securing smart contracts.

●**CTTC** contributed to the design, development and validation to exchange domain-specific information between TeraFlowSDN controller instances using DLT for deploying multi-domain network connectivity services.

●**TNOR** provided the support to experiment Scenario 2 in the TNOR testbed using the DLT-based solution. TNOR also contributed to the IEEE NFV/SDN demo paper "DLT-based End-to-end Inter-domain Transport Network Slice with SLA Management"

### 2.4.3 Task 4.3: Interworking Across Beyond 5G Networks

This task focused on designing and developing selected capabilities supported by the TeraFlowSDN controller to allow interworking / interaction with external systems. Those extended capabilities tackle diverse objectives revolving around the macroscopic idea of deploying the TeraFlow SDN controller to manage selected requirements imposed by B5G infrastructures and expected services.

Particularly, these embrace: i) enhancing the TeraFlowSDN controller with the so-called NorthBound Interface (NBI) component which allows interacting with an NFV orchestrator to support the automatic deployment of network connectivity services between remote cloud sites; ii) adding the WebUI component as a friendly tool for retrieving context, service, and slice information; iii) interworking between peering TeraFlow SDN controller to provision, update, and release network connectivity services involving two or more network domains, i.e., inter-domain network connectivity services. The following overviews these B5G-oriented capabilities implemented in the TeraFlowSDN controller, which are more exhaustively described in D4.2.

The NBI component was formerly called Compute component, which was designed and deployed to interact specifically via a REST API with an NFV Orchestrator, namely ETSI OSM. However, the enhanced NBI component extends those capabilities of the former Compute component aiming at covering more advanced functionalities required by other external entities such as OSS/BSS, parent service and resource orchestrator in a hierarchical orchestration architecture, or a generic client system, besides the NFV Orchestrator. The resulting NBI component functionalities (previous and newly added) support: 1) processing the network connectivity service creation and termination driven by the ETSI OSM (NFV Orchestrator); 2) supporting the creation of Layer 2 VPN network connectivity services being requested by an external entity (e.g., OSS/BSS); 3) provisioning of network slices demanding specific requirements / SLAs; 4) exposing detailed/filtered/abstracted topology/context information. In a nutshell, the NBI Component is the front end of the TeraFlow SDN controller to interact (via a REST API) with external entities (e.g., ETSI OSM, OSS/BSS, …). Additionally, the NBI component relies in a gRPC API to communicate with other controller's components such as Service, Context, PathComp, etc. The final supported interfaces within the NBI Component (described in D4.2) are:

- The IETF topology to disclose (abstracted) transport details upon demand to, e.g., a high-layer orchestrator entity.
- L2VPN service model to support requesting the L2VPN network connectivity services and their needs in terms of bandwidth, latency, etc.
- IETF slice which allows processing requests of a specific partition of the transport infrastructure to be managed by the TeraFlow SDN controller.

The Web-based User Interface (WebUI) component has been designed and integrated into the TeraFlow SDN controller to offer a friendly toolset to an external client for interacting with the pool of functionalities supported by the Controller. In this context, the WebUI enables, for instance, a network operator to manually perform configuration operations and collect the state of the underlying network. Specifically, the supported functionalities exposed by the WebUI component are: i) to retrieve the topology, context, and detailed information of the active services; ii) to request network connectivity services; iii) to onboard context, topology, device, etc. descriptions; iv) to plot monitoring data collected from different devices (using the Grafana dashboard); v) to interact with other controller's component to manage the above operations.

To achieve the above, the WebUI component integrates two interfaces: i) REST API to query the WebUI about specific operations and actions from an external user as detailed above; ii) gRPC API to allow the communication between the WebUI and the rest of the controller's components. Figure 17 depicts a screenshot of the WebUI, which allows creating/requesting a new network connectivity service.

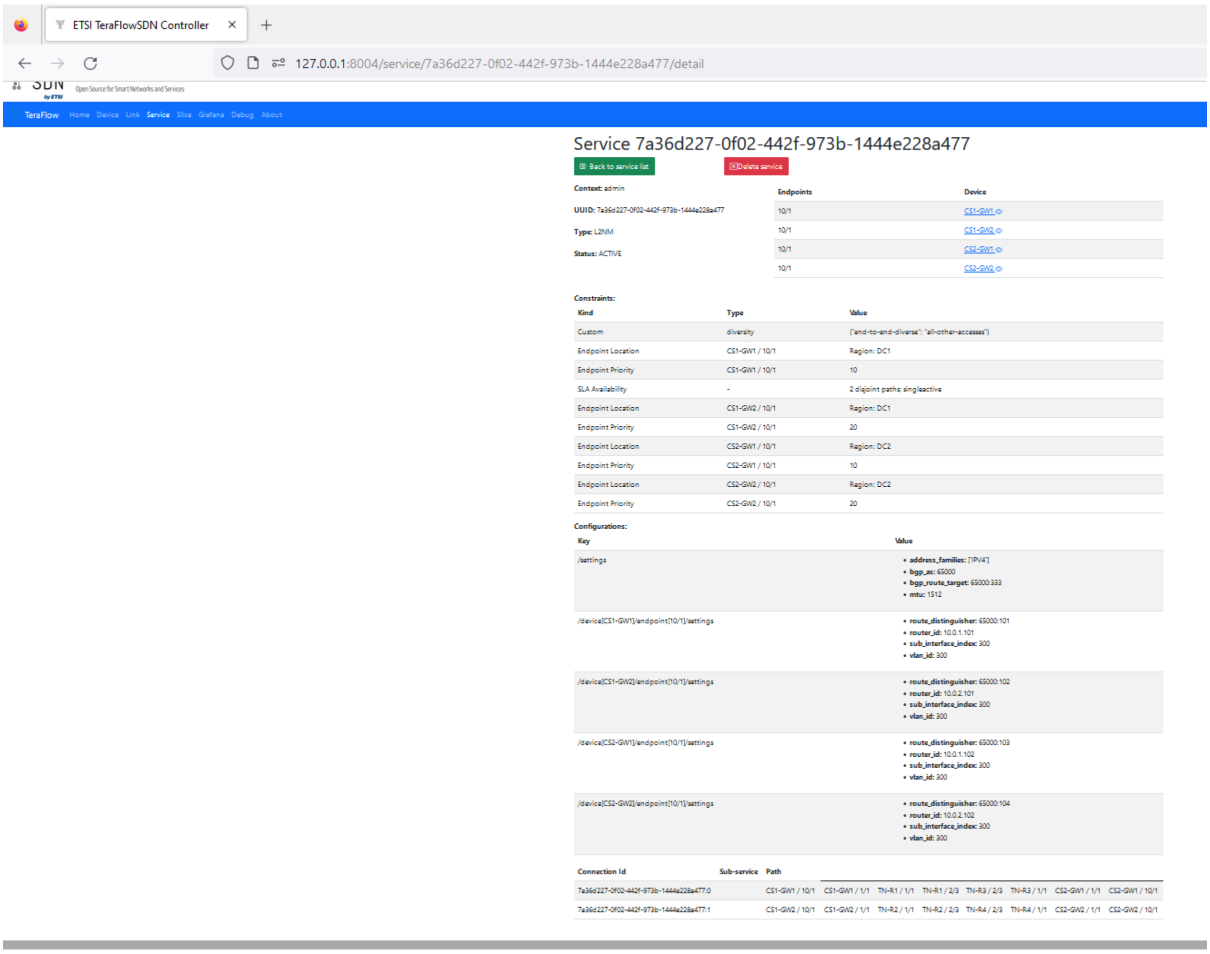



*Figure 17 ScreenShot of the WebUI Component*

The implemented Inter-Domain Component of the TeraFlow SDN Controller takes over control functions, interfaces, workflows, and operations to manage the provisioning, updating, and removal of network connectivity services through different domains governed by different controller instances. These controller instances see each other as peers, and they coordinate to manage the resource selection and configuration of their underlying network infrastructure when provisioning end-to-end network services. The primary functions supported by this Inter-Domain component are: i) the exchange of abstracted domain information between peer Controllers; and ii) the activation of slices and services encompassing two or more domains controlled by different TFS instances. Details of all the supported capabilities integrated with the Inter-Domain Component are reported in D4.2. However, from a high-level perspective, these capabilities include: i) computation and maintenance of abstracted local domain topology; ii) querying local domain path and resource selection to the PathComp Component along with deciding resources to be allocated over the inter-domain links; iii) DLT-based sharing of local topology abstraction; iv) DLT-based ordering and updating of slices in remote domains.

In this context, a public demonstration of the Inter-Domain Component functions has been conducted to deploy inter-domain services reliably and fulfil demanded SLAs automatically. To this end, exchanging basic topological domain information and providing appropriate traceability of inter-domain service requests was necessary. Additionally, blockchain technology was chosen to ensure network privacy when abstracting topology details between IDC peers. The traceability of the inter-domain services was attained by designating a leader domain controller which selects the sequence of domains, interacts with other domain controllers, monitors the end-to-end SLAs, and handles the appropriate mitigation problems if the SLA is violated.

Another contribution in the Inter-Domain component was tied to different aspects of tackling QoS-enabled inter-domain connectivity, resulting in two publications reported in D4.2. The former evaluated the traffic aggregation mechanisms for leveraging economies of scale while meeting heterogeneous QoS demands in inter-domain connectivity. The latter provided an analysis of trade-offs between the degree of slice isolation and delay performance in environments with heterogeneous traffic profiles.

#### 2.4.3.1 Partner's contributions

- **CTTC** led the technical activities in task 4.3 Specifically, CTTC designed and developed the NBI component to allow the interaction with an external ETSI OSM (NFV Orchestrator) to support the deployment of network services interconnecting through the network domain remote cloud sites. CTTC also designed, implemented, and validated the WebUI component to handle the creation/deletion of both network connectivity services and slices along with collecting context information. Finally, CTTC contributed to the definition of the Inter-Domain component mostly focusing on the interfacing between peering TeraFlowSDN controller instances. In this regard, it contributed on validating exchanged of abstracted domain information and creation/updating of inter-domain slices exploiting the benefits of DLT.

- **TID** has contributed to defining the architecture and interfaces for interdomain components.

- **ATOS** has participated in parallel discussions to adjust the monitoring data model in order to cover the cybersecurity component requirements. Additionally, ATOS has reviewed D4.2 in this period.

- **TNOR** has led the design of the interdomain component, including the architecture and workflows. TNOR also participated in the IDC-related demos. Meanwhile, TNOR is leading a paper addressing the IDC design and experiment (ongoing). In addition, TNOR combined the collaboration results on traffic engineering and energy efficiency with the IDC to further improve the performance.

- **NTNU** developed a simulation framework for assessing the relationship between fine-grained flow services and transport slice aggregates. Based on the framework, NTNU assisted in the design of the interdomain control plane by assessing operational aspects and implications of design choices. That included an analysis of the trade-offs between the degree of slice isolation and delay performance, as well as the impact of traffic aggregation on QoS for heterogeneous applications and application patterns.

- **UBI** has contributed to the alignment of Slice and Service components.

### 2.4.4 Impact of COVID-19 on WP Activities

After doing a first assessment of potential COVID-19 impact, and given the progress in WP4's activities, WP4's partners do not foresee delays, and expect that the outline objectives will be completed per the schedule.

## 2.5 WP5 - Prototype Integration, Demonstration, and Validation

WP5 is responsible for performing the TeraFlowSDN integration, followed by experimentation, validation, and evaluation using a range of benchmark indicators. In the last six months of the project, we concentrated on the collection, analysis, and reporting of KPIs. As a result, a new metrics collection framework is now fully integrated into the components, and a service mesh has been adopted to enable scalability and load balancing.

## 2.5.1 Task 5.1: Infrastructure and Testbeds

The project identified three scenarios representing some of the challenges posed by B5G networks: Autonomous Network Beyond 5G, Inter-domain, and Cybersecurity. For each one of the scenarios, we identified: the main technical challenges, the features required (i.e., from the TeraFlowSDN point of view), the TeraFlowSDN component to be developed to provide these features, and the use cases of interest to be investigated to validate and benchmark the performance of the TeraFlowSDN prototype. More details on the challenges, components, and use cases for each scenario are available in D5.1. In parallel with the scenario work, we also ran an inventory of the testbed infrastructures at each partner's premises. This work was essential to define the testbed setups for each scenario under study.

Regarding D5.2, we identified the related testbeds (scenario setup) for each scenario, and aligned TFS architecture with scenario requirements, thus, selecting the necessary TFS components to be instantiated, as shown in Figure 18. D5.2 also introduces preliminary results that are discussed in the next Tasks.

Finally, D5.3 we have completed the scenario description and detailed set-ups per each of the analysed workflows.

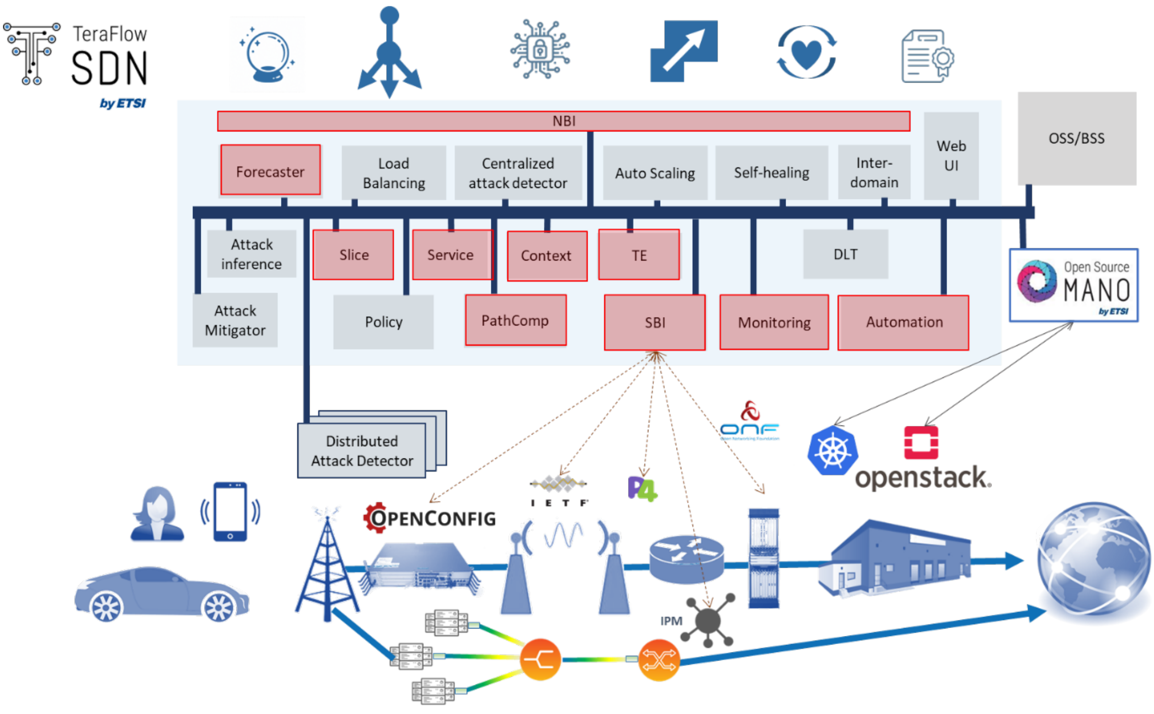



*Figure 18. Scenario 1 E2E TeraFlow instantiation*

### 2.5.1.1 Partner's contributions

●**SIAE** provided, installed and configured an MW link composed of two AGS20 terminals and an SDN intermediate controller in Telefonica Test Plant as a copy of an in-house premise installation.

●**CTTC** has provided ADRENALINE Testbed to support and test ONF Transport API plugin. Moreover, VPN services have been offered to set up testbed interconnection. Moreover, leadership in scenario 2 description and architecture has been provided.

●**TID** has set up scenarios 1 and 3 with SIAE's AGS20, physical routers (HL5) Edgecore DRX-30 and Edgecore AS7315-30X, servers and traffic generators.

●**INF** provided and maintained IPM installation and XR module emulation setup for TeraFlowSDN system/integration testing on Telefonica lab as a replica of the in-house premise setup. Additionally, in-house Infinera had a similar physical test setup in use with 2 x Edgcore DCS240/AS9726-32DB units hosting physical XR pluggables.

●**NEC** deployed the DLT component in its local testbed and provided API access to the DLT components for the use cases.

●**ATOS** contributed to the WP5 paper submitted to the EuCNC22 conference and the OFC22 demo presentation about the monitoring component role. Additionally, ATOS has contributed to the conversations for the definition of the scenarios, agreeing on the role to play by the monitoring component. ATOS has also contributed to D5.2.

● **TNOR** has built a TeraFlow testbed equipped with physical whitebox switches and connections to OSM. The testbed has interconnections with both the NTNU testbed and the CTTC testbed, prepared for Scenario 2 experiments. TNOR also contributed to the WP5 demo papers to OFC22.

●**CHAL** set up an instance of a Kubernetes cluster to run locally TeraFlowSDN to demonstrate and assess the features of the optical cybersecurity component. The cluster also supported the activities in other tasks of WP5.

●**UBI** has built a TeraFlow testbed equipped with physical P4 switches. The testbed has interconnections with Scenario 1 and has been demonstrated at several conferences and demonstrations, such as HPSR23.

●**ADVA** has contributed with ADVA Ensemble Activator licenses and integration support for scenario 1 and scenario 2 in both TID and TNOR testbeds.

●**NTNU** has set up a local Teraflow testbed and connected it via site-to-site VPN with the TNOR testbed.

### 2.5.2 Task 5.2: TeraFlowSDN Integration

The task also looked into the methodology to develop, integrate, test, and release the artefacts produced by TeraFlow. The proposed method comprises four complementary tiers: functional architecture and pipeline, TeraFlow CI/CD infrastructure, good practice and hints for CI/CD usage, and release time plan.

The methodology is described in detail in D5.1 and D5.2. In D5.2, we provide the details of the integration migration to ETSI Laboratories. In order to ease integration, we have also established project-defined workflows for feature requests, feature lifecycle, bug reporting and technical wiki.

The CI/CD environment is still based on GitLab CI, fully integrated within GitLab, which is the source code management tool used in the project. The CI/CD methodology was already described in D5.2, presenting the infrastructure, the GitFlow, the branch naming schema, and the testing methodology.

In the TeraFlowSDN CI/CD pipeline, we defined the following six stages:

- *dependencies*: this stage is devoted to deploying the dependency services of the TerFlowSDN Kubernetes cluster;

- *build*: this stage is in charge of building the micro-services and uploading the images to the Gitlab container registry;
- *unit_test*: this stage is dedicated to the unit testing of the micro-services, i.e., testing isolated, small portions of code of individual micro-services;
- *integ_test*: this stage is associated with integration testing, aiming to check whether multiple micro-services can properly work together;
- *deploy*: this stage has been created for deploying the micro-service in the development infrastructure to perform end-to-end testing;
- *funct_test*: this stage is dedicated to functional testing, aiming to find problems in fulfilling an end-to-end function.

Therefore, each micro-service implements its jobs based on the six stages defined in the global configuration file. To properly assure the testing stages' effectiveness and facilitate the integration between components, we measure the *code coverage*, a software testing metric specifying the code percentage and the number of code lines successfully validated during the testing phase.

In D5.2, we also provide the documentation accompanying the release of the TeraFlowSDN controller. The documentation includes installation instructions, a TeraFlowSDN wiki, tutorials, and a TFS virtual machine.

The installation instructions recommend using the MicroK8s Kubernetes distribution for deploying TeraFlowSDN, which is based on a micro-service architecture and consists of multiple containers. The instructions guide the user through cloning the repository from the ETSI-hosted GitLab and preparing the environment using a script called my_deploy.sh. The deploy.sh script then builds and deploys the necessary micro-services, creates an ingress controller for the WebUI, and initializes the Grafana dashboard. More detailed installation instructions can be found in the TeraFlowSDN wiki.

The TeraFlowSDN wiki is a comprehensive resource providing guidelines and reference material for installing TeraFlowSDN and reproducing experiments. It covers four main categories of pages: deployment guide, run experiments, features and bugs, and development guide. The wiki pages are regularly updated to reflect the latest developments in the components.

Additionally, a tutorial and a TeraFlowSDN virtual machine are offered to onboard users to ETSI TeraFlowSDN. The tutorial provides an overview and hands-on experience in programming tools for controlling and monitoring packet optical networks using TeraFlowSDN. It covers topics such as the YANG data modelling language, NETCONF protocol, dynamic establishment of L3VPN using OpenConfig routers, RESTconf interfaces, ONF Transport API, gRPC, gNMI protocols, and Kafka broker for data publishing/subscribing. The tutorial is aimed at network operators, service providers, system integrators, academia and universities, TeraFlowSDN developers and users, and members of other research projects. Recordings and slides of the tutorial sessions are available for reference.

A TFS virtual machine is provided for download to facilitate following the tutorial. The virtual machine contains all the tools and environments required for the tutorial. Additional information and resources can be accessed through the provided links.

#### 2.5.2.1 Partner’s contributions

●**CTTC** has done feature integration for releases 2.0 and 2.1. CTTC has contributed to several key documentation.

●**TID** has contributed to the integration of several components. Test definition and integration validation have been performed in their labs.

●**ATOS** has worked in the CI/CD system, providing the automation tools for building, upgrading and testing the various software components. ATOS has been debugging of CI/CD pipeline dependency errors and giving assistance to other partners on CI/CD procedures and DevOps good practices. It has also implemented code coverage methodologies in the CI/CD procedures for all the TeraFlow OS components. Additionally, ATOS has analyzed and implemented integration work between the monitoring and related components (device, context, automation, policy, cybersecurity) required for some scenarios, as well as for the integration monitoring-telemetry Use Case defined in WP2. ATOS has been editor of MS5.2: TeraFlow OS release v1 Report and has contributed to D5.2.

●**UBI** has contributed to the integration of multiple components, as well as the documentation of P4 support.

### 2.5.3 Task 5.3: Use Case Integration and Demonstration

In D5.3, details on the scenario are provided. Moreover, each scenario references how TFS architecture has been instantiated. Sequence diagrams have been detailed per workflow, including interactions between TFS components and related network elements. Each scenario has been demonstrated in several conferences such as IEEE NFV-SDN22 and OFC23.

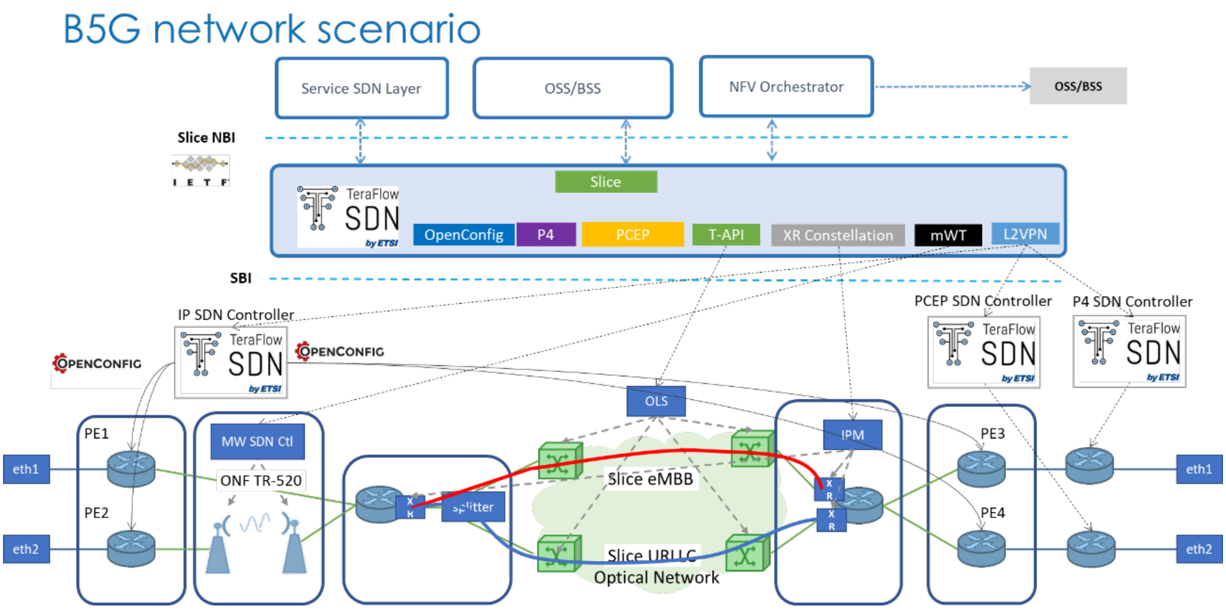



*Figure 19 Scenario 1: Autonomous Network Beyond 5G*

The high-level architecture depicted in Figure 19 illustrates the envisioned scenario 1. It includes integrated network elements within different technological domains, enabling the autonomous provisioning, configuration, and management of transport network slices. These slices consist of various Virtual Private Network (VPN) services like Layer 2 (L2VPN) and Layer 3 (L3VPN) services with dedicated Service Level Agreements (SLAs). The interaction between the NFV Orchestrator (e.g., ETSI OpenSource MANO) and TeraFlowSDN North-Bound Interfaces (NBI) allows L2/L3VPN connectivity provisioning.

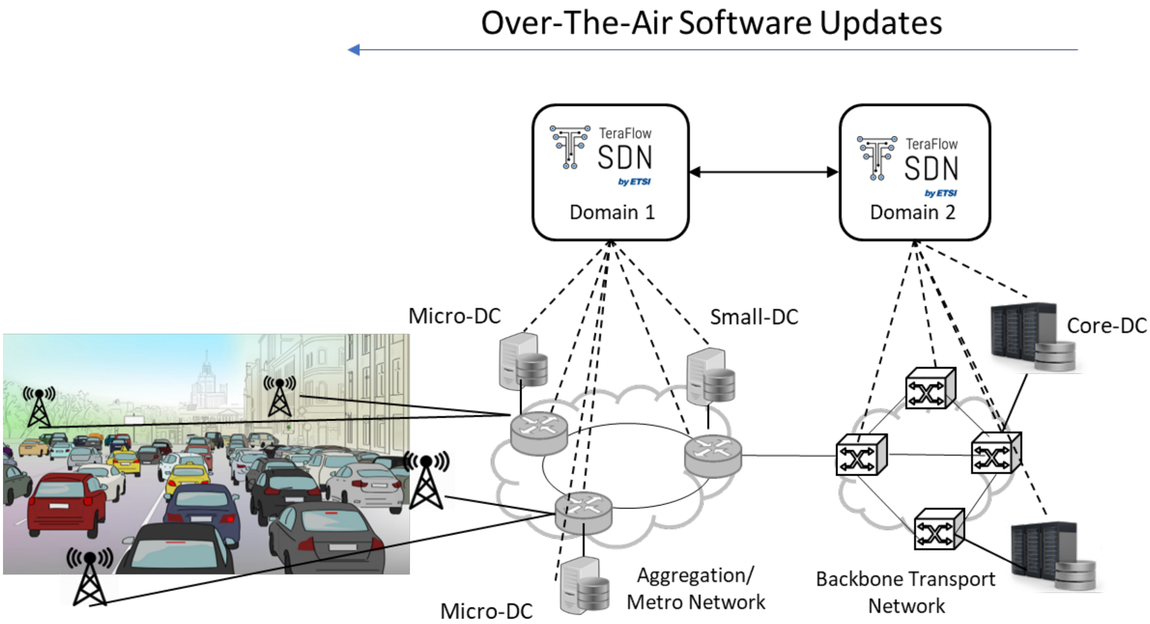



*Figure 20 Scenario 2: Inter-domain*

Deploying Cooperative, Connected, and Automated Mobility (CCAM) services over a distributed edge and cloud infrastructure presents challenges that require addressing. These challenges include unified resource management, multi-domain networking, and inter-domain slicing while preserving data confidentiality. The TeraFlowSDN Controller plays a critical role in overcoming these obstacles. It facilitates unified resource management by providing integrated services, managing computing, storage, and networking resources, and optimizing cloud and network resources. Additionally, the TeraFlowSDN Controller tackles multi-domain networking by deploying per-domain slice instances and orchestrating their integration to form end-to-end transport network slices across multiple domains. Furthermore, when dealing with different network operators, the controller incorporates a Distributed Ledger Technology component based on blockchain to ensure data privacy during inter-domain slicing while enabling collaboration between operators. These topics are considered in Scenario 2 (see Figure 20).

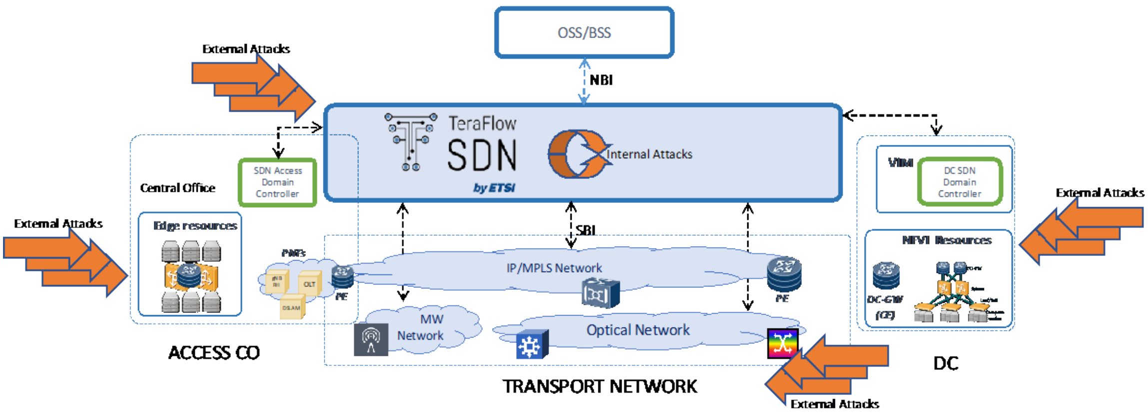



*Figure 21 Scenario 3: Cybersecurity*

Figure 21 depicts an example of the envisioned Cybersecurity scenario and the threats in the context of an automated network. Attacks may target the IP or the optical layers at the data plane. Attacks exploiting the IP layer traverse or target devices located in the access segment (e.g., edge DCs), the core network, or core DCs. In this case, per-packet inspection is necessary to detect and identify attacks, enabling their mitigation. However, inspecting packets is a demanding operation. Executing this process at a central packet inspector instance is impractical. Packets must be transported from the remote site, e.g., Central Office (CO) or DC, to a central location, incurring significant traffic and computing loads. Therefore, designing distributed packet inspection becomes necessary for efficient and effective attack detection at the IP layer. Moreover, it is necessary to coordinate the distributed packet inspectors, which means that a central entity is still necessary, but only for consolidating and coordinating the network's security status.

#### 2.5.3.1 Partner's contributions

●**CHAL** contributed to the metrics collection framework in collaboration with CTTC, setting up the initial infrastructure to be used by all components. CHAL also contributed to the set up and configuration of the service mesh, enabling other components to fully take advantage of the scalability and load balancing features of Kubernetes. Finally, CHAL supported the integration activities, contributing to evolving the overall practices, and improving the public documentation.

●**CTTC** contributed to the context of scenario 1 with multiple demonstrations, such as hierarchical TFS support or energy-aware path computation. CTTC lead scenario 2 showcasing several workflows, such as inter-domain connectivity and location-awareness.

●**TID** has led scenario 1 activities and organized the multiple workflows and setups in their laboratory. TID has also organized demonstrations related to scenario 1.

●**INF** provides XR Constellation driver plugin to TeraFlowSDN; their driver connects to IPM to create L1 services to point-to-point and point-to-multipoint services. For demonstrations, Infinera provided and maintained IPM and XR module emulators on Telefonica lab for use case integration and demonstrations.

●**SIAE** developed MW device and service driver plugin for Teraflow to manage MW portion of the transport network and contributed to maintaining test plant installation to be used used for integration and demonstrations.

●**NEC** developed the gateway interface to simplify the connection between the TeraFlowSDN and the DLT component. NEC further developed the smart contract to satisfy the requirements of the use case.

●**ATOS** has contributed to a journal paper called "A Flexible and Scalable ML-Based Diagnosis Module for Optical Networks: A Security Use Case" submitted to IEEE/OSA JOCN journal, and to a conference paper called "Cyberthreat Detection and Mitigation Using Machine Learning in the TeraFlowSDN Controller" submitted to conference Netsoft 23.

●**TNOR** has contributed to the design and deployment of Scenario 2 experiments for inter-domain services on the testbed established in T5.1. TNOR also contributed to the IEEE NFV/SDN demo paper "DLT-based End-to-end Inter-domain Transport Network Slice with SLA Management" for Scenario 2.

●**UPM** has contributed to scenario 3 with a dedicated focus on cybersecurity mechanisms for IP networks.

●**UBI** has contributed to scenario 1 with dedicated effort on Policy-driven Service Restoration with P4 devices.

●**ADVA** has contributed to scenario 1 support, focusing on Slice component demonstration.

## 2.5.4 Task 5.4: Performance Assessment and KPI Validation

D5.3 reports the elaborated metrics collection framework, developed by integrating state-of-the-art open-source software into the TeraFlowSDN architecture. As illustrated in Figure 22, two leading open-source software platforms are used:

1. *Prometheus*: a solution for exposing and collecting metrics about the software performance at run time. Its adoption has two main steps: (i) instrumenting your component to capture the relevant metrics and (ii) configuring the main Prometheus server to extract the exposed metrics periodically;
2. *Grafana*: a solution for creating graphical dashboards combining multiple data sources. This last characteristic is essential for TeraFlowSDN because we need dashboards depicting data collected from the devices (therefore coming from the database used by the Monitoring component) and data related to the performance of TeraFlowSDN itself (i.e., using the information coming from Prometheus).

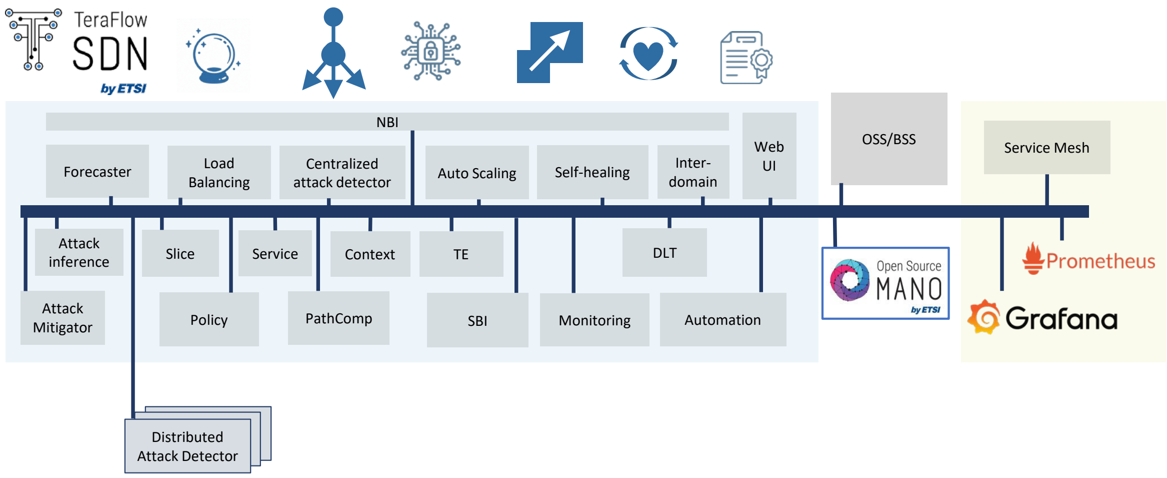



*Figure 22 TeraFlowSDN extended architecture encompassing the metrics collection framework*

In addition to these two main pieces of software, we rely on a service mesh software capable of performing load balancing for gRPC requests. Among the alternatives, Istio and Linkerd are regarded as the two most used service mesh implementations. Adopting Prometheus, Grafana, and a service mesh grants TeraFlowSDN a wide range of functionalities that can be used to understand the system's performance and identify potential bottlenecks or targets for optimization.

In D5.3, we have also extended the metrics definitions from D5.1. We first provide an overview of the metrics (shown in Table 2), and later the metrics are further detailed in the context of each scenario.

Then, a Performance evaluation section is provided per workflow, with dedicated attention to the aforementioned metrics.

| **Metric** | **Definition** | **Relevant scenarios** |
|---|---|---|
| Device on-boarding time | Control plane latency to on-board a new device and upload its configuration. Does not consider the necessary time to communicate with the device. | 1 |

| | | |
|---|---|---|
| Service setup delay | Required time to setup a new service, from control plane perspective only. Does not consider the necessary time to communicate with device. | 1,2 |
| Slice setup delay | Required time to setup a new slice, from control plane perspective only. Does not consider the necessary time to communicate with device. | 1,2 |
| Data rate | Amount of data transmitted during a specific time period over a network | 1 |
| Latency | Latency is the time it takes for a device to send one small 'echo' packet to the serving content server and the corresponding 'echo-reply' packet to return to the device. This time is also called the round-trip time. It has become common practice to use the terms synonymously. | 1 |
| Energy | Measuring the reduction in total average energy consumption and average resource utilization metrics | 1, 3 |
| Economic | Cost reduction both in CAPEX (disaggregated networks) and OPEX (automation). | 1, 2 |
| Resource efficiency | Measurement of the resources needed to serve a given traffic request with and without using integrated resource orchestration. | 1 |
| Multi-tenancy | Stress the slice/service management system and measure allocated slices | 2 |
| Trust | Secured deployment of services through DLT | 2 |
| Privacy | Percentage of exposure of physical topological details | |
| DLT transaction delay | Measurement of the delay introduced by the usage of DLT instead of other inter-domain communication mechanisms | 2 |
| Positioning | Deployment of a position-based technique for all vehicles | 2 |
| Security | Attacks need to be detected with high accuracy to make sure they do not remain undetected or unaddressed in the network | 3 |
| Reliability | Measuring the performance of the model on detecting unseen adversarial attacks | 3 |

*Table 2 Summary of metrics relevant for the TeraFlow project*

#### 2.5.4.1 Partner's contributions

●**UPM** has contributed on evaluation of scenario 3 on cybersecurity.

●**CTTC** contributed to validating and assessing multiple workflows from scenarios 1 and 2.

●**TID** contributed on KPI measurement for multiple workflows in scenario 1, setting up the lab ADVA routers, Infinera IPM XR machine and testbed for the KPI collection.

●**SIAE** contributed to scenario 1 KPI evaluation.

●**NEC** evaluated the security and performance of the DLT component workflows in scenario 2.

●**TNOR** contributed to the demo setup of Scenario 2 and prepared the testbed with physical devices using ADVA NOS. The testbed is set to collect KPIs.

●**CHAL** contributed on validating and assessing the performance of the cybersecurity use case, focusing on the proposed optical cybersecurity module. CHAL also contributed on the definition of relevant metrics to be used by other partners with the help of the metrics collection framework.

●**UBI** has validated and evaluated KPI in scenario 1 related workflows.

### 2.5.5 Impact of COVID-19 on WP Activities

During the execution of the WP5 activities, no delays were identified as a result of COVID-19.

# 3 Progress on Dissemination, Standardisation, and Exploitation

Work Package 6 in the TeraFlow project has been devoted to designinging strategies and executing plans for impact creation, to share advances and facilitate the adoption of results. After deliverable D6.1, that gave the project's strategy towards dissemination, communication, collaboration, and standardisation, D6.2 provided an initial assessment of the market environment and opportunities for TeraFlow and reported on the various activities that TeraFlow conducted until December 2021, following the strategy described in D6.1. In the project's second period, addressed by this document, D6.3 focused on the work done in T6.3 during 2022, providing an exploitation plan for all relevant results, individual exploitation plans from all partners and an action plan to promote further use of these results. And finally, D6.4 has provided a complete and detailed overview of all consortium dissemination, communication, collaboration, and standardisation activities from January 2022 to June 2023, as well as an update of the exploitation activities described in D6.3. Additionally, to close the work carried out in WP6, D6.4 also provides an analysis of the overall impact achieved by the project, explaining how, thanks to the results achieved, together with effective planning and consecution of WP6 activities, the future of TFS (main project result) looks very promising.

## 3.1 Task 6.1: Stakeholder Engagement, Communication, and Dissemination

The purpose of T6.1 has been to elaborate, maintain and execute the dissemination and communications plans during the project's whole life.

D6.4 (M36) describes the progress carried out by the Consortium in the communication and dissemination strategy and a detailed overview of all activities during the second reporting period - from January 2022 to June 2023. D6.4 includes a report on communication and dissemination activities and TeraFlow contributions to standards and open-source projects, an update on exploitation activities and collaborations with other related research projects and initiatives. Additionally, D6.4 also provides an analysis of the overall impact achieved by the project.

The proposed TeraFlow dissemination and communication strategy was described in D6.1 (M4, previous reporting period). This 3-phase strategy aimed to support the sustainability, commercialisation and further use of the project's results while raising awareness and increasing visibility about the motivation of the project, its progress and all the activities performed during the project lifetime.

Phase 2 spanned from January 2022 until December 2022. During this phase, the consortium informed key target audiences about the project's progress and engaged with them in different events to support the validation of technical and business concepts based on release v1, launched in March 2022. The last six months of the project have been devoted to Phase 3 of the dissemination and communication plan. As release v2 was launched on February 2023, TeraFlow results have been promoted amongst potential end-users and early adopters using the marketing material that has been developed.

### 3.1.1 TeraFlow Digital Ecosystem: Website and Social Media Channels

The project website (https://teraflow-h2020.eu/) created on Drupal CMS has been the main communication channel used by the project. During this second reporting period, the website has been regularly updated, and new sections have been created:

- TeraFlowSDN is a new section linked to the TeraFlowSDN community.
- The new Blog section was launched in 2022. The content presented in this section covers a wide range of topics: project technologies, technical progress, standardisation, and business models, and shares the partners' knowledge through in-depth articles.

The website metrics achieved at the moment of the consolidation of this report (26/06/2023) are:

| Type | KPI | Target by M30 | Current |
|---|---|---|---|
| Website | Unique Visitors | 5000 | 22557 |
| | Avg time | 2:00 | 0:44 |
| | Page Views | 10000 | 52936 |
| | Blogs | 20 | 20 |

TeraFlow also had an enhanced digital presence thanks to the project's social media accounts on Twitter and LinkedIn, which are used to promote and give visibility to the project updates, keep our audiences informed and continue the interactions and relationships with other projects, initiatives, standardisation bodies, etc.

The Twitter account (@TeraFlow_h2020) has been used to promote general information about the project's progress, focusing on publications, news and events. Twitter has regularly increased the number of followers during this reporting period, with no significant variation. We have generally exceeded our initial expectations in all the KPIs proposed.

Twitter metrics achieved at the moment of the consolidation of this report (26/06/2023) are:

| Type | KPI | Target by M30 | Current |
|---|---|---|---|
| Twitter | Tweets | 360 | 625 |
| | Retweets | 800 | 859 |
| | Likes | 1500 | 1894 |
| | Followers | 250 | 356 |
| | Eng rate | ≥ 1.2% | 4.4% |
| | Impressions | 100K | 125.4K |

TeraFlow's LinkedIn company page (https://www.linkedin.com/company/teraflow-h2020) focused on professional audiences and allowed us to connect the project with more specialised profiles. The LinkedIn account has achieved a significant impact, much higher than initially estimated.

The LinkedIn metrics achieved at the moment of the consolidation of this report (26/06/2023) are:

| Type | KPI | Target by M30 | Current |
|---|---|---|---|
| LinkedIn | Page views | 2000 | 1096 |
| | Visitors | 400 | 547 |
| | Post Impressions | Not defined | 46880 |
| | Reactions | ≥ 1.2% | 5% |
| | Followers | 100 | 308 |

In addition to this, and to ensure the sustainability of the project updates after the project end, two new accounts - https://www.linkedin.com/company/teraflowsdn/ on LinkedIn and @TeraFlowSDN on the Twitter platform have been created for the TeraFlowSDN community. The four accounts have remained linked, especially in the last campaigns and the latest events.

About the YouTube channel (https://www.youtube.com/channel/UCz86mcBvscgA4tS_voXokyQ) the audio-visual materials, especially those produced whenever we recorded events, have been uploaded to the channel. The project has produced 26 videos with more than 1300 views. Twelve of them have been produced during this reporting period. All the videos are also linked to our website: https://teraflow-h2020.eu/library/videos

More information and statistics about the website and social networks can be found at D6.4.

### 3.1.2 Communication Material and Newsletters

Along the project span, TeraFlow produced different types of communication material used to increase the project's visibility.

Section 2.3 on D6.4 shows a summary of the diverse materials created.

- PPT Template, Project Overview PPT, Poster Template, Virtual backgrounds, Newsletter. Template, Social Media Canva banners templates (all during the first reporting period).
- New TeraFlowSDN logo.
- TeraFlow Posters and roll up.
- TeraFlow Newsletters #1-#5.

All the communication materials can be found in the website: https://teraflow-h2020.eu/library/marketing-materials

### 3.1.3 Journal Publications and Conference Scientific Papers

A cumulative count of 51 publications has been generated during the project's lifetime. Our consortium has made diligent efforts to ensure the availability of machine-readable electronic copies of these publications. These copies have been uploaded to widely recognized platforms like Zenodo, Arxiv, or institutional repositories for scientific publications whenever feasible. In cases where Gold Open Access has been implemented, the original publication link is provided to facilitate access.

As of the creation of this deliverable, our consortium has successfully produced a total of 51 publications, with 44 of them freely accessible to the public (including 34 conference papers and 10 journal articles). The distribution across different reporting periods is as follows: In the initial period from M1 to M12 in 2021, 21 publications were made openly accessible, consisting of 19 conference papers and 2 journal articles. For the subsequent period from M13 to M30, spanning 2022-2023, 23 publications were released in open access, comprising 15 conference papers and 8 journal articles. Additionally, 7 publications are still undergoing review or not yet available in open access, consisting of 6 conference papers and 1 journal article.

A table containing links and descriptions of the papers produced is available on D6.4. All the papers are also available from the website: https://teraflow-h2020.eu/publications

### 3.1.4 Other Content

The project has also produced a total of five press releases. Four press releases have been composed and distributed from ETSI during the second reporting period. Links to all the press releases can be found at https://www.teraflow-h2020.eu/news/1st-official-press-release

Apart from these, some other press releases and news have been published occasionally on the 5GPPP website, flash news and newsletters. The project has also appeared in other corporate press releases and internal bulletins from some of our consortium partners.

Besides the list of publications for conferences and journals, TeraFlow members have participated in two whitepapers of the 5GPPP - Test, Measurement and KPIs Validation Working Group. TeraFlow also has a complete section about the project in the book: "Towards Sustainable and Trustworthy 6G: Challenges, Enablers, and Architectural Design" (ISBN: 978-1-63828-238-9).

Other dissemination and communication actions hardest to categorize were also performed; in D6.4, we included a table that compiles all these actions with links to their descriptions. (section 2.7, Other communication and dissemination activities).

We want to highlight that the ETSI TeraFlowSDN group won the 'Upstart of the Year' award in the Layer123 event, held in London in December 2022; this award recognizes the good practices applied to get an evolving standardization ecosystem. On the other hand, Silvia Almagia, CTI Technical at European Telecommunications Standards Institute (ETSI) was talking about TeraFlow in a Tech Co Talks podcast.

### 3.1.5 Events, Workshops, and Demos

TeraFlow has been presented in a total of 61 events. After the pandemic, 2022 and 2023 have been very active years, with increasing attendance to face-to-face events. **TeraFlow was presented in 61 events** during this reporting period and participated in 5 booths. A complete table that summarises all the events in which TeraFlow has been presented is included in D6.4. Also in D6.4, section 2.6 Events Highlights of the period, a summary of some of the most relevant events can be found. Our website offers a quick reference of the events at https://teraflow-h2020.eu/events. Here, we will only list TeraFlow workshops and demonstrations throughout the most recent period.

**Workshops**

During the period, TeraFlow participated and/or organised the following workshops:

- ICT-52 Workshop on 6G
- 2nd IFIP/IEEE International workshop on Fully-Flexible Internet Architectures and Protocolsfor the Next-Generation Tactile Internet (FlexNGIA 2022), colocated with IEEE/IFIP Network Operations and Management Symposium (NOMS2022)
- EUCNC 2022
- NGON-DCI 2022 (Next Generation Optical Networking)
- Workshop “TeraFlow SDN: Where research and open networking meets industry”
- SIGCOMM 2022 – TeraFlow in the Future Internet Routing and Addressing (FIRA) workshop
- 5GPPP Workshop on 6G KPIs and how to measure them: Participation of Teraflow in KPI measures (white paper)
- 6G O-RAN evolution workshop: Raúl Muñoz, CTTC: "ETSI OSG TeraFlowSDN: an open-source SDN controller for 6G xHaul transport networks"
- Workshop on 6G organized by the Hexa-X project and ICT-52 cluster, 18 January 2023, Ricard Vilalta (CTTC) presented “TeraFlow: Do we need yet another SDN controller? Use cases for a novel cloud-native SDN controller for beyond 5G networks”.
- The 27th International Conference on Optical Network Design and Modelling (ONDM 2023): TeraFlow presentation in the workshop "Challenges of optical communications in the 6G era: a view from EU projects"
- IEEE International Conference on Communications (IEEE ICC 2023) - Optical Networks & Systems Symposium: participation in a Workshop on “AI/ML-driven Autonomous 6G networks” organised by the 6G Smart Networks and Services Industry Association (6G-IA)
- NGON & 5G Transport 2023: Organisation of the workshop: “Role of Standards in Automating Intelligent Optical Networks”. Contribution in opening workshops by Raúl, with mention to TeraFlow
- NetSoft2023: organization of DataSlice Workshop

**Demos**

- OFC Conference 2022: Demonstration of Zero-touch Device andL3-VPN Service Management using the TeraFlow Cloud-native SDN Controller
- OSM Ecosystem Day: Demonstration of Zero-touch Device and L3-VPN Service Management using the TeraFlow Cloud-native SDN Controller
- IEEE International Conference on Computer Communications - IEEE INFOCOM 2022: : Demonstrating QoE-aware 5G Network Slicing Emulated with HTB in OMNeT++
- EuCNC 2022: TeraFlow demostrations
- IEEE International Conference on Network Softwarization (NetSoft2022): Experimental Demonstration of End-to-end NFV Orchestration on Top of the ADRENALINE Testbed
- ECOC2022 European Conference on Optical Communication: Experimental Demonstration of Transport Network Slicing with SLA Using the TeraFlowSDN Controller

- IEEE NFV-SDN 2022 - The 8th IEEE Conference on Network Functions Virtualization and Software-Defined Networking: TeraFlow Demo (Hands-on tutorial)
- TFS r2.0 ETSI Webinar: TFS participants introduced the new TFS release 2 along with some demonstrations of its new capabilities and use cases
- OFC 2023: two TeraFlow demos: "Slice Grouping for Transport Network Slices Using Hierarchical Multi-Domain SDN Controllers" and "Demonstration of a Scalable and Efficient Pipeline for ML-Based Optical Monitoring"
- IEEE HPSR 2023 International Conference on High Performance Switching and Routing:"P5: Event-driven Policy Framework for P4-based Traffic Engineering"

### 3.1.6 Partner's contributions

●**ATOS** coordinated the task. ATOS registered all the dissemination actions performed by partners – submission of scientific publications to relevant conferences and specialised journals, attendance to events etc). ATOS was in charge of the website updates, including a section to give the maximum visibility to TeraFlowSDN releases and to link it to the TeraFlowSDN community to ensure the project's sustainability. A blog section was also created on the website to stimulate the production of project updates from the partners. ATOS was also in charge of the social networks, increasing the frequency of publications on Twitter and Linkedin. ATOS regularly uploaded the videos generated by partners to the YouTube channel and created a video for the general public explaining the project. ATOS also supported the TeraFlowSDN booths, presentations, workshops and demos by producing marketing materials (logo redesign, posters, leaflets and graphic elements) uploaded to the website and promoted via social media accounts from the project. ATOS also continued delivering updates on the project by producing a biannual newsletter.

●**TID** has contributed to TeraFlow dissemination activities by actively promoting it during TID invited talks in multiple events. Moreover, TID has also led scenario 1, which has resulted in multiple publications.

●**CTTC** has contributed to TeraFlow dissemination activities in multiple events, including booth, special session and hackfest organization. Publication and demonstration have also been presented to promote TeraFlowSDN in mayor industry and academia events.

●**INF** contributed to industrial awareness of ETSI TeraFlowSDN and has participated in OFC23 demonstrations.

●**SIAE** contributed to industrial awareness of ETSI TeraFlowSDN and has participated in OFC22 and OFC23 demonstrations.

●**NEC** has contributed with multiple publications to TeraFlow result dissemination.

●**TNOR** has contributed with multiple has contributed with multiple publications to TeraFlow result dissemination. TNOR has also actively participated in TeraFlow HackFests.

●**CHAL** contributed by presenting TeraFlowSDN in several general-public events, in addition to presenting several conference papers, and one proof-of-concept demonstration related to the module developed in the context of optical cybersecurity.

●**UPM** has contributed with multiple publications to TeraFlow result dissemination. UPM has also actively contributed to the organization of workshops.

●**NTNU** has contributed with multiple has contributed with multiple publications to TeraFlow result dissemination. NTNU has also actively participated in TeraFlow HackFests.

●**UBI** contributed to industrial awareness of ETSI TeraFlowSDN and has participated in OFC22, OFC23, HPSR23 demonstrations. UBI also presented the TeraFlow work in P4 in the ETSI TFS Hackfest #1, while plans to lead another P4 session in the upcoming ETSI TFS Hackfest #3.

●**STR** has actively promoted TeraFlow dissemination.

●**ODC** has contributed to several actvities, and promoted TeraFlow in key workshops and IETF meetings. ODC has led IETF Hackathon actviites in the IETF.

●**ADVA** has promoted TeraFlow in multiple conferences and industrial events and has participated in OFC23 demonstrations. ADVA has participated in Scenario 1 and Scenario 2 demonstrations.

## 3.2 Task 6.2: Standardisation and Open-source Software Activities

This section summarizes the impact activities performed in Standardization and Open-Source Software Organizations. A special dedication is given to the ETSI community, both from SDO and Open-Source Software perspective.

### 3.2.1 Standardisation

#### 3.2.1.1 ETSI ISG PDL

Members: NEC Europe Ltd. (Brigitta Lange), TID (Diego Lopez), ODC (Daniel King).

NEC and Telefónica are founding members of ETSI ISG PDL (Industry Specification Group Permissioned Distributed Ledger). This group targets utilising blockchain technologies to create open and trustworthy ecosystems of industrial digital solutions. It contributes to the group's working items and reports on challenges, concepts, and features related to the operation of permissioned distributed ledgers.

TeraFlow project is already part of the PDL work items PDL 007 Research Landscape and PDL 008 Research and Innovation Landscape, where NEC has been rapporteur.

#### 3.2.1.2 ETSI ISG ZSM

Members: TID (Diego Lopez), CTTC (Ricard Vilalta), ODC (Daniel King), TNOR (Min Xie).

The ETSI Zero-touch network and Service Management (ZSM) Industry Specification Group (ISG) applies modern principles in its low-touch management framework for 5G end-to-end automation.

TNOR contributed to ETSI ZSM-011 based on the Automotive scenario and inter-domain module. The contribution has been approved and included in ETSI ZSM-011 draft (Section 4.3.1. Automotive use case).

#### 3.2.1.3 ETSI ISG mWT

Members**:** SIAE

The group's activities cover several aspects of the MW transport network and related technologies.

Great focus has been placed on defining use-cases of Software Defined Networking related to MW transmission. That activity led to identifying an appropriate ETSI standard model to be exposed through RestConf API in the northbound of a MW SDN Controller.

Several PlugTests have been done to demonstrate vendor SDN controller's capabilities and functionalities in a multi-vendor scenario. The last PlugTest took place in Sophia Antipolis 20-24 February 2023.

The standard model exposed by the RestConf API of SIAE intermediate SDN controller is the base of integrating the MW portion into the TeraFlow ecosystem with a specific focus on network topology retrieval and end2end service configuration.

#### 3.2.1.4 ETSI ISG MEC

Members: CTTC

An important aspect during TeraFlow has been to align the SDN architecture with ETSI MEC 015 to offer Bandwidth Management (BWM) Services to Multi-access Edge Computing (MEC) applications.

ETSI MEC 015 introduces optional traffic management services to address potential resource conflicts between different MEC applications running on the same MEC host. These services include Bandwidth Management (BWM) and Multi-access Traffic Steering (MTS). The Bandwidth Management (BWM) service enables allocating and adjusting bandwidth resources for MEC applications. It allows applications to specify their specific bandwidth requirements, including bandwidth size and priority. This service helps ensure that each application receives the necessary bandwidth to function optimally and prevents one application from dominating the available resources. The BWM service can handle static and dynamic bandwidth allocation, allowing applications to request changes to their bandwidth resources as needed. This flexibility accommodates varying requirements and allows applications to adapt to changing network conditions. By integrating BWM services into the SDN framework, network operators can efficiently allocate and manage bandwidth resources for MEC applications, ensuring optimal performance and quality of service for edge computing deployments.

#### 3.2.1.5 Telecom Infra Project

Members: TID (Oscar González-de-Dios, Victor López, Juan-Pedro Fernández-Palacios)

The Open Optical & Packet Transport group is a project group within the Telecom Infra Project that works on the definition of open technologies, architectures, and interfaces in Optical and IP Networking.

The project is an engineering-focused effort led by major operators, technology vendors and research institutions. It concentrates on different parts of the Transport network architecture, including optical transponders, line systems, IP access devices, open APIs and network simulation and planning tools.

Use cases and technical requirements in TeraFlow are aligned with TIP. In particular, TeraFlow follows both NBI and SBI specifications defined in Mandatory Use Case Requirements For SDN Transport (MUST) group.

Finally, the ETSI TeraFlowSDN community has announced[4] their commitment to implementing TIP's Mandatory Use Case Requirements for SDN for Transport (MUST) Requirements in their innovative cloud-native SDN Controller. This will position TeraFlowSDN as a reference implementation in the Telecom Infra Project Open Optical & Packet Transport group (TIP OOPT). This move will also make it

[4] https://www.etsi.org/newsroom/press-releases/2195-etsi-teraflowsdn-to-serve-as-reference-implementation

possible to accelerate the adoption of SDN standards for IP/MPLS, Optical and Microwave transport technologies, which is one of the main objectives of MUST.

With TeraFlowSDN as a reference implementation, the networking community will benefit from an open, standards-based solution that will make it easier to develop, test and deploy new functionality, and make it available to the broader communities. This alignment will help to foster the development and adoption of open, standards-based infrastructure solutions that can be easily integrated and deployed in real-world networks, enabling the delivery of new services and applications.

#### 3.2.1.6 ONF

Members: TID (Oscar González-de-Dios), SIAE (Roberto Servadio, Danilo Pala), CTTC (Ramon Casellas, Ricard Vilalta), ODC (Daniel King).
The ONF 5G-xHaul project charted under the ONF Open Transport Configuration & Control (OTCC) is responsible for developing a technology-specific interface definition for wireless network functions.

Activities of this group led to the definition of standard models to be implemented over NETCONF protocol for the management of MW equipment by SDN controllers.

The yang models have been tested in a multi-vendor environment in 5 PoCs (Proof of Concepts) where SIAE Microelettronica has always been present.

TR-532 model has been adopted as a reference in the TeraFlow ecosystem to manage the functionalities of MW equipment.

Another of the project work items is the specification of the Transport Application Programming Interfaces (TAPI) data models, publishing open standard interfaces, whose main application domain is the controllers North Bound Interfaces (NBI). Considering the “network layering” that TeraFlow envisions, such standard API (along with the implementation guidelines and sample model usage) becomes a target interface in view of the integration of the transport layers (L0/L1) into the network orchestration functions of the TeraFlow controller (for example, as a controller South Bound Interface, SBI, to consume the services provided by dedicated per-domain optical controllers).

#### 3.2.1.7 IETF

Members: ODC (Adrian Farrel and Daniel King), TID (Oscar González-de-Dios), CTTC (Ramon Casellas and Ricard Vilalta), TNOR (Håkon Lønsethagen).

The Internet Engineering Task Force (IETF) is at the Internet's core. A leading non-profit standards body that develops standards needed for technology interoperability. It is an international community of network designers, operators, vendors, and researchers cooperating in various working groups. The work at the IETF, and its engineers, are vital for the smooth operation of Internet innovation. The open standards it publishes underpin the infrastructure and applications to facilitate the Web. TeraFlow project members lead several technical initiatives and have leadership roles.

The projects IETF innovative contributions are spread across three distinct areas:

- Investigating and Updating the IETF Principles for Internet Traffic Engineering;
- Framework to Manage Network Slicing and Applicable Data Models for Slice Instantiation;
- YANG-based Data Models for Service Deployment via the TeraFlowSDN (TFS) Platform.

In addition, the project partners have additional IETF protocol work to support several TeraFlow components.

During one of the final IETF sessions we attended (March, 2023), we organised our first TeraFlow Hackathon. These IETF Hackathons help encourage the wider Internet community to collaborate and develop practical implementations of IETF standards.

Our objective for the event included disseminating the TeraFlow project to the wider IETF community and highlighting the ETSI TeraFlow SDN (TFS) controller. The Hackathon's practical aspect was implementing more capabilities described in the IETF service models, which have limited support in release 2.0 of the ETSI TFS platform. These YANG-based models were developed in the IETF to communicate service and network requirements between the service orchestrator and TFS controller via a Northbound Interface API.

Our Hackathon table was well attended, with industry and academics from around the world, visiting us to discuss the TeraFlow project and the ETSI TFS controller. We also used the event to discuss TFS with wider industry partners and show other engineers how the TFS open source SDN controller may be used for integrated IETF network slice management.

The 2-day Hackathon session also allowed us to identify the key capabilities required for future releases of ETSI TFS. We hope to run future IETF Hackathons, and topics for the next sessions include the emerging IETF work on Inventory Management and the current Optical Device Models.

It will be important to finalise the work that was started in the TeraFlow project but due to the time it takes to standardise; it may not be completed before the end of the project. We expect several drafts to be completed as ETSI TFS activity continues and project partners continue developing technologies within their organisations.

#### 3.2.1.8 OpenConfig

Members: TID (Oscar González-de-Dios)

TeraFlow's IP/MPLS-based use cases employ OpenConfig YANG data models at the Service-Based Interface (SBI) of the TeraFlow SDN controller, utilizing the device driver. TID, an active member of OpenConfig, has made significant contributions to fill the gaps identified by TeraFlow during their work on supporting these use cases. The contributions provided by TID include the following YANG code:

- OpenConfig EVPN YANG model: This model facilitates Layer 2 connectivity, encompassing the modelling of Ethernet segments. The contribution is thoroughly documented in https://github.com/openconfig/public/blob/master/doc/evpn_use_cases.md. It covers various technologies, such as:
    - BGP MPLS-Based Ethernet VPNs (RFC 7432) with VLAN-based service.
    - Provider Backbone Bridging Combined with Ethernet VPN (PBB-EVPN) (RFC 7263) with VLAN-based service.
    - Network Virtualization Overlay (NVO) EVPN (RFC 8365) with VLAN-based service and symmetric Integrated Routing and Bridging (IRB).
- Ethernet counters: These are Ethernet-related information retrieved from the TeraFlow SDN controller.
- Keychains and authentication of routing protocols: These additions are essential for the TeraFlow network creation use cases, ensuring the necessary security and authentication measures are in place.
- Extensions of the ACL (Access Control List) YANG model: These extensions are being developed to support the Attack Mitigator Component, enhancing its capabilities in managing network security and mitigating potential threats.

- Move ethernet segments to top-level container (EVPN) by oscargdd · Pull Request #768 · openconfig/public (github.com)
- Manage prefix list and extend ACLs to match prefix lists in source/destination by oscargdd · Pull Request #649 · openconfig/public (github.com)
- Add control word support for EVPN by oscargdd · Pull Request #792 · openconfig/public (github.com)

Furthermore, there are ongoing contributions that are currently in progress:

- Move ethernet segments to top-level container (EVPN)[5]
- Configure BFD min interval, multiplier when activated in protocols[6]

### 3.2.2 Open-Source

In this section we detail open-source software contributions to different organizations.

#### 3.2.2.1 ETSI TeraFlowSDN

Members: ALL

*Figure 23 ETSI TeraFlowSDN logo designed by ETSI (inspired by TeraFlow H2020 project)*

On May 31st 2022, ETSI announced[7] the creation of a new open-source group called TeraFlowSDN (TFS). Based upon the European Union-funded TeraFlow 5G PPP research project results, this new group hosted by ETSI provides a toolbox for rapid prototyping and experimentation with innovative network technologies and use cases. Figure 33 shows the logo designed by ETSI to promote the open-source group.

TeraFlowSDN follows up the code base from the H2020 TeraFlow project and currently develops an open-source, cloud-native SDN controller for high-capacity IP and optical networks and will support use cases, such as autonomous networks and cybersecurity, helping service providers and telecommunication operators to meet the challenges of future networks.

The software developed by the TeraFlowSDN group is a valuable tool for several ETSI industry specification groups working on network transformation. Collaboration around the software will

[5] Move ethernet segments to top-level container (EVPN) by oscargdd · Pull Request #768 · openconfig/public (github.com)

[6] Configure BFD min interval, multipleir when activated in protocols by oscargdd · Pull Request #856 · openconfig/public (github.com)

[7] https://www.etsi.org/newsroom/press-releases/2076-2022-05-etsi-launches-a-new-open-source-group-teraflowsdn

enable the alignment of goals, and mutual feedback and help to accelerate standardization cycles at ETSI. TeraFlowSDN has been integrated with current Network Function Virtualization (NFV) and Multi-access Edge Computing (MEC) frameworks and interoperates with ETSI OSM (Open-Source MANO).

Building on the success of ETSI OSM, which over 25 EU-funded research projects have adopted, TeraFlowSDN also aims to gain support and trigger collaboration with existing and future research projects in the 5G PPP or the Smart Networks and Services Joint Undertaking (SNS JU). Several projects have been identified, and a call for presentation for TFS ecosystem day has been published, expecting contributions from 8 SNS projects.

#### 3.2.2.2 ETSI OpenSource MANO

Members: TID (Diego Lopez), CTTC (Ricard Vilalta), TNOR (Pål Grønsund).
ETSI OpenSource MANO (OSM) is an initiative developing an open-source Management and Orchestration (MANO) stack which is compliant with the information models being defined within the ETSI ISG NFV standardization activities. To this end, the OSM project is being developed in a community fashion targeting the MANO implementation dealing with operators' requirements for delivering commercial and production NFV services. In this regard, the under-deployment TeraFlow OS leverages the current OSM solution to attain a tight integration with OSM acting as a WAN Infrastructure Manager (WIM) (i.e., SDN controller). This enables the OSM platform to request to the TeraFlow OS the deployment of connectivity services between Virtual Network Functions (VNFs) hosted at remoted cloud facilities (NFVI-Pops).

#### 3.2.2.3 HyperLedger

Members: NEC (Ghassan Karame)

Hyperledger is an umbrella project of open source blockchains and related tools of the Linux Foundation. Its most important project is Hyperledger Fabric, a modular open-source permissioned blockchain initiative originally led by IBM.

NEC led the development of the open-source consensus algorithm MinBFT which was accepted as an hyperledger-lab project[8]. MinBFT was designed to integrate Hyperledger Fabric and can be considered a consensus module for Fabric.

#### 3.2.2.4 rebar3_docker

Members: STR (Sébastien Merle)

STR's open-source rebar3 plugin[9] provides valuable enhancements to the TeraFlow project, facilitating the creation of Erlang-based microservices. The plugin allows Docker images to be readily generated, streamlining deployment and distribution.

With the Docker image creation automated by STR's rebar3 plugin, manual configuration complexities are notably reduced. This integration frees TeraFlow to fully leverage Erlang's robust capabilities in microservices development without cumbersome setup procedures.

#### 3.2.2.5 braidnet

Members: STR (Sébastien Merle)

[8] https://github.com/hyperledger-labs/minbft
[9] https://github.com/stritzinger/rebar3_docker

STR has developed a comprehensive software system utilizing the rebar3_docker plugin, which is crucial for managing an Erlang node cluster. braidnet[10] deftly handles all aspects of node lifecycle - creation, operation, and termination, as well as managing inter-node connectivity, which enhances system adaptability and efficiency.

#### 3.2.2.6 SONIC

INF used and extended Edgecore Enterprise SONiC funtionality, which is commercialized hardened version from Open Source SONiC from Edgecore. Infinera extended SONiC CMIS 5.1 base functionalities to support XR QSFP-DD optics and it's integration with DCS240/AS9726-32DB hardware to verify compatibilty with OCP designed HW product, see details from https://www.edge-core.com/_upload/images/2022-091-DCS240_AS9726-32DB-DS-R05-20221229.pdf. Infinera is considering working with SONiC community to back-port XR related CMIS extensions to community SONiC version with community supported HW vendor.

### 3.2.3 Partner's contributions

●**TID** has contributed to ETSI PDL, by including TeraFlow project as part of the research landscape. They have actively lead OOPT group in TIP and participated in the redaction of multiple requirements and architectures. Most of the TeraFlow requisites were contributed to TIP OOPT MUST requirements. IETF contributions have been significant and resulted in multiple standards and OpenConfig contributions. Regarding open-source, TID has been the key player in establishing ETSI TeraFlowSDN community and has contributed actively to its Leadership Group and Technical Steering Committee.

●**CTTC** has followed activities in ETSI ZSM and MEC and contributed to TeraFlow awareness ans alignment. Regarding open-source, CTTC has been established ETSI TeraFlowSDN community and contributed actively to its Leadership Group and Technical Steering Committee. In OSM, significant code contributions have been provided in order to align ETSI TeraFlowSDN and ETSI OpenSourceMANO.

●**INF** used and extended Edgecore Enterprise SONiC funtionality, which is commercialized hardened version from Open Source SONiC from Edgecore.

●**SIAE** has defined use-cases of Software Defined Networking related to MW transmission. That activity led to identifying an appropriate ETSI standard model to be exposed through RestConf API in the north bound of a MW SDN Controller. SIAE has also participated in several PlugTests.

●**NEC** has led the contribution to the Hyperledger-lab open-source MinBFT project.

●**ATOS**, as WP leader, has been monitoring the progress of the task and ensuring the reporting of the achievements.

●**TNOR** has actively participated in ETSI ZSM and contributed to ETSI ZSM-011 based on the interdomain scenario and inter-domain module. The contribution has been approved and included in ETSI ZSM-011 draft (Section 4.3.1. Automotive use case). TNOR has fostered TeraFlowSDN community and participated in its Leadership and technical groups.

●**UBI** has contributed to ETSI TeraFlowSDN and participated in its Technical Steering Committee.

●**STR** has contributed to ETSI TeraFlowSDN and generated two opensource projects focused on Erlang development due to its contributions.

●**ODC** has led and participated in IETF standardization activities, including the IETF hackathon organization.

[10] https://github.com/stritzinger/braid

●**ADVA** has monitored Telecom Infra Project and ONF activities and contributed to TeraFlowSDN, with participation in Technical Steering Committee.

## 3.3 Task 6.3: Exploitation and Sustainability of Results

During the project's second period, following market trends and the needs and challenges of TeraFlow's stakeholders addressed by communication, dissemination and standardisation activities, Project partners acknowledged the great potential of TFS for the industry. The IP management activity described in task T6.3 has monitored ownership and agreements in a dedicated Excel file ("TeraFlow IP Registry") to facilitate exploitation for project partners and third parties. Furthermore, the partners categorised the components by technology and applicability categories to explore the various paths for exploitation. The identification of several packages and their exploitation roadmap, together with the analysis of business models conducted by T2.3, has guided the partners in defining their exploitation plans during this period, which was also impacted by the creation of the ETSI Open-Source Group for TeraFlowSDN (TFS) in February 2022.

The work of T6.3 has culminated with an internal exploitation workshop held over two separate days. This workshop has been devoted to refining partners' exploitation intentions and the overall action plan to effectively carry out joint exploitation activities and facilitate the widespread adoption of TFS in the short, medium and long term.

### 3.3.1 Project innovations

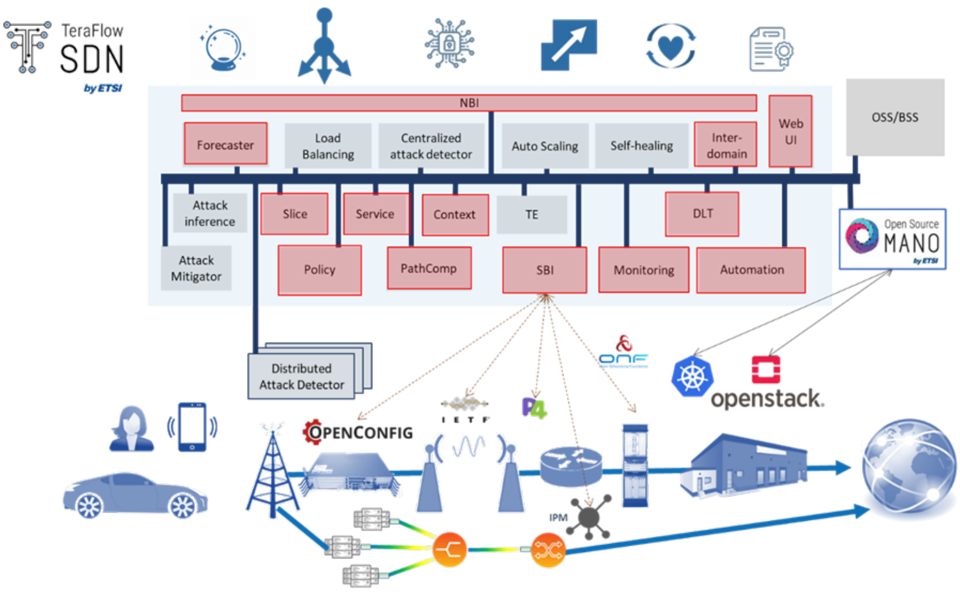
| KER | COMPONENT | OWNER1 | OWNER2 | OWNER3 | OWNER4 |
|---|---|---|---|---|---|
| 1 | Context Mngt | CTTC | TID | | |
| 2 | Monitoring | ATOS | | | |
| 3 | SBI | TID | CTTC | INF | |
| | P4 Device Driver Plugin | UBI | | | |
| | Microwave (MW) Device Driver Plugin | SIAE | | | |
| | OpenConfig | TID | CTTC | | |
| | TAPI | CTTC | | | |
| | XR Constellation Driver | INF | | | |
| 4 | Service | CTTC | INF | TID | |
| | P4 L2 Service Handler | UBI | | | |
| | L2NM Emulated Service Handler | CTTC | TID | | |
| | L2NM OpenConfig Service Handler | TID | CTTC | | |
| | L2NM IETF L2VPN Service Handler | TID | CTTC | | |
| | L3NM Emulated Service Handler | CTTC | TID | | |
| | L2NM OpenConfig Service Handler | TID | CTTC | | |
| | ONF TR532 Microwave Service Handler | SIAE | | | |

| | | | | | |
|---|---|---|---|---|---|
| | TAPI Service Handler | CTTC | TID | | |
| | TAPI XR Service Handler | INF | | | |
| 5 | Automation | UBI | | | |
| 6 | Policy Mngt | UBI | ODC | | |
| 7 | Slice Mngt | CTTC | TNOR | NTNU | ADVA |
| 8 | Distributed Ledger | NEC | CTTC | | |
| 9 | Traffic Engineering | STR | | | |
| 10 | NBI | CTTC | | | |
| 11 | Attact inference | CHAL | | | |
| 12 | Centralized attack detector | TID | UPM | CHAL | |
| 13 | Distributed Attack Detector | TID | UPM | | |
| 14 | Attack Mitigator | TID | UPM | CHAL | |
| 15 | Web UI | CTTC | CHAL | | |
| 16 | Inter-domain | TNOR | NTNU | CTTC | |
| 17 | Forecaster | CTTC | | | |
| 18 | Path computation | CTTC | TNOR | | |

To identify exploitation packages, the consortium's idea was to consider the three project scenarios and the components involved. However, in all three, the target is the telco operator, so we decided to segment the components by technology and applicability categories described in the above section to explore other paths for exploitation, more suitable for other partner profiles. Based on this, the consortium has identified four exploitation packages:

#### 3.3.1.1 EP1: TFS E2E

This package targets telco operators willing to use TFS as an E2E SDN orchestrator. The figure below shows the selected TFS architecture components.



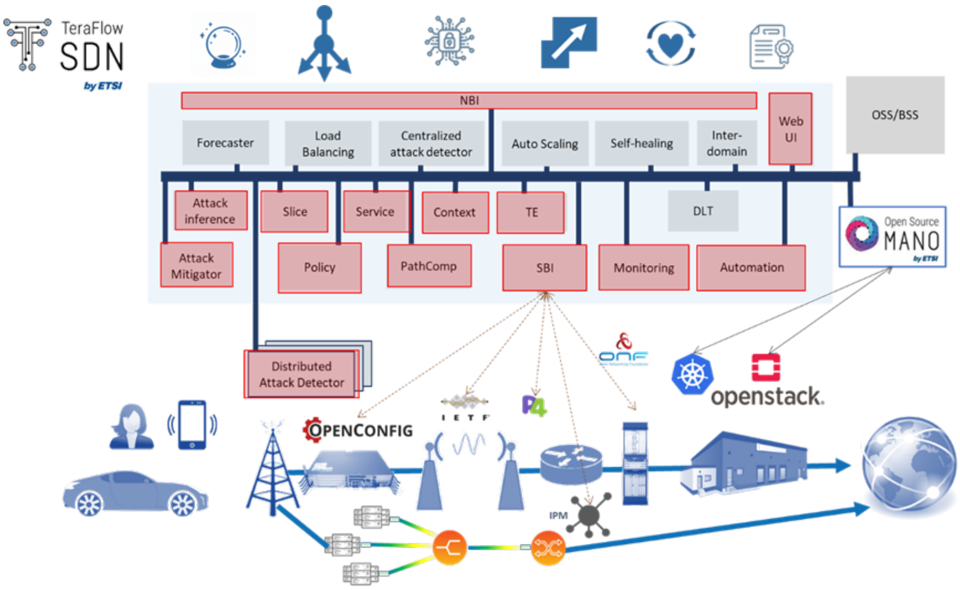

The components involved are:

- Context Management

- Monitoring
- SouthBound Interface (SBI)
    - Microwave (MW) Device Driver Plugin
    - Transport API (TAPI)
- Service
- Automation
- Policy Management
- Slice Management
- Distributed Ledger
- NorthBound Interface (NBI)
- Web UI
- Inter-domain
- Forecaster
- Path Computation

### 3.3.1.2 EP2: TFS – TECH

This package targets Data Centres and Telco providers focused on a single-layer SDN controller. Figure below shows the selected TFS architecture components.



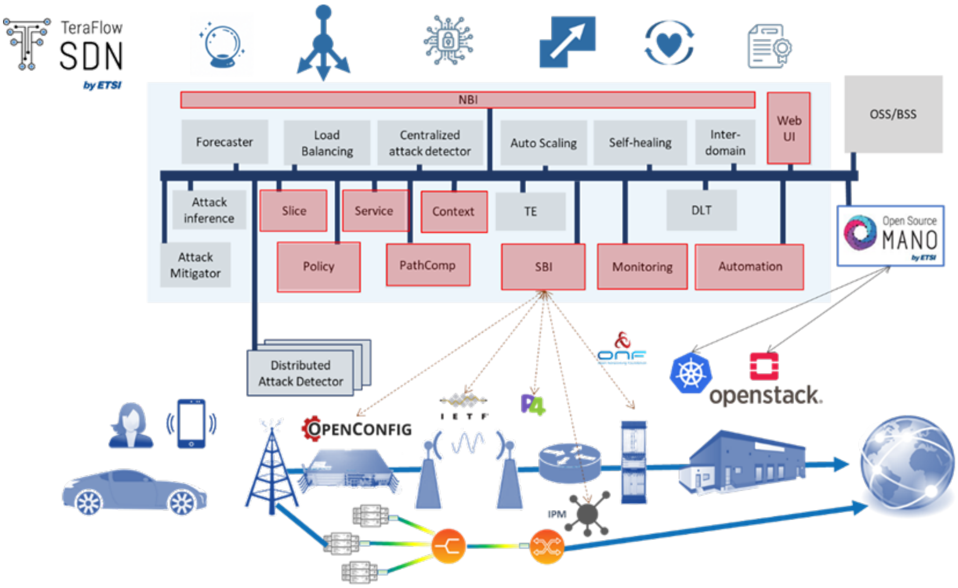

The components involved are:

- Context Management
- Monitoring
- SouthBound Interface (SBI)
    - P4 Device Driver Plugin
    - OpenConfig
- Service
- Automation
- Policy Management
- Slice  Management

- Traffic Engineering
- NorthBound Interface (NBI)
- Attack inference
- Centralised attack detector
- Distributed attack Detector
- Attack Mitigator
- Web UI
- Path Computation

### 3.3.1.3 EP3: TFS – DC

This package is targeted to a smaller footprint, like small enterprises and data centres, to which we can offer basic functionalities. Figure below shows the selected TFS architecture components.



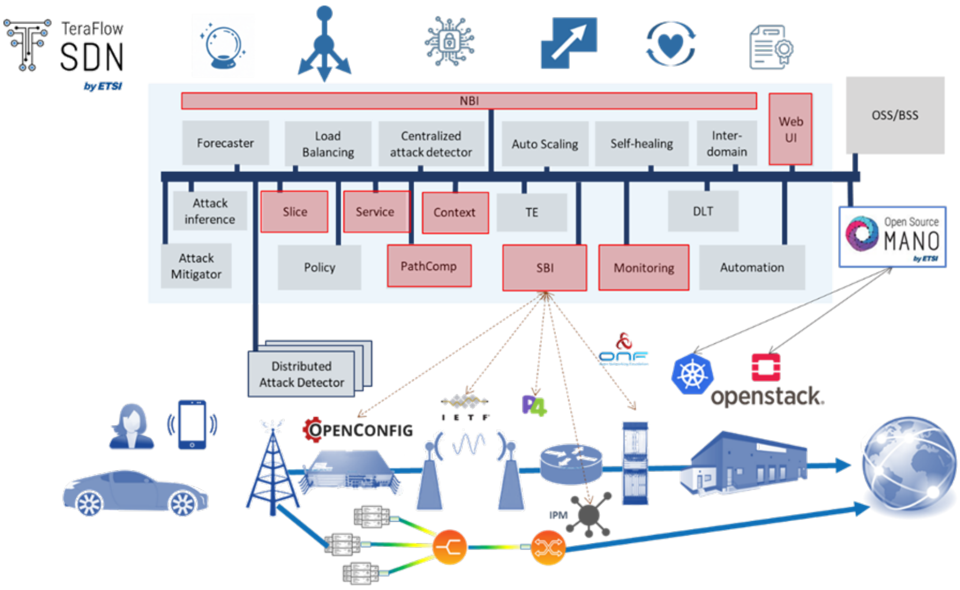

The components involved are:

- Context Management
- Monitoring
- SouthBound Interface (SBI)
    - P4 Device Driver Plugin
    - OpenConfig
    - XR Constellation Driver
- Service
- Automation
- Policy Management
- NorthBound Interface (NBI)
- Web UI
- Path Computation

### 3.3.1.4 EP4: TFS – NL

This package is intended for setting up a Neutral Lab (NL) that could give a certification of a device being OpenConfig/TAPI/P4 compliant. Figure below shows the selected TFS architecture components.




The components involved are:

- Context Management
- Monitoring
- SouthBound Interface (SBI)
- Service
- NorthBound Interface (NBI)
- Web UI
- Path computation
- Slice Management

### 3.3.1.5 Partners individual exploitation plans

| | EP1: TFS E2E | EP2: TFS – TECH | EP3: TFS – DC | EP4: TFS – NL |
|---|---|---|---|---|
| CTTC | X | X | | X |
| TID | X | X | | X |
| INF | | X | | |
| SIAE | | X | | |
| NEC | X | X | | |
| ATOS | X | X | X | X |
| TNOR | X | X | | |
| CHAL | | X | | |
| UPM | | X | | |
| VOL | | X | | |
| NTNU | X | | | |
| UBI | | X | | |
| STR | | X | | |
| ODC | | | | X |
| ADVA | X | X | | |

In the following lines, partners explain how they position themselves with respect of the exploitation packages.

**CTTC** will explore, devise, and validate/assess more advanced multi-technology route and resource selection algorithms in EP1. That is, in addition to those heuristics available and used in the TeraFlow project (e.g., energy-aware routing, resource and service-constrained shortest routing, etc.) the Path Computation component may become (as de facto) a server supporting AI/ML assistance to the whole controller. In other words, the Path Computation will be enhanced to derive a dedicated AI-server (by de facto) offering training of specific network models and providing diverse and multi-objective path and resource selection prediction. CTTC will also focus on specific technological solutions for intra-/inter- Data Centre networking in EP2. Finally, CTTC will evaluate the possibility of using TFS-NL for establishing a Neutral Lab for inter-operability tests in CTTC premises in conjunction with operators and vendors involved in the project.

**TID** will be part of the ETSI TFS community even when the TeraFlow project is finished, with a view to the evolution of this component to be aligned with market trends and our company's strategy. This work will be done under the financial support of other research projects. TID has created the steps to deploy L2VPN, L3VPN and ACL services following OpenConfig standards and YANG models. Once they are standardised and technically validated, TID will exploit this result by implementing these services in its transport networks in EP1 and EP2. Finally, TID also intends to support Neutral Lab to improve its interoperability and multi-vendor tests.

**INF** will focus in EP2. INF will use the TeraFlowSDN XR constellation Driver plugin to manage Infinera XR transceiver modules p2p and p2mp constellations via Infinera IPM (Intelligent Pluggables Manager) controller. TeraFlowSDN provides a reference design for integrating IPM as a hierarchical controller for XR optical services. TeraFlowSDN also provides an open framework/solution for XR modules dual-management (data side services and optics services) service opportunities to demonstrate network operators together with the help of third-party router NOS/HW vendors hosting XR transceiver modules. 3rd party vendors may develop their own device drivers to TeraFlowSDN to interface for their NOS or controllers or use the OpenConfig model to support dual management solutions. INF provided a TAPI variant service for configuring optical side configuration for XR constellations and WEB-GUI configuration service inside TeraFlowSDN.

**SIAE** will use the Microwave (MW) Device Driver Plugin of the TeraFlow SDN controller to validate and prove equipment and intermediate SDN controller's full compatibility with standard SBI data models, aligning with EP2. The proof of full compliance is an advantage for the Telco Operator when selecting MW Radio, which does not provide the same set of models and capabilities. Another business opportunity is the development of new Microwave specific use cases that the NetApp can offer on top of the TeraFlow SDN controller.

**NEC** aligns with EP1 and EP2. DLT solutions can be provided both E2E and in specific technological domains. TFS-E2E might use DLT for inter-connectivity scenarios, and TFS-TECH might be used for traceability.

**ATOS** is willing to perform integration tasks in any of the four exploitation scenarios. ATOS is incubating the Monitoring component to be extended and evolved in new projects. It regularly presents its capabilities to the Atos TMT business unit to follow up on touch points and potentially incorporate them into one of the company's product roadmaps when it is more mature. ATOS will be part of the ETSI TFS community even when the TeraFlow project is finished, with a view to the evolution of this component to be aligned with market trends and our company's strategy. This work will be done under the financial support of other research projects. There are future plans with CTTC to work on a new feature of the Monitoring component: persistent KPIs and alarm setting consistent in migration to the “context" database.

**TNOR** plans to exploit the result and propose practical solutions to add the inter-domain component into the management and control platform and enhance the operations of TNOR transportation networks using TFS-E2E and TFS-TECH. TNOR has started to work on green inter-domain Path Computation, where the abstracted topology used can vary according to the available energy-aware functionalities on the inter-domain links, as well as on the allowable performance degradation by the user (as a “green intent” that could become a part of the service order) with corresponding rewards/incentives. Results from the initial work are promising and foreseen to drive sustainable behaviours of users and other stakeholders in the (B)5G ecosystem. TNOR plans to continue on green business models, generalizing the work to end-to-end services and layered architectures.

**CHAL**, as an academic institution, has already exploited the attack inference component in several activities such as proof-of-concept demonstrations and scientific publications. CHAL plans to continue leveraging the attack inference component by testing and extending its functionalities to other types of ML-based monitoring and prediction tasks, so will focus on TFS-TECH. There is also a potential to exploit this component in other scientific projects such as the Celtic-Next AI-NET PROTECT project. Finally, as a member of the ETSI TFS TSC, CHAL will continue contributing to this component. CHAL also performed several exploitation activities targeting the centralized attack detector. This component uses the attack inference component to monitor, detect, classify, and mitigate attacks. In the future, this module also has the potential to be exploited in other projects, such as the Celtic-Next AI-NET PROTECT. Moreover, as a member of the ETSI TFS TSC, CHAL plans to support and evolve the centralised attack detector's functionalities, targeting functionalities relevant to the community. As a member of the ETSI TFS TSC, CHAL intends to support further and extend the functionalities of the attack mitigator with features relevant to the community. Moreover, as an academic institution, CHAL plans to enhance the attack mitigator, including novel functionalities incorporating state-of-the-art attack mitigation strategies.

**UPM** will exploit TFS-TECH, via providing security mechanisms, such as distributed attack detection and mitigation in IP domain.

**VOL** wanted to follow TFS-TECH, but due to bankruptcy terminated its involvement with TeraFlow.

**NTNU** plans to continue joint research with the partners regarding the TFS-E2E, with a dedicated focus on inter-domain components, both from a technological and business-driven perspective. For that, NTNU aims to leverage the existing implementation to explore mechanisms and solutions for reducing latency and increasing reliability for multi-domain communications, and to explore the implications on the business ecosystem. We define follow-up research projects to be submitted to national and international calls.

**UBI** focuses on TFS-TECH exploitation plan with specialized focus on P4 switch control and management. To this end, specific components and plugins have been addressed and will be jointly exploited.

**STR** focuses on TFS-TECH with a specific interest in PCEP control through TE component.

**ODC** exploitation interest involves TFS-NL based on their standards interoperability expertise.

**ADVA** will concentrate on TFS-E2E for providing E2E demonstration and support of their multiple product lines, as well as it is interested in exploiting TFS-TECH for both IP and optical specific network domains.

### 3.3.2 Partner's contributions

●**ATOS** has led this task and has been main editor and contributor of the two deliverables submitted in this period (D6.3 and D6.4). To collect the information needed from the partners and generate discussions around exploitation and sustainability of TFS, ATOS has organized several activities together with T2.3: second round of business-related interviews with partners, business model canvas activity conducted in TeraFlow plenary meeting in Castelldefels, internal exploitation workshop. ATOS has also coordinated and completed the Innovation Radar tool for reporting to the EC. On an individual note, ATOS has conducted internal activities following its own exploitation plan, as well as the required actions for being a ETSI TFS member.

●**TID** has actively contributed to all exploration activities by defining and clarifying the telecom operator ecosystem to business specialists and the multiple analysed business cases. TID has also been a prominent partner to ensure TFS sustainability through ETSI adoption of TeraFlow code base and creation of the Open Source Group.

●**INF** sees opportunity to use and promote TeraflowSDN as reference use-case of XR optics and IPM system integration to 3rd party SDN controllers and starting point for XR optics dual management (optical plane, data plane) solution with network element HW/NOS partners.

●**SIAE** has participated in exploitation packages definition and aligned its interest in microwave controller.

●**NEC** has participated in DLT exploitation definition in several exploitation packages.

●**TNOR** has focused on business analysis and exploitation of multiple project results. They have contributed to the organization of multiple exploitation workshops.

●**UBI** has contributed with SME expertise in exploitation activities from research.

●**STR** has contributed with SME expertise in exploitation activities from research.

●**ODC** has contributed to exploitation possibilities from standardized results.

●**ADVA** has contributed to exploitation analysis and development for TeraFlow exploitation packages.

All Academic partners have also contributed to this task and collaborated on the proposed workshops and deliverables.

## 3.4 Task 6.4: Liaison Activities and 5G PPP Collaboration

Partners' current involvement and participation in existing working groups (WGs) is presented in Table 3 5G-PPP Working Groups. These have been the responsible people attending meetings on behalf of TeraFlow and requesting the Consortium their contributions to the different WGs. This section details the most significant contributions to the different boards and WGs.

Table 3 5G-PPP Working Groups

| WG | Partner |
|---|---|
| 5G Architecture | TNOR |
| SN WG | CTTC |
| TMV | ODC |
| Pre-Standards | ODC |
| VSC | TNOR |
| Steering Board | CTTC |
| Technical Board | TID, CTTC |

### 3.4.1 Steering and Technical Boards

Both CTTC and TID have contributed as Project Managers and Technical Managers to coordinate contributions in the scope of steering and technical boards. We think this is a necessary effort to work with other projects together as a program, thus maximizing the impact of European R&D beyond 5G. TeraFlow has contributed to 5GPPP Reference Figure, as detailed in Figure 44.

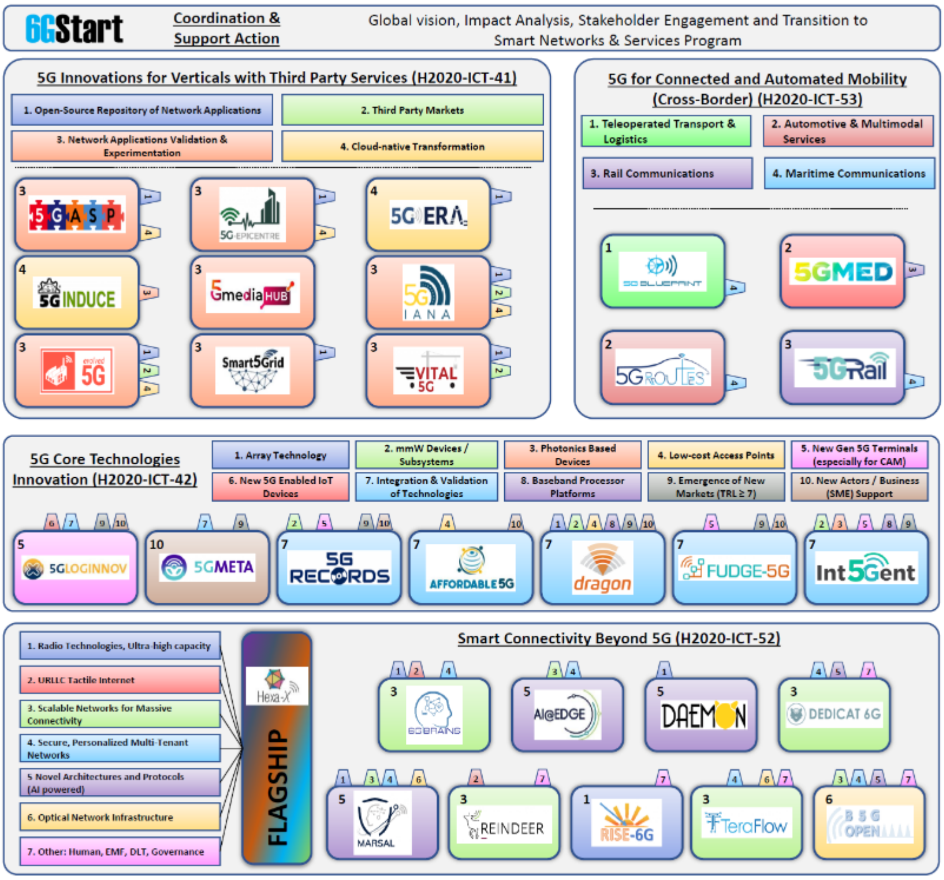



Figure 24: 5GPPP Reference Figure 2023

TeraFlow has contributed to the 7th and last issue of the European 5G Annual Journal, released at the end of May 2023. TeraFlowSDN and multiple use cases are presented to illustrate the benefits of our proposed solution.

On January 18th and 19th, 2023, the Workshop[11] organized by Hexa-X and ICT-52 projects was presented. It was a fully virtual and open to all workshop by Hexa-X and other European projects from ICT-52 call. TeraFlow contributed with the following presentation:

- TeraFlow: Do we need yet another SDN controller? Use cases for a novel cloud native SDN controller for beyond 5G networks, Ricard Vilalta (CTTC) 15 min.

### 3.4.2 Architecture WG

This Working Group aims to establish a shared platform that enables the exchange of ideas and promotes discussions among 5GPPP projects that focus on developing architectural concepts and components.

There has been active participation in conference calls and activities of this working group, like the contribution to the 6G Book and the 6G architecture landscape white paper, further details are provided in the following subsections. TeraFlow has contributed to Chapter 5 and 7 of 6G Book organized by Hexa-X and Architecture 5GPPP WG.

Authors: Ömer Bulakçi (ed.), Xi Li (ed.), Marco Gramaglia (ed.), Anastasius Gavras (ed.), Mikko Uusitalo (ed.), Patrik Rugeland (ed.), Mauro Boldi (ed.)

Publisher: Boston-Delft: now publishers[12]

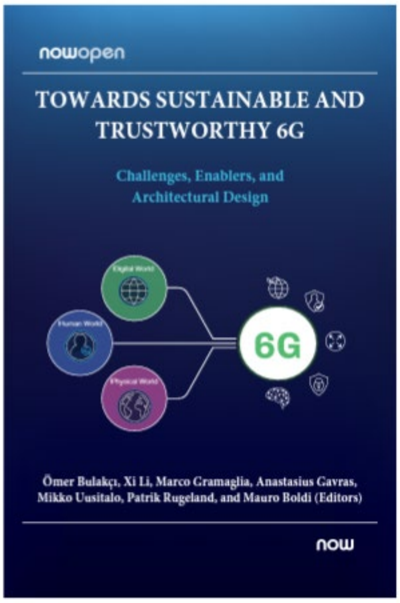



*Figure 25: 6G book*

Besides putting TeraFlowSDN into a context of transport network configuration, service provisioning, orchestration (incl. integration with OSM) and automation, we have pointed to further work in the need for specialized connectivity handling, customer-facing logical networks, mesh connectivity and directions for standardization. 6G Architecture Landscape – European Perspective

[11] https://hexa-x.eu/ict-52-workshop-on-6g-2023/
[12] https://www.nowpublishers.com/article/BookDetails/9781638282389

TeraFlow has contributed to this white paper from the 5G Architecture Working Group (February 2023). This white paper summarizes the main findings from the European research landscape on the vision of the 6G architecture. Such a design vision is derived from around 45 projects starting from October 2020 in all relevant areas of 5G while paving the way towards 6G.

TeraFlow contribution is the description of the ETSI TeraFlowSDN controller for providing logical networks as a service.

### 3.4.3 Software Networks WG

TeraFlow has contributed to the white paper: "Network Applications: Opening up 5G and beyond networks", September 2022.

This paper aims to demystify the concept of Network Applications. Different Network Applications implementations have been conducted considering various API types and levels of trust between the verticals and the CSP. TeraFlow has contributed to describing multiple data modelling languages and control and management protocols.

### 3.4.4 TMV WG

The 5GPPP TMV WG develops test and measurement methods, test cases, procedures, and KPI formalisation and validation, ranging from R&D to early-stage deployments for 5G, beyond 5G, and 6G networks. The group brings together industry stakeholders, researchers, and experts to identify and develop innovative solutions that leverage 5G capabilities.

Today, 5G networks are being widely rolled out in various deployment environments, with multiple configurations, for serving diverse public and vertical sector needs. While deployed 5G networks are still under evaluation to prove their capabilities and potential in commercial and operational environments, the requirements and KPIs are being discussed for 6G systems to properly steer the 6G research and innovation activities. To this end, besides clearly defined KPIs, it is vital to identify methodologies and tools to evaluate them even at early research stages so that the 6G technologies can be properly validated.

In June 2022, we contributed to the 5G-PPP TMV Working Group white paper "Beyond 5G/6G KPIs and Target Values"[13]. This work provides an early analysis of possible Beyond 5G/6G KPIs based on current work and perspectives from ICT-52 projects, seeking to understand the level to which existing definitions in standard documents will apply to 6G and to identify, at early stages, gaps and new candidate KPIs for being standardized for 6G systems. Authors: Nielsen, Lars (ed.); Gavras, Anastasius (ed.); Dieudonne, Michael (ed.); Mesogiti, Ioanna (ed.); Roosipuu, Priit (ed.); Houatra, Drissa (ed.); Kosmatos, Evangelos (ed.) (Daniel King is contributor on behalf of TeraFlow).

More recently, in May 2023, TeraFlow contributed to the whitepaper continuation "Beyond 5G/6G KPI Measurement"[14]. Authors: Dieudonne, Michael (ed.); Wang, Hua (ed.); Mesogiti, Ioanna (ed.); Kosmatos, Evangelos (ed.) (Daniel King is contributor on behalf of TeraFlow).

[13] https://doi.org/10.5281/zenodo.6577506
[14] https://doi.org/10.5281/zenodo.7963247

### 3.4.5 Pre-Standards WG

The 5GPPP Pre-Standards WG is crucial in driving early collaboration and research in developing 5G standards. It brings together key stakeholders, including industry, academia, and standardisation organisations, to discuss and contribute to developing technical specifications and concepts that will shape the future 5G standards.

We regularly updated the WG on TeraFlow activity during the project, especially related to the IETF and ETSI TeraFlowSDN. These updates were incorporated into the quarterly WG updates and yearly reports. The updates to the WG also provided visibility and discussion of important TeraFlow standards developments across H2020 projects.

### 3.4.6 VSC WG

TeraFlow partners are engaged in the 6G IA Vision and Societal Challenges working group, and its sub-working groups such as Business Validation, Models, and Ecosystems. In TeraFlow's project span, working groups have published white papers on European Vision for the 6G Network Ecosystem, and more recently 5G and Beyond 5G Ecosystem Business Modelling, in May 2023 [BVME23]. TeraFlow has been a place where technological disruptions and ambitions have been addressed and accompanying ecosystems and business models. Thus, partners have taken care to share and direct learnings into these 6G IA working groups to the best of the community.

### 3.4.7 EUCNC contributions in 2022

Several contributions were made for EUCNC22, as it is the best place to position 5GPPP projects and impact the community. Specifically, a Special Session was organized titled: Redesigning Transport Networks for 6G: From the cell site to the core.


*Figure 26 Special session in EuCNC22*

The European 6G flagship research project Hexa-X (H2020 ICT-52) has worked towards building the foundation for a future 6G system and exploring a plethora of technical enablers. The research in the project has consolidated the views of the 25 partners from leading academic institutions and industry players and conducting leading edge technological exploration and development related to enhanced radio performance and combined communication and localization/sensing; Connected intelligence with integrated AI/ML; Network evolution expansion, exploring new network architectures and novel verticals. As such, the workshop addressed the conference tracks '6G Enabling Technologies' and '6G Visions', by providing a consolidated view of the 6G research from the major European players. The workshop provided an opportunity to solidify Hexa-X's position as a leading 6G project on a global scale, showcasing the work done with presentations and live demos. It provided an opportunity to connect and align with the 6G research performed elsewhere. This was accomplished by inviting other ICT-52 6G technical enabler projects to present and through an open call for technical contributions.

Session 3 – Connecting intelligence (90 min):

- AI-driven communication & computation co-design Miltiadis Filippou (Intel) [20 min + 5 min Q/A].
- Design of service management and orchestration functionalities – Josep Martrat and Ignacio Labrador (Atos) [20 min + 5 min Q/A].
- TeraFlow: ML-based attack detector for TeraFlow OS – Alberto Mozo (UPM) and Antonio Pastor (Telefonica) [15 min + 5 min Q/A].
- 6G BRAINS: Bringing Reinforcement Learning to Communication and Networks – Victor Gabillon (Thales) [15 min + 5 min Q/A].

Figure 27 shows the TeraFlow booth at EUCNC22, showcasing multiple demos.

*Figure 27 TeraFlow booth at EuCNC2022*

### 3.4.8 EUCNC contributions in 2023

Several activities have been prepared to maximize TeraFlow's impact in the 2023 EuCNC & 6G Summit:

Special Session: Novel technologies in disaggregated packet-optical networks to support 6G, and TeraFlow booth, where a complete set of novel dissemination material was prepared, including three use case posters and an architectural roll-up. On-screen, we had a demonstration of TeraFlowSDN performed at the last OFC 2023.


*Figure 28 TeraFlow booth at EuCNC2023*

### 3.4.9 Partner's contributions

● **CTTC** has lead liaison activities and 5GPPP Collaboration by identifying and monitoring the different partners participation in the multiple working groups, contributing to 5GPPP Steering Board and preparing multiple activities for EUCNC to join the 5GPPP community and foster collaboration.

●**TID** has participated in 5GPPP Technical Board and contributed to activities.

●**ATOS**, as WP leader, has been monitoring the task's progress and ensuring the reporting of the achievements. ATOS has also participated in BVME SG in 5GPPP VSG, attending meetings and contributing where possible.

## 3.5 Impact of COVID-19 on WP Activities

There has been some negative impact due to COVID-19 restrictions. This is particularly true due to cancelled events and the virtualisation of other events, basically during P1 of the project. Virtualisation reduces the possibility of networking and discussions among researchers. This has impact on dissemination, communication and standardisation activities. However, it is not considered critical to the success of the project, as mitigation has been applied due to the significant predominant position of TeraFlow partners in SDO. During P2, COVID-19 did not affect project dissemination and communication activities, fulfilling all WP6 related objectives.

Similarly, exploitation activities might have been negatively impacted since it was harder to set up testbeds, and collaborate to carry out exploitation plans, during P1 of the project.

# 4 Project Management and Administrative Issues

This section provides an overview of the project management-related tasks and the administrative issues attended to during P2. It also describes the recommendations of the Advisory Board, Grant agreement amendments, Resources and Spending, updated risk management, Gender balance, project deviations, and virtual project meetings.

## 4.1 Summary

WP1 Project Management has taken care of the administrative tasks, quality assurance, management of risks and ethics, the technical management of the project, and the organisation of Advisory Board activities. WP1 Project Management examples include the timely kick-off of project activities and their overall coordination, ensuring participation from all project partners, contractual matters and the provision of collaborative tools.

*Figure 29 First face-to-face TeraFlow meeting after 17 months of the project hosted at CTTC*

The project officially started on 1 January 2021. The kick-off meeting was successfully held virtually on 21/01/21. The main objective was to get a common understanding of how the overall goals can be achieved, and to plan how to start with concrete activities. Further meetings have been organised - an overview of all meetings is given in section 3.7 below.

The TeraFlow Consortium Agreement was concluded on 20/12/20, and the signature sheets have been collected from all partners.

The first pre-payment was received from the EC and the respective shares were transferred to the project partners in mid-January 2021 after they provided their bank account details.

TID is the Technical Project Manager, has taken care of the overall technical management of the project and technical coordination between work packages. The task also included monitoring WP activities and technical work progress, the contribution to reports, and organisation and chairing of Project Board meetings. While this task was with Victor López in the first months, it was handed over to Juan Pedro Fernández-Palacios at the end of April 2020, due to Victor's departure from TID. In November 2021, Oscar González-de-Dios took over the responsibility of interim technical manager, due to long-term sick leave of Juan Pedro.

The PC, TM, and Quality Manager have jointly taken care of the quality assurance of project results.

Conference calls have been held regularly on a project level and on a WP-level to get status updates, facilitate coordination between WP activities, discuss the technical activities, and achieve early identification of any potential issues or risks.

A Management Plan has been prepared (D1.1) as a practical guideline to facilitate project management for all TeraFlow participants. It sets down and explains all contractual rules and management procedures, e.g., for delivering Deliverables. It also provides information on project tools, quality assurance, and reporting procedures.

Several tools have been deployed to support communication and collaboration in the project. These include:

- Several mailing lists (all partners, one per WP, financial and legal matters, etc.) and corresponding mailing list archives.
- A Web-conferencing system (Microsoft Teams) available 24/7 for conference calls
- A workspace for document storage and joint editing (Microsoft Teams)
- Excel and Word Templates for partners' quarterly report of their work, efforts spent, and expenses made.
- An Excel document for keeping an overview of all project dissemination activities.

**Templates** for project documents have been prepared, including templates for Deliverables, presentations, and meeting minutes.

TeraFlow has also achieved a strong presence at 5G PPP Programme level. The Project Coordinator and Technical Manager attended 5G-I SB and TB activities and meetings. Overall, project representatives participate in 5 Working Groups of the PPP, providing direct contributions from TeraFlow.

The COVID-19 restrictions have also had an impact on the TeraFlow project activities. Details are reported in below section 3.6.

Preparations for the first project review started. The review date and virtual format were agreed. The review was a success, and recommendations from the reviewers have been taken into account during P2.

During P2, Juan Pedro Fernández-Palacios was reappointed in the position of TM. There has only been a minor amendment during this period, related to the change of business priorities in Infinera. This has brought more network elements to consider in TeraFlow and has extended its scope.

In May 2022, a face-to-face meeting was held in Castelldefels (Spain) (see Figure 29). As the project progress was positively evaluated and our methodology was successful, we decided to keep the regular meetings on-line, with technical WP bi-monthly regular meetings and a monthly plenary.

All partners decided the creation of ETSI TeraFlowSDN and joined ETSI community. All partners agreed to bring our gitlab repository to ETSI to finalize the transition to an open-source community.

WP1 leader discussed the multiple ETSI TeraFlowSDN legal and organizational documents, and a structure for the opensource group was defined with a leadership group and a technical steering committee.

At the time of writing, all deliverables follow the review procedure to be submitted due date and final project review preparation has started.

The sections below provide more detailed information on several activities in the scope of WP1.

## 4.2 Advisory Board Activities

TeraFlow has set up an Advisory Board (AdvB). Its main purpose is to get advice on the direction of TeraFlow's technical work and the best ways to exploit the project results and create innovations. The setup process started in September 2021 with the search for suitable AdvB member candidates, considering the members in the original proposal.

As of November 2021, the AdvB has 3 highly qualified members with complementary backgrounds and expertise (see Table 4).

*Table 4 Members of TeraFlow Advisory Board*

| # | Name | Organisation | Job Title |
|---|---|---|---|
| 1 | Noboru Yoshikane | KDDI Research | Senior Manager of Photonic Transport Network Laboratory |
| 2 | Silvia Almagia | ETSI | Technical Expert - ETSI's Centre for Testing and Interoperability |
| 3 | Diego Mari | TIP OOPT | Technical Lead - Open Optical Packet Transport Project Group |

The first Advisory Board meeting occurred virtually on December 17th, 2020, at 9:00 AM. Due to technical issues, Diego Mari could not attend, so the questions for him were sent to him offline. The Advisory Board gave very positive feedback, proposed international events where TeraFlow can be presented, and motivated the TeraFlow partners to contribute to the ETSI work groups with proof-of-concept proposals and the Open Source MANO project with bug fixes and new features. Additionally, they gave very interesting feedback on ensuring the sustainability of the TeraFlow SDN controller after the H2020 TeraFlow project ends. Finally, the intention of open sourcing the TeraFlowSDN components had very good feedback.

*As per recommendation of the reviewers to make more extensive use of Advisory Board, we have proceeded to regular one-to-one interviews with advisory board members, including TeraFlow PM and TM, among other.*

The multiple discussions with Diego Marí Moretón, Connectivity Technologies & Ecosystems Manager at Meta Spain, have been about the collaboration between TIP (Telecom Infra Project) and TeraFlowSDN in the context of the OOPT (Open Optical & Packet Transport) project group within TIP. The OOPT group is working on defining test and validation requirements for the MUST (Minimum Use Case Requirements for SDN for Transport) initiative.

TIP and the OOPT project group are developing a robust test and validation framework for MUST. They are creating a set of test plans to ensure interoperability between the SDN (Software-Defined Networking) components for Transport architecture. The goal is to give network operators confidence when selecting SDN and networking devices. Both the existing TIP community labs and authorized third-party labs will be leveraged to scale the testing phase and accommodate multiple solutions.

TeraFlow is seen as a crucial component in the test and validation phase. Its open nature makes it an ideal tool for validating the conformity of different solutions against the MUST test plans. TeraFlow will be used to build the framework and define the low-level designs for testing.

TeraFlow's test suite is expected to play a significant role in granting MUST compliance badge for vendors. The badge aims to provide visibility to vendors among TIP operators and other connectivity service providers. Diego Marí Moretón expresses confidence that TeraFlow will be one of the solutions receiving the first set of badges, as it contributes to the maturity of solutions in the SDN for Transport domain.

Our discussions were summarized in a TeraFlow Blog post that can be consulted at: https://teraflow-h2020.eu/blog/interview-diego-mari-moreton-connectivity-technologies-ecosystems-manager-meta-spain


*Figure 30 Blog post with Diego Marí Maretón*

Silvia Almagia is a Technical Expert at ETSI's Centre for Testing and Interoperability. Her current activities include providing technical management and expertise in open source, interoperability testing and proofs of concept (PoC). Among others, she oversees the Open Source MANO project (ETSI OSM), TeraFlowSDN (TFS), the NFV Plugtests Programme, and the NFV and ZSM PoC Frameworks.

From her position, Silvia has first identified the feasibility of creating a new OpenSource Group (OSG) inside ETSI with the code seed of TeraFlow project. Her role was key to understanding the need for a neutral organisation's support for defining the structure, governance and processes that would enable the onboarding of new members, managing a growing number of contributions and building a healthy and diverse community. Evolving from a research project towards a global open source community was key to maximising the outreach and ensuring the long-term sustainability of TeraFlow.

With her help, we drafted a project proposal and identified all the potential benefits - both for ETSI and TeraFlow - of creating an open source community. We presented our Open Source Group proposal to the ETSI Director General, which was well received and appreciated. With the support from Silvia and her previous experience with ETSI Open Source MANO (OSG OSM), we started drafting the Terms of Reference, Member and Participant Agreements and detailed Working Procedures dealing with the governance and decision-making for code development activities. The OSG proposal and Terms of Reference were also presented to the ETSI Board, who gave positive feedback.

Another important milestone was the re-branding. It was not an easy challenge to find a way to distinguish (while connecting) the EC-founded H2020 project TeraFlow and the ETSI Open Source Group TeraFlowSDN. To this end, big thanks to the support of both the TeraFlow H2020 communication leader (ATOS) and the ETSI branding team.

ETSI OSG TFS was officially kicked off on June the 20th, 2022. Since then, we have started onboarding all project partners to the open source community while incorporating several new members and participants. Silvia has included technical support in her daily activities at ETSI and helped us to promote and disseminate TeraFlowSDN (Figure 31).


*Figure 31 Silvia Almagia presenting Software Development Groups in Layer 1-2-3 World Congress 2022*

Noboru Yoshikane is a Senior Manager of Photonic Transport Network Laboratory, KDDI Research. He has contributed to identifying multiple gaps and requisites for TeraFlow since its foundations. To this end, CTTC and KDDI Research have started a joint activity to analyse the potential of TFS to integrate with SDM networks, using intermediate controllers. As a result of these activities, several publications have emerged:

- Raúl Muñoz, Carlos Manso, Filippos Balasis, Ramón Casellas, Ricard Vilalta, Ricardo Martínez, Cen Wang, Noboru Yoshikane, Takehiro Tsuritani, Itsuro Morita, "Dynamic Reconfiguration of WDM Virtual Network Topology over SDM Networks for Spatial Channel Failure Recovery with gRPC Telemetry", 2022 Optical Fiber Communications Conference and Exhibition (OFC).
- R. Muñoz, C. Manso, F. Balasis, C. Wang, R. Vilalta, R. Casellas, R. Martínez, N. Yoshikane, T. Tsuritani, "Dynamic Upgrade/Downgrade of WDM Link Capacity in SDN-enabled WDM VNTs over SDM Networks", ECOC2022.
- R. Muñoz, C. Manso, F. Balasis, D. Soma, S. Beppu, R. Casellas, Ll. Gifre, R. Vilalta, R. Martínez, N. Yoshikane, T. Tsuritani, "Dynamic bypass of wavelength switching in SDN-enabled WDM VNTs over SDM Networks with high bit-rate optical channels", 2023 Optical Fiber Communications Conference and Exhibition (OFC).
- Carlos Manso, Ricard Vilalta, Raul Muñoz, N. Yoshikane, Ramón Casellas, Ricardo Martínez, C. Wang, F. Balasis, T. Tsuritani, I. Morita, "Scalability analysis of machine learning QoT estimators for a cloud-native SDN controller on a WDM over SDM network", Journal of Optics Communications and Network, 2022.

## 4.3 Grant Agreement Amendments

Three Grant Agreement Amendments have been prepared in the first period, and a single amendment during P2. In this section, we provide an overview of the proposed changes.

- The first GA Amendment (finished: 3/8/2021) was initiated by TeraFlow to make several small changes. ATOS IT introduced an affiliate company named Atos Spain SA (ATOS SP) as a linked third party in the consortium. ATOS SP is a company of the Atos group that offers business and IT services consulting and vertical solutions in financial, utilities, and telecom services. ATOS IT shares projects and activities with its affiliate ATOS SP in the project. Due to the nature of some project tasks, the expertise of members of both organisations is needed.
- Moreover, CTTC and TID exchanged effort due to the departure of the Technical Project Manager. CTTC is responsible for D2.1 and MS1. CTTC assumes more workload on WP1 and WP2.
- TeraFlow initiated the second GA Amendment due to Volta departing from the consortium (25/10/2021). Volta Xarxa S.L. lost its only customer, Volta Networks Inc, as Volta Networks Inc ceases its operations.
- The third GA Amendment is related to including ADVA in the TeraFlow consortium to provide the necessary activities due to VOLTA's departure (28/12/2021). It includes ADVA in addition to the consortium incorporating NOS activities after VOLTA termination.
- The fourth amendment was proposed on 9/11/2022. Due to COVID19 project budget needs some budget adjustments. Moreover, Infinera business focus has shifted from whiteboxes routers to XR optics transceivers plugged in whiteboxes. Regarding T2.3, the partner NTNU changes experts, and Iwona Windekilde replaces Harald Øverby. However, she can only start her contribution in January 2023. Furthermore, constitution of the SDN market we study and available data do not allow "quantitative agent-based simulation model". The task will apply other appropriate methods to analyse "business transactions between stakeholders and how the market evolves over time". Results of T2.3 from M24 to M30 were expected to be provided in D6.4.

## 4.4 Resources and Spending

In TeraFlow, the effort of each partner (in PM) was initially planned linearly over the duration of each respective task where a partner has effort allocated. From experience this is a good approximation of actual spending to be expected, although it is often observed that partners backload their efforts in EC projects, i.e., consume below average in the first half and above average in the second half of the project. Nevertheless, any deviation that might come up needs to be checked to see whether the deviation is highlighting any issue in work progress, or whether the linear planning was simply not appropriate.

The chart below (Figure 12) gives an overview of the planned versus reported efforts of the TeraFlow beneficiaries in P1 (M1-M12) and P1+P2 (M1-M30).

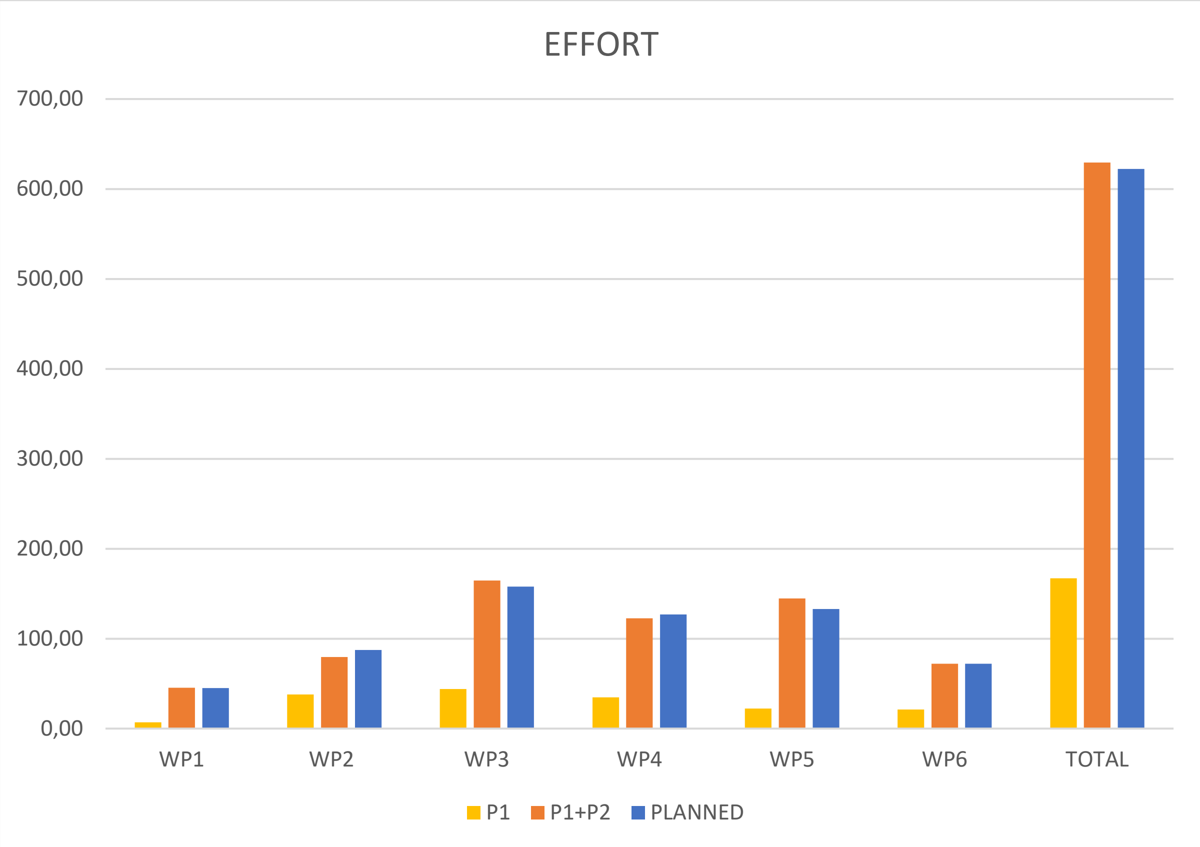



*Figure 32 Consumed PMs per WP*

Overall, the project has spent the planned effort: Of a total of 622 PM planned, about 629 PM were actually spent. From the monetary perspective, personnel direct costs have less than 1% deviation, and significant deviation is on other direct costs (mainly due to COVID19 restrictions for traveling).

Nevertheless, the individual deviations of partners have been scrutinised in order to identify whether there is any reason pointing to a problem that needs to be addressed, and also in terms of whether the deviation will have any impact on the progress of project activities or the future work. Details have been provided on a WP-level in the individual WP report sections. Figure 13 and Table 6 give a detailed overview of the consumption of efforts in the reporting period.

Effort usage will be further monitored in order to detect any problems well in advance of becoming critical.

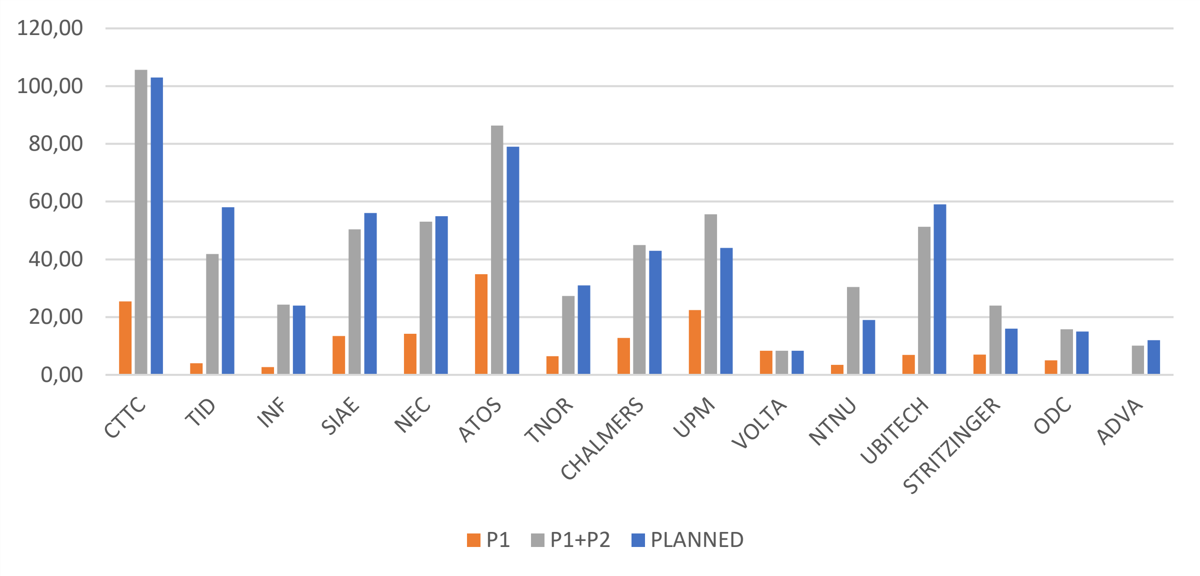



*Figure 33 Consumed resources per partner*

| | TOTAL PM | P1 PM | P1+P2 | Deviation |
|---|---|---|---|---|
| CTTC | 103,00 | 25,45 | 105,61 | 3% |
| TID | 58,00 | 4,07 | 41,85 | -28% |
| INF | 24,00 | 2,65 | 24,36 | 1% |
| SIAE | 56,00 | 13,40 | 50,41 | -10% |
| NEC | 55,00 | 14,27 | 53,08 | -3% |
| ATOS | 79,00 | 34,89 | 86,33 | 9% |
| TNOR | 31,00 | 6,45 | 27,34 | -12% |
| CHALMERS | 43,00 | 12,79 | 44,92 | 4% |
| UPM | 44,00 | 22,46 | 55,61 | 26% |
| VOLTA | 8,30 | 8,30 | 8,30 | 0% |
| NTNU | 19,00 | 3,49 | 30,38 | 60% |
| UBITECH | 59,00 | 6,91 | 51,27 | -13% |
| STRITZINGER | 16,00 | 7,05 | 23,96 | 50% |
| ODC | 15,00 | 5,05 | 15,74 | 5% |
| ADVA | 12,00 | 0,00 | 10,10 | -16% |

*Table 5 Planned vs actual effort in P1, P1+P2, and deviation*

### 4.4.1 Effort deviations justification per partner

#### 4.4.1.1 Telefónica I+D

This deviation is mainly due to changes in how our workforce is structured and the strict procedures we follow to make activity reporting compliant with the grant conditions. This had an impact on the formal reporting, but not our actual activity, nor its result due to the strong synergies with Telefonica internal projects (iFUSION, TIP-MUST) including workforce from other Telefonica companies."

#### 4.4.1.2 SIAE

We took advantage from activities performed during the plug test ETSI, where the NBI of our controller (later integrated in Teraflow project) have been studied, designed and developed with the result of an advantage in the integration of this component in the Microwave and Service Driver in terms of worked hours.

This has implied a reduced utilization of professional with lower skills (and lower cost), but - in the other hand - the involvement of higher skilled professionals for the analysis and then the set-up of the test plan used to perform the integration test into the Teraflow ecosystem.

#### 4.4.1.3 Telenor

In the 1st periodic reporting, a formula error did not include hours in one of the columns, counting 38.5 hours. This equals effort for WP2 of 0.15, for WP3 of 0.04, for WP4 of 0.04, for WP5 of 0.06 or total of 0.29: 0.15+0.04+0.04+0.06 = 0.29. Periodic Report 1 has been corrected, due to a mistake in the previous reporting. Due to formula error, December 2021 was accidentally not included in the total in period 1.

For Reporting period 2:

Underspending in WP2: TNOR reallocated more resources to the component design and testing in WP2-WP5 after the architecture design of T2.2 was completed.

Underspending in WP3: due to the change of task leader, there was not too much activity in the task/component of network slicing, to which TNOR planned to contribute more.

Underspending in WP4: TNOR mainly contributed to the design of the inter-domain component and then spent more time on testing the inter-domain scenario in WP5.

#### 4.4.1.4 UPM

At the beginning of the project, it was necessary to replace senior researchers, as initially proposed in the proposal, with junior researchers who required additional effort to carry out the tasks originally outlined. This change was reflected in WP2, where an extra 0.34 PMs were required, and in WP4, where the effort increased by 1.67 PMs. The 4.5 PMs increase in WP5 was additionally influenced by the fact that the integration of cybersecurity components with other open-source components of the Teraflow SDN required additional effort not initially foreseen during the proposal phase. Finally, the preparation of scientific articles in high-impact factor journals (4 journal articles indexed as highly relevant in the prestigious WoS JCR ranking, one of them in the 96th percentile of its category and another in the 90th percentile) by junior researchers with little experience in the field of high-quality scientific publishing required more PMs than initially planned.

#### 4.4.1.5 NTNU

Professor Harald Øverby left NTNU, and his tasks were overtaken by the remaining project team and further researchers. This reduced the overall average PM rate. Besides, we reallocated other costs to personal costs and together with the favorable exchange rate we were able to increase the overall amount of PMs we could spent on the project without affecting the overall budget.

#### 4.4.1.6 UBITECH

In Ubitech, more senior staff was involved than originally planned, due to the specificities of the project. This led to an increase of PM rate (original: 6K, real: 7.1K). The involvement senior staff has resulted in less PM consumed.

#### 4.4.1.7 STRITZINGER

STR planned initially to work with VOLTA to create a Erlang based implementation of some of the specifications that were used for the implementation of TFS. However, VOLTA was not there to complete their part, so some re-planning had to be done. At first STR turned their already done PCEP implementation into a standard TFS component. After that STR decided to build part of the planned infrastructure in the form of the Braid orchestrator. To achieve a rounded useable deliverable STR overspent 26% in personal cost. In turn the other cost were reduced by 9.2% resulting in a total overspending of 21.7%. At the same time STR was using more junior developers than planned which changed the PM amount from the planned 16PM to 24 PM which is a 50% increase.

#### 4.4.1.8 ADVA Optical Networking

ADVA successfully completed the planned implementation of the Network Slicing component and supported the demonstration at OFC 2023 in March 2023. Unfortunately, our main TeraFlow contributor left ADVA in April 2023. The loss of the main contributor could be mitigated in advance, as ADVA successfully aligned the TeraFlow project with other funded projects (AI-NET-PROTECT, B5G-OPEN, SEASON) where we defined the TeraFlowSDN controller as ADVA's reference open-source parent SDN controller, and we aligned the streaming telemetry and data analytics pipeline implementation. Thus, we could fully complete our committed TeraFlow contribution despite the PM deviations.

## 4.5 Updated Risk Management

The situation regarding potential project risks, as listed in the Grant Agreement, has been regularly reviewed by both TM and PC and in project plenary meetings. We have updated the information in the ECAS portal, where some detailed comments on the state of play for each risk can also be found.

## 4.6 Gender balance

This section highlights the importance of gender balance in TeraFlow and outlines initiatives to foster a more inclusive environment. The following information provides a comprehensive overview of TeraFlow's gender balance efforts and the specific activities implemented to promote gender equity.

### 4.6.1 Gender balance information

Partners have updated the gender balance information in the Sygma system. Table 5 provides the results.

| | Total number of females in the workforce | Total number of males in the workforce |
|---|---|---|
| CTTC | 2 | 7 |
| TID | 0 | 9 |
| INF | 2 | 8 |
| SIAE | 0 | 8 |
| NEC | 1 | 3 |
| ATOS | 4 | 7 |

| | | |
|---|---|---|
| TNOR | 4 | 1 |
| CHAL | 1 | 3 |
| UPM | 1 | 3 |
| VOL | 0 | 1 |
| NTNU | 6 | 5 |
| UBI | 0 | 3 |
| STR | 1 | 5 |
| ODC | 2 | 2 |
| ADVA | 0 | 3 |
| Total | 24 (26%) | 68 (74%) |

*Table 6 Gender Balance Information*

### 4.6.2 Activities to promote gender balance

Moreover, TeraFlow has implemented a series of activities to promote gender balance. This section documents the efforts to improve the gender balance. Figure 32 shows our campaign on #InternationalWomenInEngineeringDay 23/06/22 to encourage more women to take up a career in engineering.


*Figure 34 Campaign on International Women in Engineering Day 2022*

In 2023 we participated again in the International Women in Engineering campaign on social Networks, with a special activity on LinkedIn. The International Women in Engineering, organised by the Women's Engineering Society (WES) celebrated its 10th year in 2023. This time we tagged all our posts with #INWED23 (a tag of the official campaign), and we created 10 different posts with the short CV of some of our women in engineering, describing also what they did in TeraFlow and the importance of their contribution to our project (Figure 33).


*Figure 35 Campaign for International Women in Engineering Day 2023*

Finally, in all proposed Special Sessions, we tried to include a female representative, but due to different circumstances, we did not completely succeed with this objective.

## 4.7 Deviations, Delays and Remedial Actions / Impact from COVID-19

The project has achieved all Deliverables and Milestones according to plan, as shown in section 4.

However, the COVID-19 restrictions have had a negative impact on the progress of TeraFlow activities, especially during P1. This was caused by the fact that hardly any of the partners could access their regular workplaces for many months, especially labs and development environments. Moreover, dissemination activities were online only or hybrid events with few attendees. By 2023 the situation had improved, and all project objectives were fulfilled.

## 4.8 Project Virtual Meetings and Other Key Events

Due to the COVID-19 pandemic, few face-to-face meetings could be organised within the project. To keep track of the project activities and ensure proper behaviour, the PM and TM decided to have a monthly regular plenary meeting and bi-monthly per WP-based meetings. Dedicated meetings have also been held as needed. Per-partner meetings have also been realised between PM, TM, and partners in order to address contributions properly.

Table 6 lists all major project meetings and conference calls during P2. Single WP meetings or side meetings between partners have also been held for specific topics and are not covered in the list.

*Table 7 Project virtual meetings and other key events during P2 period*

| Event | Date | Purpose | Participants |
|---|---|---|---|
| Plenary | 2022/01/14 | ETSI TeraFlow OSG, Review preparation, MS2.2, Release 2 features to be discussed in WP3 and WP4, Demo Status, Integration and release | All |
| Plenary | 2022/02/25 | ETSI TeraFlow OSG creation, Review preparation, MS2.2 | All |
| Plenary | 2022/04/22 | ETSI TeraFlow OSG, F2F Agenda, WP status | All |
| F2F BCN | 2022/05/24 and 25 | Scenario meetings, WP3, WP4 activities, WP6 planning | All |
| Plenary | 2022/07/08 | WP status, MS3.3, MS4.3 | All |
| Plenary | 2022/09/09 | 4$^{th}$ amendment, Milestone status, ToC for D2.2, D3.2, D4.2, D5.2, D6.3 | All |
| Internal Virtual Hackathon | 2022/09/27 and 28 | Scenarios' responsibility: Get scenarios running and generating KPIs into the monitoring component.<br><br>Fix the integration between the monitoring database and Grafana. | WP5 |
| Plenary | 2022/10/28 | New ammendment. MS2.2 delivered end of July, MS3.3 delivered, MS4.2 delivered, MS5.3: end of dec. TFS Release 2<br><br>WP and Deliverable status. | All |

| | | | |
|---|---|---|---|
| Plenary | 2022/11/25 | Focus on deliverable status | All |
| Plenary | 2022/12/16 | WP1 – 2023 dates, Deliverables,<br>WP6 activities | All |
| Plenary | 2023/01/27 | MS5.3 – release 2.0, WP1 – 2023 dates, Deliverables, WP6 activities | All |
| Internal Virtual Hackathon | 2023/02/08 and 09 | Scenario Status update, Possible venues for demonstration, Action points & next steps | WP5 |
| Plenary | 2023/03/24 | WP1, WP5, WP6 updates | All |
| Internal Virtual Hackathon | 2023/03/30 and 31 | collect metrics from the metrics collections framework | WP5 |
| Internal Virtual Hackathon | 2023/04/26 and 27 | Status of metrics collection framework in each component, Scenario updates, D5.3 status check, Creating dashboards | WP5 |
| Plenary | 2023/05/12 | Deliverable status | All |
| Plenary | 2023/06/23 | Deliverable status, review preparation | All |

# 5 Status of Deliverables and Milestones

The preparation of Deliverables has been monitored, and quality checks have been made. All project Deliverables and Milestones due in the reporting period have been reached. Details are given in Table 7.

*Table 8 Deliverable status – due in the reporting period*

| Deliv. Number | Deliverable Title | Lead beneficiary | Planned due date | Submitted | Comment |
|---|---|---|---|---|---|
| D1.1 | Management plan | CTTC | 28/02/21 | 25/02/21 | |
| D6.1 | Dissemination, Communication, Collaboration and Standardisation Plan | ATOS | 30/04/21 | 30/04/21 | |
| D1.2 | Quality assurance plan and data management guide | CTTC | 30/04/21 | 30/04/21 | |
| D1.5 | Data Management Plan | CTTC | 30/09/21 | 28/09/21 | |
| D2.1 | Preliminary requirements, architecture design, business models and data models | CTTC | 31/12/21 | 31/12/21 | |
| D3.1 | Preliminary evaluation of Life-cycle automation and high performance SDN components | UBITECH | 31/12/21 | 29/12/21 | |
| D4.1 | Preliminary evaluation of TeraFlow security and B5G network integration | NEC | 31/12/21 | 29/12/21 | |
| D5.1 | Testbed setup and prototype integration report | CHALMERS | 31/12/21 | 29/12/21 | |
| D6.2 | Market and business opportunities analysis and intermediate report on Dissemination, Communication, Collaboration, and Standardisation | ATOS | 31/12/21 | 31/12/21 | |
| D1.3 | First project periodic report | CTTC | 31/12/21 | 31/01/22 | Delay due to preparation of resource spending and effort deviations. |
| D2.2 | Final requirements, architecture design, business models and data models | TID | 31/12/22 | 31/12/22 | |
| D3.2 | Final evaluation of Life-cycle automation and high performance SDN components | UBITECH | 31/12/22 | 31/12/22 | |

| | | | | | |
|---|---|---|---|---|---|
| D6.3 | Exploitation Plan and Roadmap | ATOS | 31/12/22 | 31/12/22 | |
| D4.2 | Final evaluation of TeraFlow security and B5G network integration | UPM | 31/12/22 | 01/01/23 | |
| D5.2 | Implementation of pilots and first evaluation | CHALMERS | 31/12/22 | 16/01/23 | Final version of D5.1. Submitted with 16 days of delay. The delay is because the partners needed more time to review the document, due to the large amount of deliverables submitted at M24. This has benefited the document with improved quality. |
| D6.4 | Final report on Dissemination, Communication, Collaboration, Standardisation and Exploitation | ATOS | 30/06/23 | 30/06/23 | |
| D5.3 | Final demonstrators and evaluation report | CHALMERS | 30/06/23 | 07/07/23 | Delay to the large deliverable size. |
| D1.4 | Final project periodic report | CTTC | 30/06/23 | 15/07/23 | Delay due to preparation of resource spending and effort deviations. |

Table 8 gives an overview of the status of Milestones achievements due in the reporting period. All Milestone documents are available at: [TeraFlow Milestones](https://bit.ly/teraflow_milestones) (https://bit.ly/teraflow_milestones)

*Table 9 Milestone achievement – due in the reporting period*

| Mile-stone No. | Milestone Title | WP | Lead benefic | Planned due date | Achieved | Comments |
|---|---|---|---|---|---|---|
| 12 | Establish Web & social presence | 6 | ATOS | 28/2/21 | 26/2/21 | Small Report available as MS6.1 |
| 3 | Study of technical aspects of relevant SDN, | 3 | ATOS | 30/4/21 | 1/7/21 | Small report available as MS31. Delay was agreed with PO, due to the fact that the WP3 was not started by |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Cloud-native and SDO solutions | | | | | delivery date. This has no impact on the project plans, as it was an error in the proposal scheduling. |
| 1 | Initial use case definition, requirements and architecture for v1 | 2 | CTTC | 30/6/21 | 1/7/21 | Small report available as MS2.1. |
| 8 | Infrastructures, Continuous integration approach | 5 | CHALMERS | 30/6/21 | 5/7/21 | Small report available as MS5.1 |
| 4 | Code freeze for TeraFlowSDN WP3 components (v1) | 3 | UBITECH | 31/10/21 | 10/12/21 | Small report available as MS3.2. Delay to give more time to consolidate the internal data models and features that will be available for TeraFlow release 1. This extra time has allowed us to consolidate a better software product and has not limited the evolution of the project in any way. |
| 6 | Code freeze for TeraFlowSDN WP4 components (v1) | 4 | NEC | 31/10/21 | 10/12/21 | Small report available as MS4.1. Delay to give more time to consolidate the internal data models and features that will be available for TeraFlow release 1. This extra time has allowed us to consolidate a better software product and has not limited the evolution of the project in any way. |
| 9 | TeraFlowSDN v1 | 5 | ATOS | 31/12/21 | 31/01/22 | Integration has taken longer than expected. In order to plan a proper release, the schedule has been slightly moved. Small report available as MS5.2. |
| 2 | Update of use case requirements and architecture for TeraFlow v2, including feedback | 2 | TID | 30/06/22 | 35/07/22 | Small report available as MS2.2. It includes the analysed use cases, business models, requirements, received feedback, updated architecture and sequence diagrams between components to be used in TeraFlowSDN release 2. Small delay due to inclusion of more details and |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | | alignement of the protocol buffers and sequence diagrams (this will ease integration). |
| 5 | Code freeze for TeraFlow OS WP3 release components (v2) | 3 | UBI | 30/09/22 | 30/09/22 | Small report available as MS3.3. The final version of the core TeraFlowSDN components' protocol buffers. |
| 7 | Code freeze for TeraFlow OS WP4 components (v2) | 4 | UPM | 30/09/22 | 24/10/22 | Small report delivered to PO as MS4.2. Small delay due to a delay in feature implementation. We expected to recover the delay during integration. |
| 10 | TeraFlow OS v2 | 5 | ATOS | 31/12/22 | 01/02/23 | Small report delivered to PO as MS5.3. Small delay due to a delay in feature integration. Many bugs have been fixed in integration, so work for r2.1 has been advanced. |
| 11 | TeraFlow OS v2.1 | 5 | ATOS | 30/06/23 | 07/07/23 | Small report delivered to PO as MS5.4. Small delay due to the need of branch integration and verification of the release. |

# 6 Conclusions and Next Steps

The TeraFlow project has reached its conclusion, and several important lessons have been learned throughout its course. One significant challenge encountered was the difficulty of establishing a common way of working among different companies involved in the project. Despite this challenge, the project successfully utilized a reference project, such as OpenSource MANO (OSM), to guide its implementation and foster collaboration.

To ensure the sustainability of the TeraFlow ecosystem, efforts were made to establish a presence in Standards Development Organizations (SDOs) such as the Internet Engineering Task Force (IETF), Telecom Infra Project (TIP), and the European Telecommunications Standards Institute (ETSI). This involvement in SDOs allowed TeraFlow to contribute to developing standards and specifications, ensuring interoperability and industry-wide adoption.

The project recognized that while Software-Defined Networking (SDN) may have lost momentum, its foundational principles are crucial for successfully implementing emerging applications such as Zero-Touch Service Management (ZSM) and Automation. Therefore, exploring new business models that leverage SDN as a fundamental component is necessary.

The support from ETSI has been instrumental in the success of TeraFlow. The research and development work undertaken by the project has been remarkable, making a real impact in both SDOs and Open-Source Software (OSS) communities.

TeraFlow has also enhanced its visibility in research and industrial conferences. Numerous workshops, paper presentations, demonstrations, and booths have been organized to showcase the project's achievements and engage with the wider community. It is worth noting that the project was not significantly impacted by the COVID-19 pandemic, allowing it to continue its activities uninterrupted.

With the conclusion of the TeraFlow project, its legacy and ecosystem sustainability has been ensured. However, specific actions need to be taken in the future to build upon the project's achievements. One such action is incorporating TeraFlow solutions into other projects within the SNS (Service Network Systems) framework, with up to eight projects utilizing and further developing TeraFlow's work.

Additionally, there is a recognized need for a project focused on integration costs and further research work. This would enable the exploration of potential challenges and costs associated with integrating TeraFlow's solutions into existing network infrastructures while fostering continued research and innovation in the field.

# 7 References

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