SEMIoTICS

Deliverable D3.7: Software-Defined programmability for IoT Devices (Final)

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Acronyms Table

Acronym	Definition
ASIC	Application-Specific Integrated Circuit
CPU	Central Processing Unit
DoS	Denial of Service
DPDK	Data Plane Developer's Kit
FPGA	Field-Programmable Gate Array
BFT	Byzantine Fault Tolerance
IBC	In-Band Control Plane
OOBC	Out-Of-Band Control Plane
IoT	Internet of Things
IIoT	Industrial Internet of Things
KVM	Kernel-based Virtual Machine
LXD	Linux Containers
JSON	JavaScript Object Notation
FW	Firmware
LWM2M	Lightweight Machine-to-Machine
mW	Milliwatts
M2M	Machine-to-Machine
MCU	Micro Controller Unit
MQTT	Message Queuing Telemetry Transport
NETCONF	Network Configuration Protocol
NFV	Network functions virtualization
NFVO	NFV orchestrator
OFCONF	OpenFlow Configuration
OVSDB	Open vSwitch Database Management Protocol
ODL	OpenDaylight
POP	Point of Presence
QoS	Quality of Service
RO	Resource Orchestrator
SDN	Software-Defined Networking
SoS	System of System
SARA	Socially Assistive Robotic Solution for Mild Cognitive Impairment or mild Alzheimer's disease
SEMIoTICS	Smart End-to-end Massive IoT Interoperability, Connectivity and Security
SFC	Service Function Chaining
SLAM	Simultaneous Localization and Mapping
SPDI	Security, Privacy, Dependability, and Interoperability
SSC	SEMIoTICS SDN Controller
SSD	Solid State Disk
UC	Use Case
VIM	Virtualized Infrastructure Manager
VLAN	Virtual Local Area Network
VM	Virtual Machine
VNF	Virtual Network Function
vSwitch	Virtual Switch
VTN	Virtual Tenant Network
WoT	Web of Things

1 INTRODUCTION

The SEMIoTICS SDN Controller (SSC) is the centralized network intelligence responsible for mapping of Virtual Tenant Networks (VTNs) and Application Services (i.e., “connectivity patterns”) onto the underlying physical network topology. The SSC is furthermore aware of the network devices’ capabilities and resources.

The SSC is a typical example of a Network Operating System (NOS) to which the forwarding devices offload essential management and control tasks (i.e., path finding) to effectively decrease the data plane complexity and thus simplify the forwarding device costs. Contrary to specialized NOSs, which define the control plane of network devices and run independently of other NOS instances in the network, the SSC centralizes the NOS functions and provides a single logical entry point to the control plane.

The SSC aims to allow for centralized control plane manipulation of devices. It does so by configuring intelligently the forwarding tables (filters and FIBs) according to a pattern specification and the included SPDI and QoS properties and constraints. For the purpose of fault tolerance and high availability, it is capable of enforcing redundant paths, with respect to the up-to-date status of network topology. The global view of the topology and reservation states is leveraged in order to solve tasks where deployment of custom-tailored distributed protocol solutions might result in additional overhead and added complexity in the network. For example, centralized constraint-based routing based on actual network load allows for a higher degree of bandwidth utilization for guaranteed QoS, than the protocol-based approaches, which perform routing and reservation in sequence. Configuration of forwarding databases, queue and ingress policing are some additional management tasks that the SSC is responsible for. Furthermore, in its latest design iteration, SSC is tolerant against Byzantine failures (stemming from inconsistency of controller state or bugs) and is capable of in-band bootstrapping of arbitrary network topologies. In addition to QoS, the SSC thus implements a number of features necessary to provide industrial-grade operation.

In this deliverable, being the final output of Task 3.1 (“Software defined Aggregation, Orchestration and cloud networks”), we present the SSC architecture that encompasses the various functions required to fulfil the network-related requirements defined in WP2. To this end, in this deliverable:

- We present the high-level workflow of interactions between higher-layer instances of the SEMIoTICS architecture (Pattern Orchestrator) and the SSC.
- We reiterate on the network-specific requirements, required by various SEMIoTICS cases.
- We propose and discuss each of the controller functions necessary to realize the SEMIoTICS approach.
- We discuss the selected SSC components that have had additions to their basic functionality in SEMIoTICS or were developed from scratch, in exhaustive detail. Otherwise, we refer the reader to baseline introduced in related projects.
- We discuss the existing interfaces between the SSC and the data-plane forwarding devices.
- We compare the proposed architecture to the two state-of-art architectures, the generic OpenDaylight architecture and the project VirtuWind-specific SDN Controller solution [1].
- We analyze existing wireless communication technologies that could be used for communication with the IoT devices in SEMIoTICS use cases requiring radio access network.

The SEMIoTICS SDN Controller (SSC) is the centralized highly-available network control entity responsible of establishing isolated and QoS-enabling network services in both physical and virtual network topologies (i.e., in site-local and backend networks). To this end, SSC is enabled with an interface to parse SPDI pattern instance requests and is capable of evaluating and transforming the requests into network-specific configurations. To isolate the accessibility between end-points belonging to different tenants, SSC is capable of establishing Virtual Tenant Networks, i.e., a virtualized topology on top of the shared physical substrate.

1.1 SEMIoTICS approach – Networking Aspects

In the SEMIoTICS approach, network operators and end-points, via architectural patterns or directly via the controller's northbound interface, specify the required properties, derive network-related patterns or poll the network for statistics through abstracted and simplified northbound interfaces (NBIs) of the SSC. The SSC abstracts away the details of network configuration and the corresponding interface details by internalizing the decision making and enforcing the computed decisions upon network devices without user involvement in the process, thus supporting the semi-autonomous operation of the SEMIoTICS framework.

For the specified network-related patterns, the SSC executes the appropriate admission control and routing algorithms and automatically takes appropriate low-level actions to enforce the service requirements in the network. The SSC serves each communication service by manipulating the paths and allocating resources associated per service based on an abstract model of the network and its offered resources. The resulting configuration is then mapped to the realization method offered by each node that allows for configuration of a forwarding entry per service, including the associated resources.

The higher-level network management systems thus gain access to exposed functions (e.g. rule specification, overlay and tenant configuration) and monitoring APIs without needing to internally implement the technology-specific network logic - device-compatible southbound interfacing. Thus, moving the burden of network configuration from the management application to a centralized network controller.

The southbound interface technology plugins allow for interface-specific enforcement of technology-agnostic network functions. This is achieved by mapping of abstracted and generally valid configurations to low-level device- and technology-specific configurations. Thus, an administrator polling the forwarding database of a network device need not require knowing the exact technology at hand (e.g. a FIB status or OpenFlow [2] flow table database) in order to fetch the needed information.

Furthermore, the SSC is able to execute its core functions, e.g. topology database population, constrained path computation etc. in a generic manner, and map the results to any controlled network device using the corresponding technology plugin.

In case of an OpenFlow device, the OpenFlow technology plugin takes care of translation of generic controller computation results to a configuration compliant with the standardized OpenFlow data model. In addition, the non-OpenFlow data objects can be configured using a single flexible management protocol (e.g. NETCONF [3]) thus supporting standardized and extended information models, modeled using the IETF YANG language (e.g. [4]).

1.2 Logical link with WP2 beneficiaries – T2.3

The use case definitions in D2.2, as well as the extracted use case requirements described in D2.3 affect the WP3 tasks dealing with SDN and NFV, especially the ones dealing with networking requirements. Namely, these include:

- Network level requirements at the control plane level.
- Network level requirements at the data plane level.
- Domain specific networking requirements.

Thus, they provide an input for definition of controller functions in T3.1. We reiterate the networking-related requirements in Section 2. Furthermore, this deliverable provides the architectural input for the networking-related components described in D2.4, with each of the presented SDN Controller components being directly mapped to the architectural components of the SDN/NFV layer.

1.3 Logical link with WP3 beneficiaries – T3.3, T3.4

Task 3.2 discusses the role of the NFV-related management infrastructure and its interaction with the SDN Controller. Its output, i.e. deliverable D3.2, details the requirements of the exchange of Service Function Chains-related information between the MANO and the Controller, for the purpose of enabling the dynamic interconnection of the VIM-instantiated services at network layer at runtime.

Task 3.4 and the corresponding deliverable (D3.4) defines the initial design and specification of the network programming interfaces that enable the development, optimization and adaptation properties required for the SEMIoTICS framework to support the deployment of network services from all SEMIoTICS layers and its seamless interaction with IoT Applications, as specified by SPDI patterns. T3.3 and T3.4 furthermore detail the application relations, i.e., the field and cross-domain connectivity (IIoT Gateway to Backend) relevant for service profiling in the SSC, and the associated semantic descriptions and pattern-driven NBI specification facilitating interoperability.

Task 3.5 is an overarching integration/implementation task that aims to describe the integration path of the SSC in the generic SEMIoTICS middleware, as well as its implementation, comprising the networking toolkit.

1.4 Logical link with WP4 beneficiaries – T4.1

WP4 tackles the pattern-related approach examined by the project. This includes, among others, the development of patterns for orchestration of smart objects with guaranteed properties. Apart from security, privacy, dependability and interoperability-related (SPDI) patterns, we have observed the need for another category describing the connectivity-related pattern definition. Connectivity patterns are needed to express the need for enabling basic and fault-tolerant application relationship. While connectivity-related patterns are defined in T3.4 in detail, T4.1 presents the according pattern language and syntax, as well as the representative pattern definitions. WP4 will implement the Pattern Orchestrator component, that directly interacts with the SSC (and more specifically, the pattern engine component of the SSC) for the purpose of enabling the network connectivity between the specified application end-points.

1.5 Changes introduced in this deliverable compared to D3.1

As a core component, positioned between the SEMIoTICS backend/cloud (more specifically the Pattern Orchestrator) and physical forwarding data plane, the SSC is a complex piece of software. Thus, we have built and extended the SEMIoTICS controller based on the existing open-source and on the VirtuWind code base, instead of initiating an error-prone and costly from-the-scratch development. The overview of the existing implemented SSC components that were reused, and those that were developed from scratch / newly implemented is provided in Figure 5 and individual component sections in this document.

In the following, we summarize the most important content changes introduced in the final version of the T3.1 deliverable:

- **Pattern Engine Design and Implementation (Sec. 4.2):** To support pattern-model in specification of connectivity requirements, we have developed and integrated the Pattern Engine component in the SSC. Description of the functional scope and the final design of the Pattern Engine is presented in Sec. 4.2 and the newly added Sec. 4.2.2, respectively. Slight changes to other relevant modules of the controller were made to support the Pattern Engine interactions (i.e., that of Path Manager and VTN Manager), but they are limited to interface refactoring. To support the connectivity specific requirements and QoS properties, we have developed the support for patterns capable of requesting, enforcing and monitoring QoS-enabled connectivity. Details on the specification of the pattern-driven NBI enabling interactions with said Pattern Engine can be found in the corresponding final deliverable of T3.4, i.e. D3.10 (“Network-level Semantic Interoperability (final)”).
- **Enabling Byzantine Fault Tolerance in distributed SSC (Sec. 4.7):** The SSC’s Clustering Manager component was developed / extended from existing OpenDaylight-based release, in order to support Byzantine Fault Tolerance (BFT) approach to high availability of the controller instances. Section 4.7

now discusses the large overhead of control flow replication in current BFT solutions for SDN control plane that rely on redundant decision-making by multiple controller instances and subsequent agreement. In the newly added Section 4.7.2, we present the final design and implementation of Proof-of-Concept Byzantine Fault Tolerant SSC supported by P4-based in-data plane mechanisms. We showcase the resulting overhead minimization from using the proposed approach, which was experimentally validated in small-scale SEMIoTICS Use Case 1 network and in emulated data center and ISP networks. The resulting minimized control plane load showcases the scalability advantages of the BFT-enabled SSC compared to existing state-of-the-art BFT solutions.

  - *The newly developed design has been evaluated, peer-reviewed and accepted in the high-ranking flagship annual conferences ACM SIGCOMM 2019* [5] *and IEEE GLOBECOM 2019* [6].

- **Automated establishment of infrastructural Virtual Tenant Network (Sec. 4.3):** Enabling point-to-point connectivity in OpenDaylight and reference VirtuWind implementations requires manual or scripted specification of end-points to be interconnected by the network flows. This leads to significant manual effort and complexity, especially considering the high number of infrastructural services necessary by SEMIoTICS components in the field and backend layer that require such connectivity. To resolve this issue, we have implemented a feature of automated default VTN installation. Furthermore, an automated instantiation of network services for infrastructural network flows (e.g., for Thing Directory synchronization, IoT Gateway <-> Router <-> Internet flows) as required by the SEMIoTICS use cases to minimize the scenario deployment efforts, is now provided in the enhanced revision of the SEMIoTICS VTN Manager. These updated functionalities are described in the newly added Section 4.3.3.
- **Iterative Bootstrapping of an In-Band Control SDN**: Work within T3.1 also includes the design and development of a completely automated bootstrapping scheme for a multi-controller in-band network control plane resilient to link, switch, and controller failures. This scheme uses an incremental approach that circumvents distributed protocols executed in data plane, i.e., the (R)STP and, thus, minimizes the implementation complexity. The presented scheme is discussed in full detail in the newly added Section 4.1.3.
  - *The newly developed design has been evaluated, peer-reviewed and accepted in a high-ranking ACM SIGCOMM-sponsored conference ACM SOSR 2020 (Symposium on SDN Research). The presented bootstrapping design was since also published as open-source on GitHub: https://github.com/ermin-sakic/sdn-automated-bootstrapping*

1.6 PERT chart of SEMIoTICS

Figure 1 shows the positioning of T3.1 within the SEMIoTICS effort. Please note that the PERT chart is kept on task level for better readability.

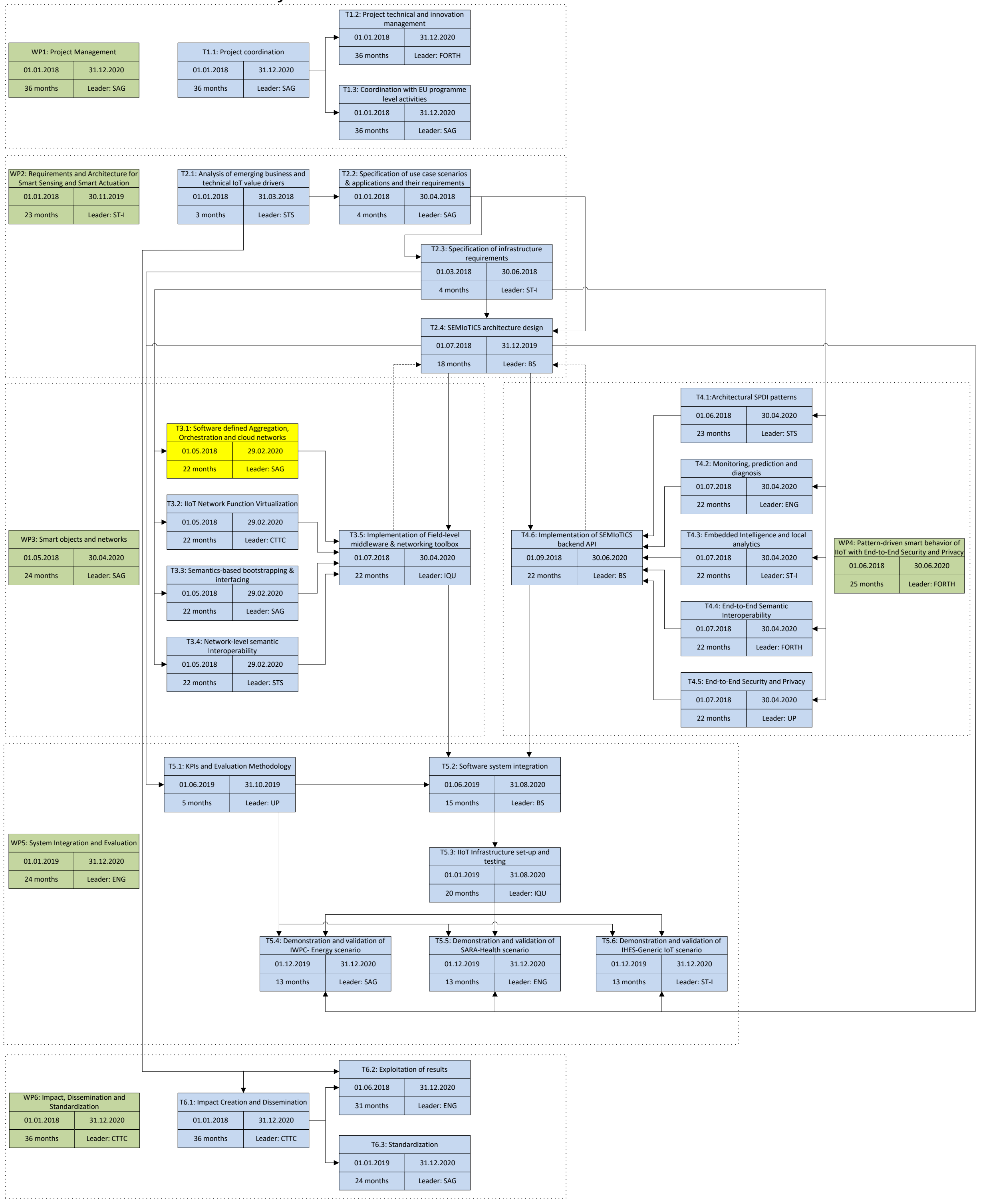

WP1: Project Management
01.01.2018
31.12.2020
36 months
Leader: SAG
T1.1: Project coordination
01.01.2018
31.12.2020
36 months
Leader: SAG
T1.2: Project technical and innovation management
01.01.2018
31.12.2020
36 months
Leader: FORTH
T1.3: Coordination with EU programme level activities
01.01.2018
31.12.2020
36 months
Leader: SAG
WP2: Requirements and Architecture for Smart Sensing and Smart Actuation
01.01.2018
30.11.2019
23 months
Leader: ST-I
T2.1: Analysis of emerging business and technical IoT value drivers
01.01.2018
31.03.2018
3 months
Leader: STS
T2.2: Specification of use case scenarios & applications and their requirements
01.01.2018
30.04.2018
4 months
Leader: SAG
T2.3: Specification of infrastructure requirements
01.03.2018
30.06.2018
4 months
Leader: ST-I
T2.4: SEMIoTICS architecture design
01.07.2018
31.12.2019
18 months
Leader: BS
T3.1: Software defined Aggregation, Orchestration and cloud networks
01.05.2018
29.02.2020
22 months
Leader: SAG
T3.2: IIoT Network Function Virtualization
01.05.2018
29.02.2020
22 months
Leader: CTTC
WP3: Smart objects and networks
01.05.2018
30.04.2020
24 months
Leader: SAG
T3.3: Semantics-based bootstrapping & interfacing
01.05.2018
29.02.2020
22 months
Leader: SAG
T3.4: Network-level semantic Interoperability
01.05.2018
29.02.2020
22 months
Leader: STS
T3.5: Implementation of Field-level middleware & networking toolbox
01.07.2018
30.04.2020
22 months
Leader: IQU
T4.6: Implementation of SEMIoTICS backend API
01.09.2018
30.06.2020
22 months
Leader: BS
T4.1:Architectural SPDI patterns
01.06.2018
30.04.2020
23 months
Leader: STS
T4.2: Monitoring, prediction and diagnosis
01.07.2018
30.04.2020
22 months
Leader: ENG
T4.3: Embedded Intelligence and local analytics
01.07.2018
30.04.2020
22 months
Leader: ST-I
WP4: Pattern-driven smart behavior of IIoT with End-to-End Security and Privacy
01.06.2018
30.06.2020
25 months
Leader: FORTH
T4.4: End-to-End Semantic Interoperability
01.07.2018
30.04.2020
22 months
Leader: FORTH
T4.5: End-to-End Security and Privacy
01.07.2018
30.04.2020
22 months
Leader: UP
T5.1: KPIs and Evaluation Methodology
01.06.2019
31.10.2019
5 months
Leader: UP
T5.2: Software system integration
01.06.2019
31.08.2020
15 months
Leader: BS
WP5: System Integration and Evaluation
01.01.2019
31.12.2020
24 months
Leader: ENG
T5.3: IIoT Infrastructure set-up and testing
01.01.2019
31.08.2020
20 months
Leader: IQU
T5.4: Demonstration and validation of IWPC- Energy scenario
01.12.2019
31.12.2020
13 months
Leader: SAG
T5.5: Demonstration and validation of SARA-Health scenario
01.12.2019
31.12.2020
13 months
Leader: ENG
T5.6: Demonstration and validation of IHES-Generic IoT scenario
01.12.2019
31.12.2020
13 months
Leader: ST-I
T6.2: Exploitation of results
01.06.2018
31.12.2020
31 months
Leader: ENG
WP6: Impact, Dissemination and Standardization
01.01.2018
31.12.2020
36 months
Leader: CTTC
T6.1: Impact Creation and Dissemination
01.01.2018
31.12.2020
36 months
Leader: CTTC
T6.3: Standardization
01.01.2019
31.12.2020
24 months
Leader: SAG

FIGURE 1: TASK 3.1 WITHIN THE SEMIOTICS PERT CHART

2 SEMIOTICS NETWORKING INFRASTRUCTURE REQUIREMENTS

The following subsections summarize the SDN-related requirements as defined in T2.3. The requirements can be abstracted into the main set of features of our controller:

- The SSC must enable flexible end-to-end QoS-enabled connectivity at any level of the infrastructure.
- The SSC should provide for a scalable control plane operation (i.e., the SSC should provide support for a large number of end-devices).
- Fault-tolerant SSC operation (including the defense mechanisms for enabling Byzantine Fault Tolerance) – the controller must be resistant against availability issues and Byzantine attacks for arbitrary amount of failures *F*.
- The SSC must abstract away the details of network control using the means of a northbound interface.
- The SSC must enable a secure access to all exposed interfaces of the controller.
- The SSC should support OpenFlow 1.3-based interactions with either virtualized or physical data-plane components.
- The SSC should expose an interface to the external VIM for the purpose of SFC specification and the corresponding functions for enforcement of the same.
- The SSC should provide for an automated establishment of basic infrastructure services requiring network connectivity (initial bootstrapping).

More details on the above are provided in the Tables below, aggregated as Control Plane, Data Plane and Domain-specific requirements. The Reference column links to the section providing more details on the method to handling the described requirement - often a component introduced in the SDN controller necessary to provide for the required functionality.

2.1 Control Plane Requirements

The following table portrays the control plane requirements fulfilled mainly by the SDN controller solution.

TABLE 1: NETWORK CONTROL PLANE REQUIREMENTS

Req-ID	Functional	Description	Req. level	Addressed in / Adressed by component
R.GP.1	Yes	End-to-end connectivity between the heterogeneous IoT devices (at the field level) and the heterogeneous IoT Platforms (at the backend cloud level)	MUST	Section 3.1.1 **Enabling components:** Pattern Engine, VTN Manager, Path Manager, Resource Manager, SFC Manager, SDN Data-Plane Devices

R.GP.2	Yes	Scalable infrastructure due to the fast-paced growth of IoT devices	MUST	Sections 3.1.1.1, 4.7 **Enabling components:** SDN Data-Plane Devices, overall SSC solution, Clustering Manger
R.GP.3	Yes	High adaptation capability to accommodate different QoS connectivity needs (e.g. low latency, reliable communication)	MUST	Section 4.4 **Enabling components:** Pattern Engine, VTN Manager, **Path Manager**, Resource Manager
R.GP.4	Yes	Detection of events requiring a QoS change and triggering network reconfiguration need by SPDI pattern	MUST	Section 4.2 **Enabling components:** Pattern Engine
R.GP.5	Yes	Interaction between SDN controller and IoT backend cloud through a dedicated interface (called northbound software interface)	MUST	Section 4.2 **Enabling components:** Pattern Engine
R.GP.6	Yes	Interaction between SDN controller and network nodes (e.g. switches, routers or IoT Gateways) through dedicated interface (called southbound software interface)	MUST	Section 4.5 **Enabling components:** Resource Manager
R.GP.7	Yes	SDN controller giving feedback for a future generation of SPDI patterns to avoid using the same pattern in case of failure	MUST	Section 4.2 **Enabling components:** Pattern Engine
R.S.2	Yes	Authentication and authorization of the stakeholders MUST be enforced by the Network controller, e.g. through access and role-based lists for different levels of function granularities (overlay, customized	MUST	Section 0 **Enabling components:** Security Manager

		access to service, QoS manipulation, etc.)		
R.S.7	Yes	The negotiation interface of the SDN Controller SHALL be secure against network-based attacks	SHALL	Section 0 **Enabling components:** Security Manager
R.NL.8 / R.BC.12	Yes	The VIM and Virtual Network frameworks must support Interfaces that enable VM tenant networking	MUST	Section 4.3.1 **Enabling components:** Virtual Tenant Network Manager
R.NL.9 / R.BC.13	Yes	Interface between the VIM and the SDN controller to allow VTN	MUST	Section 4.3.1 **Enabling components:** Virtual Tenant Network Manager
R.NL.1	Yes	Controller Node requirement: At least 6 CPU cores and 32 GB RAM	SHOULD	Trivial hardware requirement (i.e., not specifically discussed further in text).
R.NL.2	Yes	Controller Node requirement: At least 2 Network interfaces	SHOULD	Trivial hardware requirement (i.e., not specifically discussed further in text).
R.NL.3	Yes	Controller Node Requirement: Linux OS	MUST	Trivial software platform requirement (i.e., not specifically discussed further in text).
R.NL.4	Yes	Yes, Controller Node Requirement: Solid State Disk (SSD) of at least 1 TB	SHOULD	Trivial hardware requirement (i.e., not specifically

				discussed further in text).

2.2 Data Plane Requirements

The following table portrays the data plane requirement to be fulfilled by the SDN switches.

TABLE 2: NETWORK DATA PLANE REQUIREMENTS

Req-ID	Functional	Description	Req. level	Addressed in / Adressed by component
R.NL.7 / R.BC.10	Yes	Virtual Physical SDN Switch requirement: Support for OpenFlow v1.3 protocol or greater	SHOULD	Section 4.5 **Enabling components:** Trivial software platform requirement for switch implementation. OpenFlow v1.3 supported by Resource Manager.

2.3 Use Case-Specific Scenario Requirements

The following table portrays the use case-specific requirements to be fulfilled by the SDN components.

TABLE 3: DOMAIN-SPECIFIC SCENARIO REQUIREMENTS

Req-ID	Functional	Description	Req. level	Addressed in / Adressed by component
R.UC1.1	Yes	Automatic establishment of networking setup MUST be performed to establish end-to-end connectivity between different stakeholders	MUST	Section 3.1.1 **Enabling components:** Bootstrapping Manager, Pattern Engine, VTN Manager, Path Manager, Resource Manager, SFC Manager, SDN Data-Plane Devices
R.UC1.3	Yes	There MUST be enabled the definition of network QoS on application-level and automated translation into SDN controller configurations.	MUST	Section 4.4 **Enabling components:** Pattern Engine, Path Manager, Resource Manager
R.UC1.4	Yes	Network resource isolation MUST be performed for guaranteed Service properties – i.e. reliability, delay and bandwidth constraints.	MUST	Section 4.4

				Enabling components: VTN Manager, Path Manager
R.UC1.5	Yes	Fail-over and highly available network management SHALL be performed in the face of either controller or data-plane failures.	SHALL	Section 4.4 and 4.7 **Enabling components:** Path Manager, Clustering Manager
R.UC1.6	Yes	Decisions made by unreliable, i.e. faulty or malicious SDN controllers, SHALL be identified and excluded.	SHALL	Section 4.7.1 **Enabling components:** Clustering Manager
R.UC1.7	Yes	The operation of the SDN control SHALL be scalable to cater for a massive IoT device integration and large-scale request handling in the SDN controller(s) using a (near-) optimal IoT client – SDN controller assignment procedure.	SHALL	Section 4.7.1 **Enabling components:** Clustering Manager**.** Overall SSC solution is scalable. However, due to Clustering being the largest scalability bottleneck, we focused on enhancing its design in Deliverable D3.7.
R.UC2.3	Yes	The SEMIoTICS platform SHOULD guarantee proper connectivity between the various components of the SARA distributed application. The SARA solution is a distributed application not only because it uses different cloud services (e.g. AREAS Cloud services, AI services) from different remote computational nodes, but also because the SARA application logic itself is distributed across various edge nodes (SARA Hubs). The following diagram shows the components of the SARA system:	SHOULD	Section 3.1.1 **Enabling components:** Pattern Engine, VTN Manager, Path Manager, Resource Manager, SFC Manager, SDN Data-Plane Devices
R.UC2.15	No	The SEMIoTICS platform SHOULD provide low latency connectivity between the SARA hubs and cloud services (i.e. AREAS cloud services and AI services) to allow offloading of near real-time computation intensive tasks to the cloud. Examples include: • the robotic assistant (RA) employing AI services to analyse Patient's speech (audio) and body language (video) to identify significant events – e.g. "Patient requests an escort", "Patient asks where his glasses are • the robotic rollator (RR) exploiting AI Services to analyse Patient's gait and posture to identify significant events – e.g. "Patient has fallen”.	SHOULD	Section 4.4 **Enabling components:** Path Manager

		• mobile robotic Devices (RA/RR) exploiting cloud resources for simultaneous localization and mapping (SLAM) Therefore, SARA hubs need to send with minimal delay: • raw range data (e.g. from Lidar sensors) to identify proximal objects/objects, • real-time audio stream for speech analysis, • and real-time raw video stream (object/people recognition, gesture recognition, posture analysis).		
R.UC2.17	No	The SEMIoTICS connectivity SHOULD support real time exchange of raw sensor data among sensors/actuators and SARA Hubs.	SHOULD	Section 4.4 **Enabling components:** Path Manager

3 SEMIOTICS NETWORK CONTROLLER ARCHITECTURE

The architecture proposed by SEMIoTICS relies on a set of virtualized services that allow the secure and reliable transport of sensor data from field devices towards their final destination for processing or storage. Such final destinations are subject to applications' requirements, e.g.: bounded latency; are satisfied by "smart" path planning and embedding of network paths so that the application requirements are fulfilled. The virtualization dimension also includes dynamically and securely instantiating Virtual Network Functions (VNFs) at appropriate locations in the SEMIoTICS architecture (e.g.: at IoT Gateways, network layer, or the backend cloud), so to fulfil the low latency and storage requirements of the application. In light of such a dynamic network environment, the need for a centralized control of the whole network (physical and virtual) is paramount.

Similarly, obliging to industrial applications' requirements in terms of a deterministic upper bound end-to-end latency, high reliability of the application flows, is simplified through the centralization of the network view and serialization of configuration changes decisions. SDN Controller thus must internalize the path finding algorithms and configuration capabilities to serve the flows.

In an SDN framework, the SEMIoTICS SDN Controller (SSC) employs a set of Southbound interfaces (SBI) for configuring network devices (such as NETCONF or OF-CONFIG), and to control such devices' forwarding table (using protocols like OpenFlow). As network devices boot-up, they reach for the controller in order to register the devices for configuration and forwarding table modifications. After this process is finished, the SSC establishes a complete, centralized view/control of the network, whose topology may be visualized employing the SSC's northbound interfaces (usually RESTful APIs).

Physical Network Functions (PNFs) in the SEMIoTICS architecture, such as the IIoT Gateway, as well as the switches and routers at the Field and Network layers, are equipped with compute and storage resources, which, in combination with the Backend-Cloud's resources, are managed and exposed by the Virtual Infrastructure Manager (VIM). These devices and their resources may be used for the spin-off of VNF (like virtual switches, routers, firewalls, load balancers, processing or storage endpoints), and are (virtually) connected together in the form of VNF Forwarding Graphs (VNF-FG) to offer network services. Such connections are achieved by virtual network overlays (or Virtual Tenant Networks (VTN)) built by the SSC on top of the underlying physical network infrastructure. In order to provide a network service, the VIM and the SSC share a common VNF-FG. As the VIM spins-off VNFs (e.g., virtual switches) and specifies how these should be connected together, the SSC modifies the forwarding table of the appropriate VNFs in order to ensure secure and reliable communication of the whole VNF-FG.

The remainder of the section details the role of the SSC in the SEMIoTICS architecture, as well as its functionality exposed to the NFV Management and Orchestration framework.

3.1 Role of the SDN Controller in SEMIoTICS Architecture

Mainly driven by the explosion of the cloud technologies, networking is again returning to a more centralized model. For decades, network protocols such as Open Shortest Path First (OSPF), Border Gateway Protocol (BGP), Routing Information Protocol (RIP), or Spanning Tree Protocol (STP) have worked on top of the premise that "no entity has a complete view of the network". This fact significantly stirred the design of networks and protocols.

Software Defined Networking (SDN) seeks to disaggregate the control and data planes[1]. In this approach, a central control plane, i.e. SDN Controller, is endowed with a complete view of the network. This attribute

[1] Which previously resided inside network devices. Cross compatibility is ensured by following standardized protocols.

dramatically changes the way networks are now conceived, transitioning to SDN networks composed of a single SDN Controller[2] and many bare-metal SDN-enabled forwarding devices.

This section describes the role of the SSC in the SEMIoTICS architecture, including its physical location in the SEMIoTICS topology, and how it achieves data plane control through the control plane.

3.1.1 SDN CONTROLLER POSITIONING IN THE SEMIOTICS ARCHITECTURE

The SDN components in the context of SEMIoTICS use-cases include the control and data plane counterparts, comprising:

- The SEMIoTICS SDN Controller (SSC) as the main point of logic computation and data planes rules configuration
- Data Plane components, i.e. physical or virtual switches with an interface exposing APIs for controller-based reconfiguration.

The deployment of the SSC is expected in the Network Layer, i.e., at the site-level backbone. Thus, the SSC manages the ingress and egress connections stemming at field level. The data-plane devices, i.e. the switches are available both at Network and Field Layer, with a particular subset of devices available in either Network Layer only (serving as a gateway for external connections), or both in field and network layer, for setups requiring more than a single Layer 2 domain and thus having higher scalability requirements.

While topology-agnostic, the SSC is expected to operate on a multi-ring network or partial mesh topologies, offering support for disjoint path establishment and thus fault-tolerance for critical services in the face of data-plane failures. A topology depicted in Figure 2 depicts an exemplary fully-meshed network layer, tolerant against both link and switch failures, also highlighting data and control plane connections.

Summarized, the controller manages the ingress and egress connections stemming at field level, targeting both other field level devices as destinations or remote sinks located in cloud / backend layer. By providing the generic and QoS-constrained connectivity, controller addresses the R.GP.1, R.UC1.1 and R.UC2.3 requirements. In the remainder of the document we discuss the individual development plan for functions of the controller, comprising the capabilities necessary to enable the connectivity requirement.

3.1.1.1 ACHIEVING GLOBAL CONTROL OF THE NETWORK FROM A CENTRALISED SDN CONTROLLER

There are two main ways in which an SSC manages the underlying fabric namely, directly or via network overlays [7]. The former consists of the SSC directly communicating with SDN-enabled switches via southbound interfaces (SBI) such as OpenFlow [2], NETCONF [3], OVSDB, OpFlex, and others. These SBIs allow the controller privileged access to the devices' forwarding tables, as well as other device configurations per se. This method is the one used by most popular off-the-shelf controllers i.e.: ODL; and its variation SSC which is to be developed in SEMIoTICS. The latter method uses encapsulation protocols (e.g.: VXLAN, NVGRE, IPSEC) on top of conventional networks[3] to build the desired network topologies. Even though it is debatable whether overlays are SDN or not, they are indeed software defined[4].

[2] High-Availability (HA) clusters may host a single logical SDN Controller instance with multiple dislocated replicated instances.
[3] By conventional it is meant that there exists L2 or L3 connectivity among components of the network.
[4] In fact, Virtualized Infrastructure Managers (VIM, e.g.: OpenStack) employ an SDN Controller and overlays to provide private tenant networks.

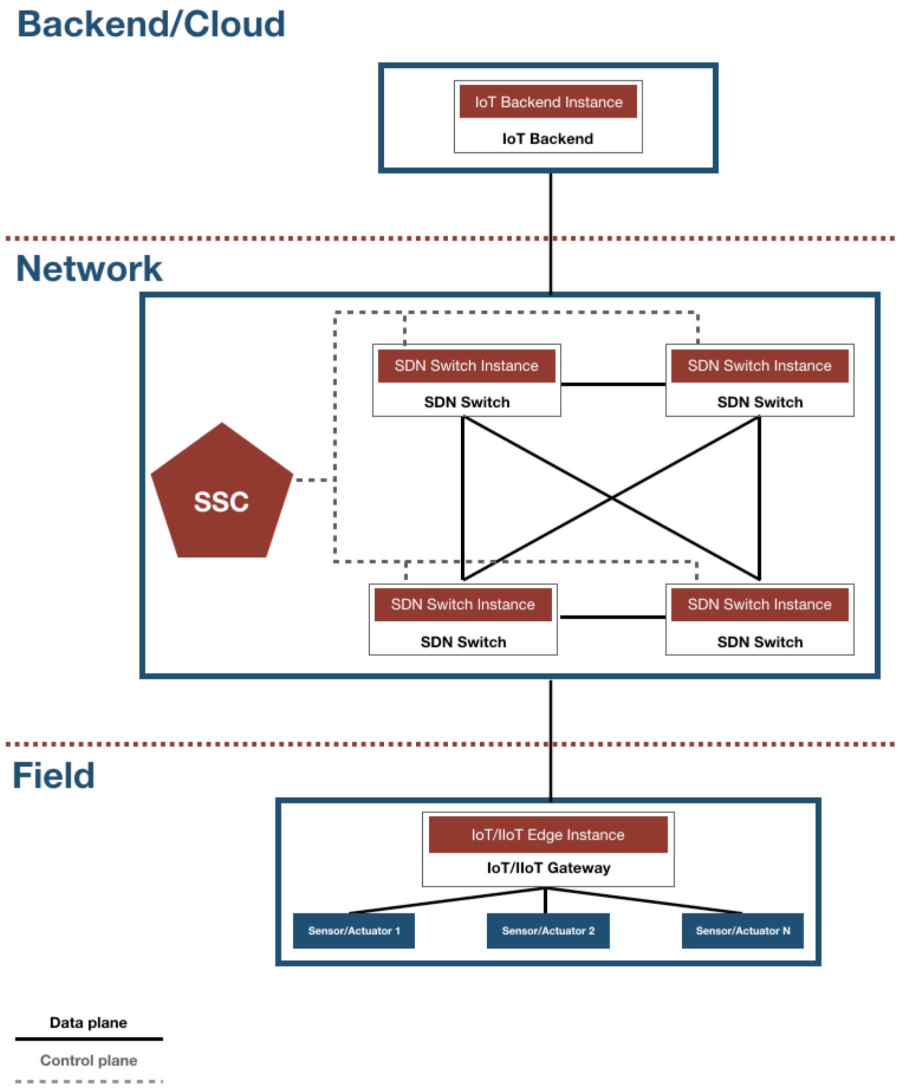


FIGURE 2: INSTANCE OF THE SEMIOTICS ARCHITECTURE DEPLOYMENT VIEW

Regardless of the SDN Controller vendor, there are core features that must be supported by an industrial variant of an SDN Controller. A non-exhaustive description of these is provided below and [7]:

- Data plane programmability: change the way flows are forwarded, apply filters, or dynamically changing packet headers. Via northbound interfaces control information concentrated at the SDN Controller could be accessed/changed by SDN Applications. Such applications may then use such information to apply templates that effectively change the network configuration, e.g.: satisfy bandwidth constraints, QoS enforcement, forward through least expensive paths, and so on.

- Southbound protocol support: the most widely used southbound protocol is OpenFlow. An SDN Controller should be able to interact with OpenFlow agents (or other southbound protocol) in SDN-enabled forwarding devices in order to control the different actions to be performed while forwarding.
    - As mentioned previously, OpenFlow is not the only protocol supported by ODL as SBI. NETCONF, OVSDB and SNMP are some of the other alternatives [8, 7].

- External API support: to ensure it could be used within various cloud orchestration environments, e.g.: OpenStack. Through well specified APIs, network policies exchange is realized, allowing the control of the networking resources of a virtual infrastructure.

- Centralization: allowing administrators a complete view of the network. It should also support discovery protocols so new network devices are registered and bootstrapped if necessary.

- Performance: as network devices rely on the SDN Controller for handling incoming flows not contained in the current flow table, controllers should ensure such requests are handled as fast as possible, otherwise the SDN Controller is prone to become a network bottleneck.

- High Availability and Scalability: the ability to work as a cluster allows an SDN Controller to expand its performance and availability by adding more controller nodes and load balancers.

- Security: as the functioning of the network depends on the SDN Controller, it should be capable of authenticating/authorizing members of the network while performing intrusion detection and prevention, e.g.: secure southbound channels, encryption.

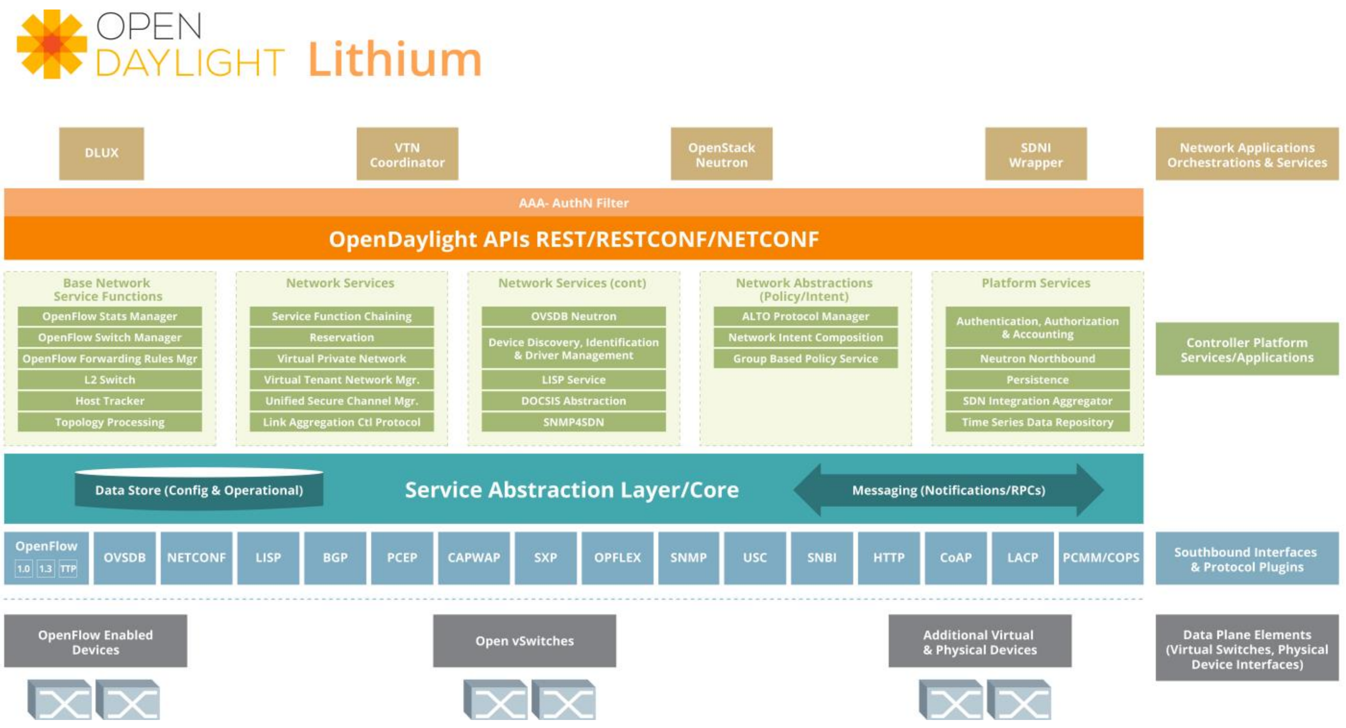

OPEN DAYLIGHT Lithium
DLUX
VTN Coordinator
OpenStack Neutron
SDNI Wrapper
Network Applications Orchestrations & Services
AAA- AuthN Filter
OpenDaylight APIs REST/RESTCONF/NETCONF
Base Network Service Functions
OpenFlow Stats Manager
OpenFlow Switch Manager
OpenFlow Forwarding Rules Mgr
L2 Switch
Host Tracker
Topology Processing
Network Services
Service Function Chaining
Reservation
Virtual Private Network
Virtual Tenant Network Mgr.
Unified Secure Channel Mgr.
Link Aggregation Ctl Protocol
Network Services (cont)
OVSDB Neutron
Device Discovery, Identification & Driver Management
LISP Service
DOCSIS Abstraction
SNMP4SDN
Network Abstractions (Policy/Intent)
ALTO Protocol Manager
Network Intent Composition
Group Based Policy Service
Platform Services
Authentication, Authorization & Accounting
Neutron Northbound
Persistence
SDN Integration Aggregator
Time Series Data Repository
Controller Platform Services/Applications
Data Store (Config & Operational)
Service Abstraction Layer/Core
Messaging (Notifications/RPCs)
OpenFlow
1.0
1.3
TTP
OVSDB
NETCONF
LISP
BGP
PCEP
CAPWAP
SXP
OPFLEX
SNMP
USC
SNBI
HTTP
CoAP
LACP
PCMM/COPS
Southbound Interfaces & Protocol Plugins
OpenFlow Enabled Devices
Open vSwitches
Additional Virtual & Physical Devices
Data Plane Elements (Virtual Switches, Physical Device Interfaces)

FIGURE 3: OPENDAYLIGHT SDN CONTROLLER PLATFORM [8]

Modern SDN Controllers, such as OpenDaylight (ODL), are built following a modular architecture (see Figure 3). Each independent module could leverage services exposed by other modules in order to provide composite functionality. Focusing on the configuration of the data plane, the following details the most relevant southbound protocol modules implemented by ODL (or Southbound Interfaces and Protocol Plugins, as referred to at the bottom of Figure 3), which must also exist in SEMIoTICS SDN Controller:

- **NETCONF:** ODL supports communication with NETCONF servers at SDN-enabled forwarding devices. Additionally, this module may work as a NETCONF server itself in order to expose Control plane information to external entities, e.g.: SDN applications.

- **OpenFlow:** Enables the SDN Controller to configure the flow table of OpenFlow enabled SDN devices remotely. OpenFlow Library allows the SDN Controller to listen for OpenFlow messages (spawns a daemon), as well of supporting multiple OpenFlow versions.
- **OVSDB:** It is used for managing[5] OVS-enabled switches (physical or virtual). OVS [9] is an open-source software that implements virtual switching that is interoperable with almost all popular hypervisors. OVS uses OpenFlow to perform message forwarding in the control plane for both virtual and physical ports. OpenDaylight's OVSDB southbound plugin manages OVS devices supporting OVSDB schema and the OVSDB management protocol,
- **SNMP4SDN:** This module allows ODL to interact with SNMP-enabled switches. It uses SNMP methods for writing forwarding as well as configuration information into the devices.

Previously mentioned SBI establish communication through the control plane (see Figure 2). One module or a combination of these are required for effective SDN-enabled device configuration in SEMIoTICS. In the remainder of the document, we assume the OpenFlow-connector as the only fully required protocol in SEMIoTICS use cases.

Modern SDN controllers (i.e., ODL) are equipped with an east-westbound connectivity, allowing for multi-controller-based interaction when establishing connections across multiple administrative domains. By separating network control into multiple administrative domains, higher scalability of the overall system can be supported, due to individual controllers experiencing a lower load on average, than when controlling all devices in a single domain. By extending an OpenDaylight based platform, SSCremains compatible with the east-westbound implementations and thus enables the scalability requirement R.GP.2.

3.1.1.2 ACTING UPON NETWORK STATE AND SERVING NETWORK STATE INFORMATION

To showcase the internal state handling and algorithms internalized in the centralized controller, we list below the scenario of pre-configuration, network bootstrapping and a trivial connectivity pattern evaluation and its enforcement; these are also depicted in the Figure 4.

Startup Phase: The user pre-configures the controller and forwarding devices, i.e., using a configuration file, with the set of IP addresses and executes the boot up procedure. Additional, security related actions are executed by the user, including the roll-out of public certificates to switches associated with the allowed controller instances. Optionally, the devices are capable of executing the DHCP/DHCPv6/SLAAC bindings and autonomously receiving and applying a discovered IP address, instead of the manual configuration.

Default Bootstrapping Phase: SSC must discover the devices in its network, i.e., the switches using the OpenFlow discovery protocol, SNMP LLDP MIB crawling or similar bootstrapping mechanism. Following the discovery and establishment of control session, the controller listens for incoming packets from end-devices (hosts), e.g., the IIoT Gateway, SCADA application etc. and updates its host database with the corresponding attachment points behind which the hosts are located. The SSC then proceeds to install the required flow rules, so to enable basic infrastructural services, i.e., a network connection between the IIoT Gateway and backend, in order to provide for a possibility of IIoT Gateway to report its status and the capabilities of its field devices (i.e., sensors and actuators) in the Thing Directory in the Backend (please refer to Deliverable D3.3).

Runtime Phase: SSC is capable of accepting pattern rules specified as a set of properties, encompassed in invariants, that describe the intent which is to be fulfilled by the underlying data substrate. The SSC accordingly processes the patterns posted as REST requests, in Drools format, at its northbound interface and validates the viability of its enforcement in the internal modules. For example, a controller might be requested with a pattern necessitating and end-to-end flow embedding in a higher-than-best-effort service class, i.e., with specific bandwidth and delay requirements.

[5] View, create, modify, and delete.

To adhere to the rule specification, the controller internally evaluates the topology state for a path that would fulfill the named criteria, i.e., using a combination of routing algorithms, designed to consider a set of constraints (including delay and bandwidth) [10]. If the connectivity is possible given the current amount of resources, the controller propagates the enforcement request for individual flow rules to the lower-level southbound interface (i.e., the OpenFlow plugin). The OpenFlow plugin is then in charge of sending the according flow modification messages to the corresponding data plane switches.

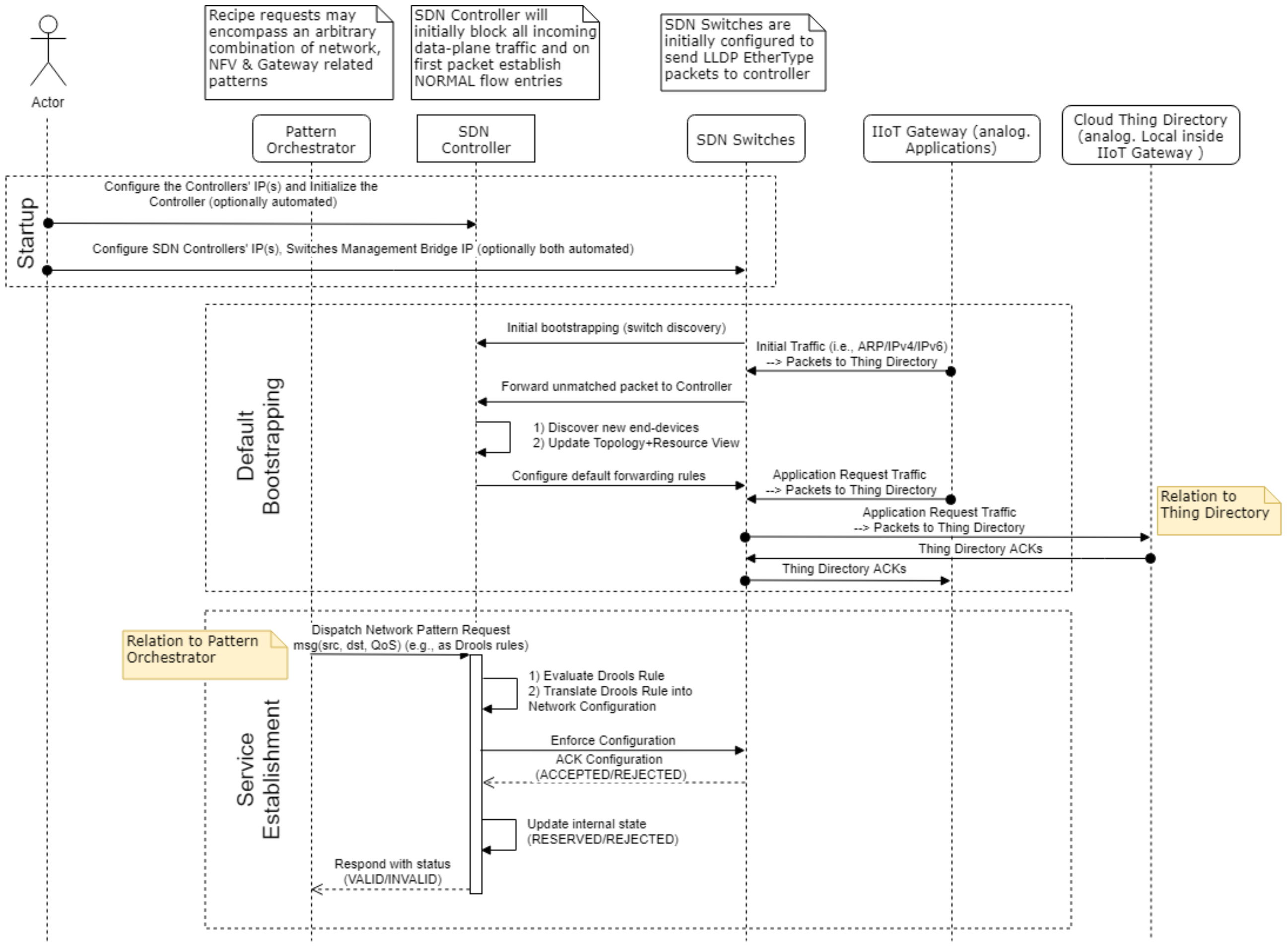

Actor
Recipe requests may encompass an arbitrary combination of network, NFV & Gateway related patterns
SDN Controller will initially block all incoming data-plane traffic and on first packet establish NORMAL flow entries
SDN Switches are initially configured to send LLDP EtherType packets to controller
Pattern Orchestrator
SDN Controller
SDN Switches
IIoT Gateway (analog. Applications)
Cloud Thing Directory (analog. Local inside IIoT Gateway)
Startup
Configure the Controllers' IP(s) and Initialize the Controller (optionally automated)
Configure SDN Controllers' IP(s), Switches Management Bridge IP (optionally both automated)
Default Bootstrapping
Initial bootstrapping (switch discovery)
Initial Traffic (i.e., ARP/IPv4/IPv6) --> Packets to Thing Directory
Forward unmatched packet to Controller
1) Discover new end-devices
2) Update Topology+Resource View
Configure default forwarding rules
Application Request Traffic --> Packets to Thing Directory
Application Request Traffic --> Packets to Thing Directory
Relation to Thing Directory
Thing Directory ACKs
Thing Directory ACKs
Relation to Pattern Orchestrator
Service Establishment
Dispatch Network Pattern Request msg(src, dst, QoS) (e.g., as Drools rules)
1) Evaluate Drools Rule
2) Translate Drools Rule into Network Configuration
Enforce Configuration
ACK Configuration (ACCEPTED/REJECTED)
Update internal state (RESERVED/REJECTED)
Respond with status (VALID/INVALID)

FIGURE 4: THE ABSTRACTED WORKFLOW OF BASIC SYSTEM INITIALIZATION, BOOTSTRAPPING AND PATTERN ENFORCEMENT IN THE SEMIOTICS SDN CONTROLLER

3.1.2 PATTERN ENFORCEMENT USING A LOCAL PATTERN ENGINE

Pattern Enforcement is used to find or verify suitable paths in order to pre-plan and reserve paths with respect to the SPDI properties. After evaluating the available network components and flows, SPDI patterns are executed to realize the verification process where new paths can be inserted (i.e. add the required flow rules), removed (i.e. delete flow rules) or modified (post flow rules) in the controller and consequently in the programmable switches. The patterns are used not only for the verification of network paths but also at runtime i.e., following a network link failure or when a SPDI property is not guaranteed, to reconstruct or restore required SPDI properties when such properties have been violated.

These features are part of the SEMIoTICS efforts towards multi-layered embedded intelligence, focusing on the network layer and enabling the semi-autonomous operation of the network based on reasoning upon pre-defined pattern rules.

3.1.3 NETWORK OVERLAYS SUPPORTING NFV: SDN AND NFV FROM THE SDN CONTROLLER'S PERSPECTIVE

VNFs are seen as virtual counterparts of physical switches, routers, firewalls, load balancers, IDS, IPS, and so on. As opposed to conventional Physical Network Functions (PNF), VNFs bring significant reductions in the total cost of the infrastructure, mainly because from a set of fairly generic hardware (i.e.: data center) many VNF can be spawned, used and terminated; effectively creating customized network services when needed, and freeing their used resources when terminated.

As hinted previously, infrastructure flexibility is one of the most relevant features provided by Network Functions Virtualization (NFV) [11] (either at the compute, storage or networking level), and network overlays play a crucial role in network virtualization. Through overlays, the SDN Controller is able to create different network topologies for each project, dubbed VTNs, which are effectively isolated from each other.

Specifically, in purely virtualized networking environments (i.e., in Backend layer networking), we rely on instantiation of network services, including the VTNs, as well as the actual end-point VNFs using a single interface, i.e. a single Network Service Description (NSd files). This is in contrast to field layers of infrastructure, that may have to rely on controlling physical SDN infrastructure, as well as establishing communication flows between non-virtualized end-points, such as programmable logical controllers and field sensors. There, specification of virtual tenant networks is explicit, at the level of VTN Manager SSC's component.

ODL (the reference SDN Controller for SEMIoTICS) is equipped with a VTN module for interfacing with Virtualized Infrastructure Managers (VIM) such as OpenStack [8]. The ODL's VTN module is a policy manager that registers any tenant resource in the VIM via ODL's ML2 plugin[6], so any tenant configuration modification at the VIM is reflected in ODL, too. That is, by analyzing the information gathered for each tenant (network topologies, VNFs, MAC, IPv4 addresses, and so forth), VTN is able to replicate such policy[7] using the VIM's exposed networking APIs and ODL's SBIs.

Service Function Chains (SFC) are a particular case for policy enforcement. SFC specifies the order of PNFs/VNFs packets should flow through in order to provide a Network Service (NS). ODL is equipped with an SFC module which feeds from control information (including VTN received from the VIM) and builds flow policies to handle the sequence of VNFs a specific flow should go through. It includes the following components:

- Classifier: selects flows for traversing a specific SFC based on a flow match policy.
- Service chain: refers to the list of devices the matched flow should traverse.
- Service path: the actual VNF instances traversed.
- Service overlay: a topology created to visualize the service path.
- Metadata: information passed between service functions.

The SFC is also able to receive SFC designs/recipes via an exposed northbound API.

[6] The ML2 plugin was created for ODL-OpenStack integration. It passes all OpenStack's Neutron API calls to ODL's VTN manager via REST calls [4].
[7] I.e. What nodes should be able to communicate with which ones.

3.1.3.1 ACHIEVING DATA TRANSPORT LEVERAGING VIRTUAL NETWORK FUNCTIONS

NFV and SDN are the key enablers of interconnected virtual functions. The virtualized application elements for each UC are conceived as VNFs instantiable by the Virtual Infrastructure Manager (VIM) on top of a NFV infrastructure. Networking for both these virtual and physical application functions is provided in the form of overlays handled by the SDN Controller, while VNF instantiation and lifecycle management[8] is handled by the NFV Orchestrator. Table 4 provides an overview of requirements relying specifically on interaction or depending on SDN/NFV function calls and discusses our method of handling the requirement.

TABLE 4: UC2 NETWORK REQUIREMENTS (SARA HEALTHCARE)

Req-ID	General Description	Specific NFV/SDN Requirements	Reference / Enabled by
R.UC2.1	The SEMIoTICS platform SHOULD support time- and safety-critical requirements by allowing SARA application logic to be deployed on resource-constrained edge gateways (e.g. smartphones, vehicles, mobile robots). SEMIoTICS platform functionalities SHOULD be locally available even in case of failure of communication with the SEMIoTICS cloud nodes.	IIoT devices MUST support virtualization and MUST be reachable by NFV MANO components. Furthermore, the topology supporting the UC MUST be expressed in form of a NFV MANO-compatible network service via the corresponding descriptors.	While the first requirement on generic connectivity is discussed throughout this document, the fulfilment and the format of the network service specification (using NSd – networking service descriptors) is detailed in Deliverable D3.2.
R.UC2.2	The SEMIoTICS platform SHOULD support the SARA solution to manage the trade-off between different requirements (e.g. reliability, power consumption, latency, fault-tolerance) by allowing both SARA application logic and platform features to be distributed over a cluster of gateways (SARA Hubs).	VNF network overlays MUST exist among SARA Hubs.	The fulfilment of this requirement is enabled by Virtual Tenant Network instantiation, as described in Section 4.3.1 and to more extent in Deliverable D3.2. **Enabling components:** VTN Manager.
R.UC2.3	The SEMIoTICS platform SHOULD guarantee proper connectivity between the various components of the SARA distributed application. The SARA solution is a	VNF network overlays MUST exist among SARA Hubs. Achieving the network overlays is to be done by use of Virtual Tenant Network instantiation using the VTN Manager component of the SDN Controller.	The fulfilment of this requirement is enabled by Virtual Tenant Network instantiation, as described in Section 4.3.1.

[8] Including scaling in or out.

	distributed application not only because it uses different cloud services (e.g. AREAS Cloud services, AI services) from different remote computational nodes, but also because the SARA application logic itself is distributed across various edge nodes (SARA Hubs).		**Enabling components:** VTN Manager.
R.UC2.5	The SEMIoTICS platform should allow the SARA solution to discover the IoT devices that are registered in the system. IoT devices deployed by the SARA solution are expected to register themselves into the system using various standard protocols (e.g. LwM2M, MQTT, Bluetooth LE, ZigBee, etc.).	SARA components handling the registration of devices, and supported IoT devices MUST be located in the same VTN.	The fulfilment of this requirement is enabled by allocating the SARA devices in a single Virtual Tenant Network. **Enabling components:** VTN Manager.
R.UC2.15	The SEMIoTICS platform SHOULD provide low latency connectivity between the SARA hubs and cloud services (i.e. AREAS cloud services and AI services) to allow offloading of near real-time computation intensive tasks to the cloud. Examples include: • the robotic assistant (RA) employing AI services to analyse Patient's speech (audio) and body language (video) to identify significant events – e.g. "Patient requests an escort", "Patient asks where his glasses are • the robotic rollator (RR) exploiting AI Services to analyse	The SDN Controller SHOULD be able to modify the path followed by packets from this UC VTN if necessary. Such modifications seek to reduce end-to-end delay and comply with UC constraints.	The fulfilment of this requirement is enabled by path computation that is aware of QoS constraints on the resulting identified paths, as discussed in more detail in Section 4.4. **Enabling components:** Path Manager, SFC Manager.

	Patient's gait and posture to identify significant events – e.g. "Patient has fallen". • mobile robotic Devices (RA/RR) exploiting cloud resources for simultaneous localization and mapping (SLAM) Therefore, SARA hubs need to send with minimal delay: • raw range data (e.g. from Lidar sensors) to identify proximal objects/objects, • real-time audio stream for speech analysis, • and real-time raw video stream (object/people recognition, gesture recognition, posture analysis).		

TABLE 5 UC3 NETWORK REQUIREMENTS (AI SENSOR FOR EVENT DETECTION)

Req-ID	Description	Specific NFV/SDN Requirements	Reference / Enabled by
R.UC3.6	MCU into IoT Sensing unit should be associated with a high-level tool for automatic generation of optimized code to support pre trained neural networks.	There MUST be network connectivity among components (UC components may reside in the same VTN). Such components may be VNFs on top of IIoT Gateways, or PNFs.	The fulfilment of this requirement is granted by providing generic connectivity property by the networking infrastructure, as discussed in Section 3.1. **Enabling components:** Pattern Engine, VTN Manager, Path Manager, Resource Manager, SFC Manager, SDN Data-Plane Devices
R.UC3.7	MCU IoT Sensing unit shall be able to send change detection and signal local changes / anomalies to IoT Sensing gateway.		
R.UC3.14	The specific M2M protocol adopted on UC3 is based on MQTT. A MQTT broker	An MQTT broker MUST exist within this VTN in order to support MQTT.	The fulfilment of this requirement is enabled by interconnecting an MQTT

	service will be available to dispatch messages between the coordinating Sensing gateway and its associated Sensing units.		broker with other sensing devices in a single Virtual Tenant Network. **Enabling components:** VTN Manager

SDN/NFV in context of Backend Layer Networking: Deployment of interactions between NFV/SDN in the backend relies on Network Service descriptors (NSd[9]) [12]. NSd descriptors are static text files that describe the desired network topology, VM images to use, resources to be used, scaling factors, event triggers, KPIs, physical location of the instantiation, among others. Later on, NSd are onboarded onto the NFV Orchestrator (NFVO), which in turn translates them into API calls to the VIM in order to instantiate a copy of said virtual network service.

As opposed to a traditional PNF network deployment, typical for the flexibility provided by NFV/SDN admits fast deployment modifications. This attribute allows the Network Service (or UC in this context) to scale in/out[10] according to the load and subject to NFVI resources availability, as well as constant monitoring and modification of forwarding paths according to UC constraints.

3.1.4 MANAGING VIM NETWORKS WITH AN EXTERNAL SDN CONTROLLER

VIMs often incorporate their own SDN Controller, e.g.: Neutron in OpenStack; but there are a number of benefits associated with delegating the management of the network to another software. These range from fault tolerance through service isolation, or simply additional functionality.

Most popular VIMs are composed of different isolated projects that work together. For instance, OpenStack Nova [13] handles compute, Cinder [14] storage, Neutron [15] networking, and so on. It is also possible to keep each project on a separate physical node (or cluster of nodes) in order to provide resilience against network or resource outage/saturation.

The SEMIoTICS SDN Controller falls within this model. That is, a stand-alone external SDN Controller which uses the ML2 northbound plugin [16] in order to relay/retrieve network information to/from VIMs [7]. Furthermore, it uses the OpenFlow and OVSDB southbound plugins to act upon the virtual network devices (e.g.: OVS) running on compute hosts within the VIM domain, as well as the underlying physical network connecting compute nodes to the network. This characteristic allows for a central network policy enforcement entity, where virtual and physical networks may be jointly optimized to provide UCs with the necessary network performance.

3.2 SDN Controller Function Blocks

In the following section we provide a brief overview of the internal architecture of the SEMIoTICS SDN Controller and its differentiation to related state-of-the-art activities, such as the controller developed in the context of the VirtuWind project.

3.2.1 SEMIOTICS SDN CONTROLLER FUNCTION BLOCKS: COMPONENT DIAGRAM

In the network control approach in SEMIoTICS, we leverage the centralized control plane and programmability offered by the SDN paradigm and exploit the flexibility of NFV. Each authorized application or tenant that needs connectivity is served one or multiple related communication services. Specification of application recipes ensures the composition of application relations at global level. Connectivity patterns stem from a combination of

[9] Even though NSd are in turn composed by other descriptors (for VNFs, virtual links, among others), here the generic NSd term is preferred.
[10] E.g.: increase or reduce the compute/storage resource of a VM.

different connectivity and QoS service requirements, ranging from E2E-delay and bandwidth requirements, to different path protection schemes (e.g. duplication or fast-failover).

As in previous related projects from the industrial domain (i.e., VirtuWind [1]) each request is mapped to a unique network tenant. To ensure isolation when competing for a limited set of network resources, in an industrial network, each tenant must be served a guaranteed pool of resources (e.g., in scope of its Virtual Tenant Network).

Figure 5 depicts the key architecture blocks of our SDN approach, a brief description of which can be found below:

1) **Pattern-based northbound interface of the SSC:** Allows the network operator to specify and collect information about enforced patterns. Similarly, it allows for specification of pattern rules and thus the orchestration of network from perspective of an automated service, such as the Pattern Orchestrator (please see D4.1) or pattern-enabled end-devices.
2) **The set of core SSC components:** They enable the decision-making related to pattern enforcement, reference storage and pattern eviction at runtime. The core components are furthermore in charge of collecting, maintaining and modifying the network configuration according to the presented set of pattern rules.
3) **An exposed interface for NFV Management and Orchestration (MANO)** interactions: MANO components (i.e., the VIM or VNF Manager) may interact with the SEMIoTICS SDN Controller so to interconnect the virtual network functions (VNFs) and thus enable the required service function chains (SFCs) interconnection at network layer;
4) **The set of southbound interfaces providing connectivity between the SSC and network devices.**
5) **Network Devices**: Which expose the set of standardized interfaces so to allow for enforcement of network configurations (i.e., the packet matching rules composed of filters and actions).

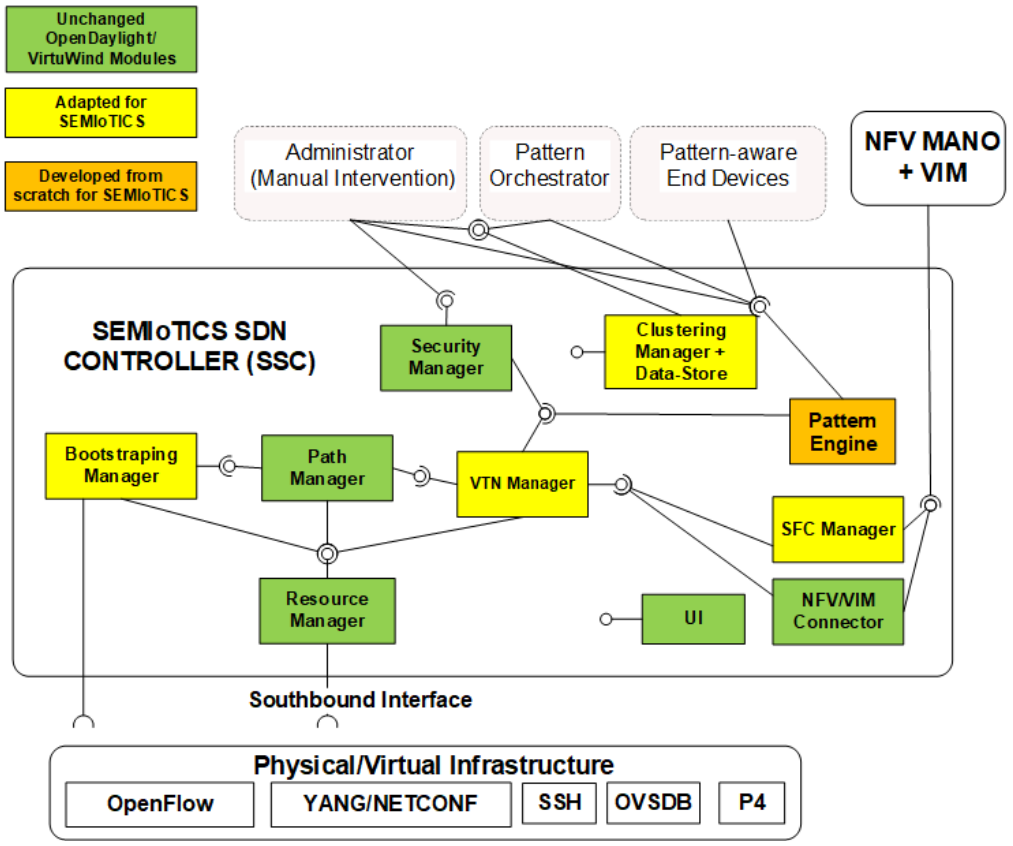

Unchanged OpenDaylight/ VirtuWind Modules
Adapted for SEMIoTICS
Developed from scratch for SEMIoTICS
Administrator (Manual Intervention)
Pattern Orchestrator
Pattern-aware End Devices
NFV MANO + VIM
SEMIoTICS SDN CONTROLLER (SSC)
Security Manager
Clustering Manager + Data-Store
Pattern Engine
Bootstraping Manager
Path Manager
VTN Manager
SFC Manager
Resource Manager
UI
NFV/VIM Connector
Southbound Interface
Physical/Virtual Infrastructure
OpenFlow
YANG/NETCONF
SSH
OVSDB
P4

FIGURE 5: SEMIOTICS SDN CONTROLLER ARCHITECTURE

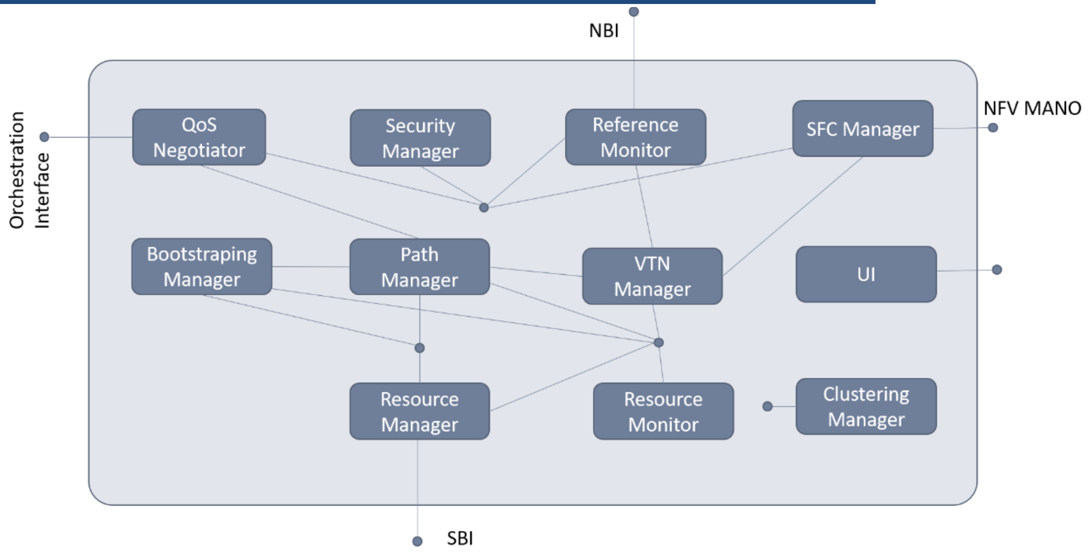


FIGURE 6: COMPONENT OVERVIEW OF THE VIRTUWIND SDN CONTROLLER

3.2.2 COMPATIBILITY WITH STATE-OF-ART SDN CONTROLLER ARCHITECTURES

In the following sub-sections, we discuss the compatibility and extensions of the SEMIoTICS controller architecture with the state-of-art distributions controllers proposed in the ODL and VirtuWind projects. OpenDaylight and VirtuWind are the only SDN controller platforms fulfilling a larger subset of proposed SEMIoTICS system and networking requirements, hence they were selected for the reference implementation in SEMIoTICS.

3.2.2.1 COMPATIBILITY WITH VIRTUWIND SDN CONTROLLER ARCHITECTURE

As we have previously mentioned, the SSC is responsible for the orchestration of field- and network-level switching devices and is implemented on top of the revised SDN controller ODL, which was published as a result of the VirtuWind project. SEMIoTICS employs many of the VirtuWind's built-in SDN components for the initial implementation. For example, VirtuWind's Path Manager is reused for QoS-based path identification for realizing the end-to-end connectivity between the connecting partners. On the other hand, some off-the-shelf modules from ODL platform, such as its OpenFlow implementation (OpenFlowPlugin) is leveraged to enable interaction with the OpenFlow enabled SDN switches, but also to utilize and extend its data-store implementation and data models for storage of the SDN controller information.

In Figure 6 the components of the VirtuWind SDN controller are presented. By comparing Figure 6 with Figure 5, it can be observed that many of the components in both architectures are common. In both cases, each authorized application or tenant that needs connectivity requests an appropriate VTN, and later issues communication service flow requests to the system. The isolation of tenants is administered using the VTN north-bound interface of the SDN Controller, while the service requirements define a communication service interface as per tenant's intent specification. Each application service is mapped to a unique VTN and a network tenant.

The main difference between the two architectures is that, in SEMIoTICS, the north-bound interface is generic-pattern-based, allowing the network operator to specify and collect information about enforced patterns, while allowing for specification of pattern rules and thus the orchestration of network from the perspective of an automated service, hence the exclusion of Reference Monitor component in our architecture.

On the other hand, due to the QoS-constrained nature of power control systems, the north-bound interface in VirtuWind is specialized in QoS metrics. For instance, the flow requests are a combination of different connectivity and QoS service requirements, ranging from E2E-delay and bandwidth requirements, to different path protection schemes (e.g. duplication or fast-failover).

To that end, instead of a pattern orchestrator, there is a QoS orchestrator that is specialized for setting up a QoS-enabled end-to-end connectivity service via multiple network operator domains. Moreover, a QoS negotiator is responsible for the communication between the SDN Controller and the QoS Orchestrator and the translation of orchestrator's requests to domain-specific actions.

Furthermore, SSC implements mechanisms for iterative bootstrapping of the SDN data plane using an in-band control channel. Additionally, in contrast to VirtuWind, SEMIoTICS controller model allows for supporting Byzantine faults in controller instances using a replication approach.

3.2.2.2 COMPATIBILITY WITH OPENDAYLIGHT MODULAR CONTROLLER ARCHITECTURE

OpenDaylight (ODL)[11] is an SDN controller that lets the user to programmatically manage OpenFlow capable switches. ODL is a large open-source project with a number of features and compatible northbound applications. OpenStack, as described in the previous sections, is a cloud orchestration platform that can work independently without ODL, but with the SDN controller provides the user more programmatic control over the infrastructure; hence, improving the scope for automation.

In SEMIoTICS, one of the advantages of using an ODL-based implementation is the compatibility with OpenFlow, NETCONF/YANG and OVSDB protocols, supported by numerous of network vendors. Similarly, ODL already internalizes particular functions useful for the SSC UCs, including topology discovery and graph population, capability discovery and JAVA-to-REST API bindings (using the YangTools [17] project).

As a modular framework, ODL allows the developers and the users to:

- Install the protocols and services needed on-demand.
- Combine multiple services and protocols to solve more complex problems when needed.
- Develop custom functionality for extending the existing platform to support the specialized use cases.

The modular development pursued by the ODL project furthermore allows us a relatively straightforward extension, so to include the modules necessary for industrial use-cases, e.g., to enable flexible QoS, pattern-based service instantiation as well as the multi-tenant operation, Byzantine Fault Tolerance and iterative in-band bootstrapping, which are some of the pillars of the SEMIoTICS networking realization.

[11] https://www.opendaylight.org

4 DETAILED SDN CONTROLLER FUNCTION DESCRIPTIONS

The subsections below provide details on the individual building blocks comprising the SEMIoTICS SDN Controller (SSC).

4.1 Control / Data Plane Bootstrapping Manager

Implementation Status: The Bootstrapping Manager was initially adopted over from VirtuWind project and updated afterwards. In SEMIoTICS, the Bootstrapping Manager is updated with extensions to not rely on complex distributed data plane protocols (i.e., the Rapid Spanning Tree Protocol). This results in a provably faster bootstrapping convergence time and lessened implementation complexity of the data plane devices.

Industrial SDN networks require a highly available control plane. The control plane may require an in-band or out-of-band control plane realization depending on the exact use case. In-band control (IBC) plane revolves around reusing the physical SDN data plane to host the control plane flows - i.e., the control traffic exchanged between the SDN Controller and switches shares the same network as the application flows. In contrast to in-band, the out-of-band-control plane relies on exclusive physical links for interconnection of the controller and managed switches. The wind park Use Case 1 assumes an in-band deployment, so to minimize the Capital Expenditures (CAPEX) related to out-of-band cabling requirements. By means of an automated network bootstrapping procedure, the SSC guarantees a robust and resilient control plane configuration at network runtime.

The robustness to *controller failures* is ensured by a multi-controller state replication design as described in Section 4.7.

To handle the *data plane failures*, and their effect on the control plane flows, redundant control flow embedding is leveraged in the final implementation of Boootstrapping Manager. While recent works propose slower, restoration-based techniques in industrial scenarios, industrial scenarios typically use 1+1 protection by duplicating controller-to-controller and controller-to-switch TCP-based flows on maximally disjoint paths, thereby ensuring zero packet loss for control flows, at the expense of doubled bandwidth requirements per control flow connection. Since these typically have low bandwidth requirements, we do not consider it a crucial drawback in our approach.

Enabling point-to-point connectivity in OpenDaylight and reference VirtuWind implementations requires manual or scripted specification of end-points to be interconnected by the network flows. This would lead to a large manual effort complexity due to a high number of infrastructural services necessary by SEMIoTICS components in the field and backend layer that require such connectivity. To this end, we have extended the Bootstrapping Manager and VTN Manager modules from VirtuWind project, to support an automated instantiation of network services for infrastructural network flows (e.g., Thing Directory synchronization, IoT Gateway <-> Router <-> Internet flows) as required by the SEMIoTICS use cases to minimize the scenario deployment efforts. More details on this aspect are given in the VTN Manager Section 4.3.3. In the remainder of this Section, we discuss the final design of in-band control plane bootstrapping in SEMIoTICS.

The interaction and placement of the Bootstrapping Manager component in the SEMIoTICS architecture is portrayed in Figure 5.

4.1.1 SUMMARY OF SEMIOTICS CONTRIBUTIONS IN THE BOOSTRAPPING MANAGER

In the second phase of T3.1, we tackled the challenge of bootstrapping a reliable in-band controlled softwarized network with multi-controller support. Succinctly, our resulting SEMIoTICS contributions are:

- We proposed an in-band control (IBC) approach for bootstrapping industrial networks with resulting resiliency and reliability guarantees for the control plane flows – i.e., controller-to-switch and controller-to-controller communication.
- We introduced the support for dynamic network extensions during runtime operation of industrial network, previously unavailable in the VirtuWind-proposed approach
- We covered implementation aspects relevant for the successful introduction of our design in networks equipped with off-the-shelf OpenFlow agents.

4.1.2 STATE-OF-THE-ART BOOSTRAPPING DESIGN PROVIDED BY VIRTUWIND PROJECT

Project VirtuWind first introduced the Hybrid Switch (HSW) bootstrapping scheme that heavily relies on existence of (R)STP, Standalone, In-band modes, and NORMAL forwarding for bootstrapping of OpenFlow-enabled SDN. Their proposed approach leverages (R)STP to establish an acyclic graph and thus remedy the potential storm issues stemming from traffic broadcasts (e.g., from ARP and DHCP requests). The VirtuWind-proposed approach does not support network extensions.

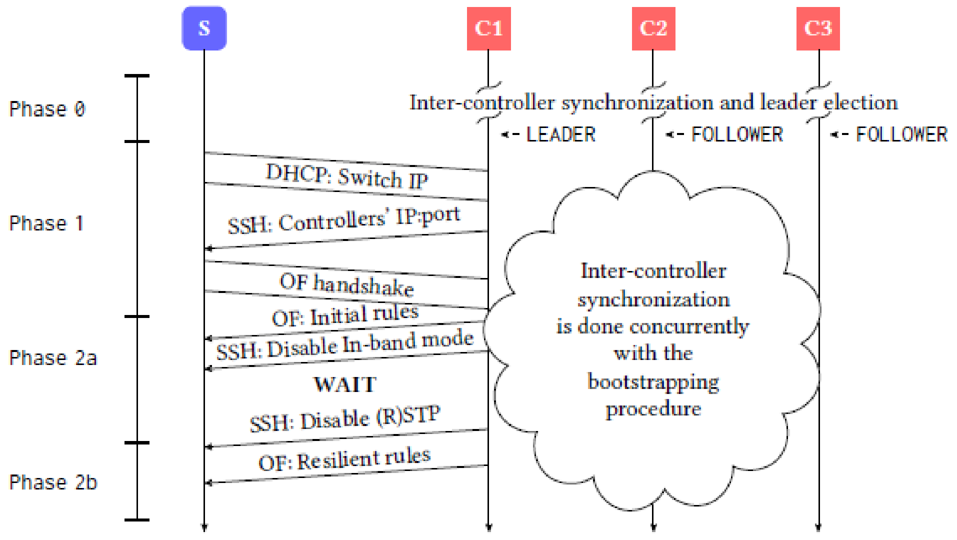

S
C1
C2
C3
Phase 0
Phase 1
Phase 2a
Phase 2b
Inter-controller synchronization and leader election
<- LEADER
<- FOLLOWER
<- FOLLOWER
DHCP: Switch IP
SSH: Controllers' IP:port
OF handshake
OF: Initial rules
SSH: Disable In-band mode
WAIT
SSH: Disable (R)STP
OF: Resilient rules
Inter-controller synchronization is done concurrently with the bootstrapping procedure

FIGURE 7: HSW - MESSAGE SEQUENCE DIAGRAM OF THE BOOTSTRAPPING PROCEDURE (VIRTUWIND STATE-OF-THE-ART)

Figure 7 summarizes the workflow of VirtuWind's HSW approach. In Phase 0, controllers establish the controller-to-controller communication over the spanning tree autonomously computed by the network. In Phase 1, switches are provided dedicated management IP addresses and controllers' IP/port pairs. In Phase 2a, controller replicas establish the control over the connected switches, install a set of initial rules and eventually disable (R)STP in switches so to enable blocked ports. To ensure the topology is entirely discovered, the leader controller waits for a predefined period (manually / empirically estimated and specific to the underlying topology) and eventually computes and installs the resilient rules. Explicit resilient flow rules are embedded in Phase 2b, so to fulfill the fault-tolerance requirements.

HSW requires the following assumptions to hold at startup: i) Controllers are aware of IP addresses of other controllers, or are capable of resolving these using standardized DNS queries; ii) Switches are initialized in Standalone mode with (R)STP and In-band mode enabled; iii) Switches are provisioned with controllers' public certificates or symmetric Message Authentication Code keys.

4.1.3 UPDATED AND FINAL DESIGN OF THE BOOTSTRAPPING MANAGER IMPLEMENTATION IN SEMIOTICS

Improving upon the above state of the art solution, we instead propose and implement the Hop-by-Hop scheme (HHC) which realizes an iterative approach to switch discovery. In contrast to HSW approach proposed in VirtuWind, this alleviates the need for (R)STP and thus the manual effort of designing the (R)STP expiration timer. As will be shown in our experimental study, it bootstraps the in-band controller network quicker than VirtuWind's HSW, as well. As before, a number of minimum constraints must hold at network startup: i) Controllers are aware of IP addresses of other participants, or are capable of discovering them using standardized DNS queries; ii) Switches are initialized in Secure mode without (R)STP and with disabled In-band mode; iii) Switches are provisioned with controllers' public certificates (PKI) or symmetric Message Authentication Code keys.

Figure 8 depicts the abstract sequence diagram of HHC. In Secure mode, a switch relies on the initial generic (non-customized) flow table rules, available at boot time. By leveraging these, in Phase 0, the controllers establish bilateral connections. In Phase 1, switches are assigned management IP addresses and controller lists. Using the generic rules, the switches adjacent to controller establish their OpenFlow sessions.

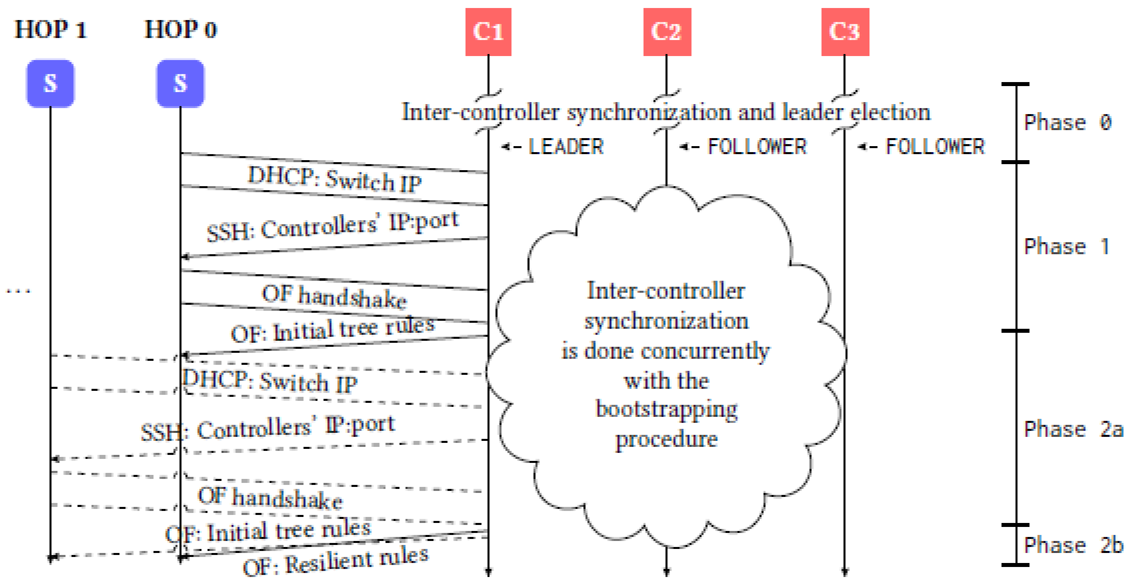
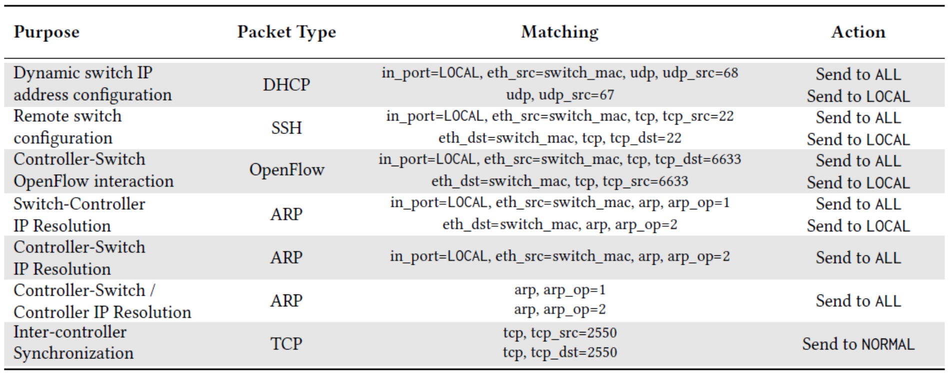


FIGURE 8: HHC - MESSAGE SEQUENCE DIAGRAM OF THE IN-BAND BOOTSTRAPPING PROCEDURE (DEVELOPED IN SEMIOTICS)

Appropriately, in Phase 2a, the leader rolls out the control plane flow rules to these switches. The provisioned rules realize the spanning tree forwarding functionality, used for iterative propagation of next hop switch's control traffic to the SSC. With each newly discovered network element, HHC iteratively updates the tree. In Phase 2b, the leader controller computes and installs resilient paths for all control plane flows, whenever such paths become feasible. The attachment of new switches to an already bootstrapped network is possible by gradually expanding the spanning tree.

4.1.3.1 PHASE 0 - NETWORK STARTUP

Phase 0a - Pre-Configured Flow Rules. HHC assumes a set of initially preconfigured generic OpenFlow rules, necessary: i) to allow an initial connection with the controllers while in Secure mode; ii) to prevent broadcast storms in non-bootstrapped parts of a network. In contrast to HSW, which bootstraps individual switches concurrently in first-come-first-serve manner, HHC bootstraps the network iteratively hop-by-hop, starting from switches adjacent to the leader controller. The non-customized generic rules (ref. Figure 9) allow receiving traffic addressed to the switch itself, i.e., dropping any other traffic, except for the traffic generated by the switch itself. Traffic initiated by a switch is flooded on all its ports. This traffic should only be allowed to reach the leader controller, and is therefore, dropped by any neighboring switches. These rules thus prevent the occurrence of broadcast storms (special case being the inter-controller flow rules, ref. Sec. 4.1.5). Furthermore, they allow the controller to configure the switches connected directly to it.



Purpose	Packet Type	Matching	Action
Dynamic switch IP address configuration	DHCP	in_port=LOCAL, eth_src=switch_mac, udp, udp_src=68 udp, udp_src=67	Send to ALL Send to LOCAL

Remote switch configuration	SSH	in_port=LOCAL, eth_src=switch_mac, tcp, tcp_src=22
		eth_dst=switch_mac, tcp, tcp_dst=22
			Send to ALL
			Send to LOCAL

Controller-Switch OpenFlow interaction	OpenFlow	in_port=LOCAL, eth_src=switch_mac, tcp, tcp_dst=6633
		eth_dst=switch_mac, tcp, tcp_src=6633
			Send to ALL
			Send to LOCAL

Switch-Controller IP Resolution	ARP	in_port=LOCAL, eth_src=switch_mac, arp, arp_op=1
		eth_dst=switch_mac, arp, arp_op=2
			Send to ALL
			Send to LOCAL

Controller-Switch IP Resolution	ARP	in_port=LOCAL, eth_src=switch_mac, arp, arp_op=2	Send to ALL
Controller-Switch / Controller IP Resolution	ARP	arp, arp_op=1 arp, arp_op=2	Send to ALL
Inter-controller Synchronization	TCP	tcp, tcp_src=2550 tcp, tcp_dst=2550	Send to NORMAL

FIGURE 9: HHC - PRE-CONFIGURED OPENFLOW RULES

Phase 0b - Controller Synchronization. Excluding (R)STP implies we should avoid forwarding controller synchronization traffic using NORMAL port so to avoid broadcast storms. However, Secure mode implies that this traffic must be handled with additional initial preconfigured rules that match and forward this traffic type (ref. last four rules of Figure 9), prior to establishing OpenFlow connection with controller. Thus, it is impossible to come up with the generic set of preconfigured flow rules that do not leverage the ALL or NORMAL ports. Using either, however, initially results in broadcast storms. Therefore, apart from the preconfigured flow rules, we deploy a mechanism to cope with broadcast storms for controller-to-controller traffic (as discussed later in Sec. 4.1.5).

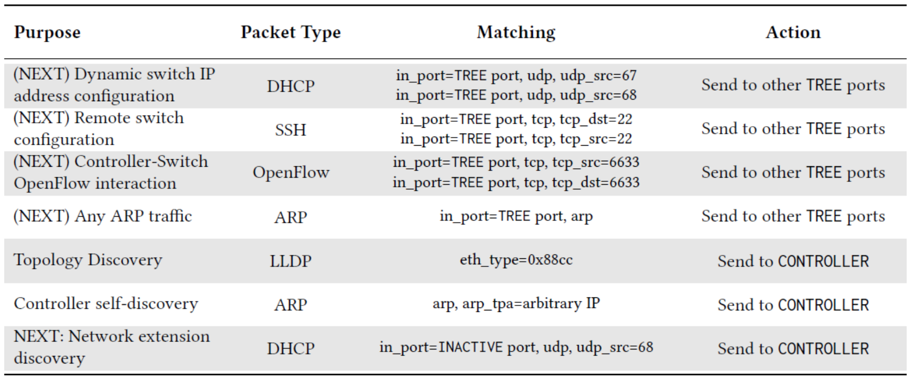
4.1.3.2 PHASE 1 - DISTRIBUTION OF SWITCH AND CONTROLLER CONNECTION IDENTIFIERS

The leader controller assigns the IP addresses initially only to its direct neighbor switches, and subsequently provisions them with controller lists. In order for the switches located two hops away from leader to receive their IP addresses, the generic preconfigured rules in the direct neighbor switches must first be extended with a new set of rules in Phase 2a.

4.1.3.3 PHASE 2 - ENABLING A FUNCTIONAL AND RESILIENT CONTROL PLANE

In contrast to HSW, which computes the resilient control plane flows after disabling (R)STP, HHC tries to compute and deploy resilient flow rules whenever feasible. Namely, it installs the resilient flow rules as soon as there exist *k + 1* disjoint paths for a single switch-controller communication pair. If the current discovered topology does not allow for identifying all required paths, flow rules are provisioned for a single path only. Whenever there is a change in topology, the leader retries computing the remaining disjoint paths.

Phase 2a - Initial OpenFlow Flow Rules. In this sub-step, leader provides the direct neighbor switches with rules that allow for the next-hop switches to communicate with all controllers (ref. Figure 10). These rules have a lower priority than the resilient rules computed in Phase 2b. Since (R)STP is unavailable, broadcast storms must be avoided. Thus, in addition to the base topology discovered by LLDP and ARP-probing, HHC maintains a virtual spanning tree. The tree topology is updated and enforced upon switches on every topology change using Figure 10 rules. Packets used in topology and controller discovery are sent directly to CONTROLLER port as OpenFlow PACKET-INs. In OVS, packets forwarded to CONTROLLER port leverage the NORMAL data-path, which initially may seem problematic. However, due to not relying on Standalone operation, MAC-learning tables are empty, and every packet is flooded instead. The flooded traffic cannot create broadcast storms as it can only reach two types of switches: i) those with TREE rules installed and, ii) those with generic preconfigured rules, which drop all traffic except their own. The discovery traffic is hence broadcasted only in the tree, since the PACKET-INs match the OpenFlow type.



Purpose	Packet Type	Matching	Action

(NEXT) Dynamic switch IP address configuration	DHCP	in_port=TREE port, udp, udp_src=67
		in_port=TREE port, udp, udp_src=68
			Send to other TREE ports

(NEXT) Remote switch configuration	SSH	in_port=TREE port, tcp, tcp_dst=22
		in_port=TREE port, tcp, tcp_src=22
			Send to other TREE ports

(NEXT) Controller-Switch OpenFlow interaction	OpenFlow	in_port=TREE port, tcp, tcp_src=6633
		in_port=TREE port, tcp, tcp_dst=6633
			Send to other TREE ports

(NEXT) Any ARP traffic	ARP	in_port=TREE port, arp	Send to other TREE ports
Topology Discovery	LLDP	eth_type=0x88cc	Send to CONTROLLER
Controller self-discovery	ARP	arp, arp_tpa=arbitrary IP	Send to CONTROLLER
NEXT: Network extension discovery	DHCP	in_port=INACTIVE port, udp, udp_src=68	Send to CONTROLLER

FIGURE 10: HHC - INITIAL AND NETWORK EXTENSION (NEXT) FLOW RULES INSTALLED ON SWITCHES IN PHASE 2A

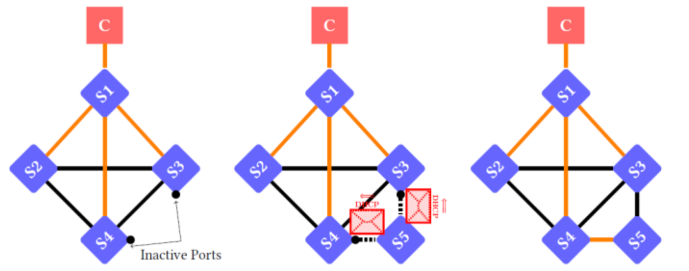
Phase 2b - Enabling Control Plane Resilience. To compute resilient paths, we deploy Dijkstra's algorithm. HHC does not assume visibility of entire topology to compute per-switch resilient paths. Instead, resilient paths are installed iteratively, whenever disjoint paths become available. This results in a quicker control plane resilience than with VirtuWind's HSW approach.

4.1.3.4 PHASE 3 - DYNAMIC NETWORK EXTENSIONS

To enable dynamic network extensions at runtime, the managed switches which are direct neighbors of the newly booted switches must forward the control plane traffic between the newly connected switches and controllers. In particular, DHCP, SSH, OpenFlow and ARP traffic forwarding must be enabled so that newly added switches can be bootstrapped.

Due to HHC's requirements on disabled (R)STP, the rules that should match above mentioned traffic may not rely on MAC-learning based NORMAL forwarding. Instead, the leader controller maintains a virtual tree topology, used to compute and install the network extension (NEXT) rules that broadcast the control plane traffic to and from newly attached switches on the tree links only.

Due to generic match semantics, NEXT rules are installed with a lower priority than Phase 2b rules. A special discovery rule matches packets arriving on inactive ports (i.e., the last rule of Figure 10). An inactive port is a port without an active neighbor, i.e., initially unconnected to another switch. If a new switch is connected to an already bootstrapped network, the discovery rule will forward its DHCP Discover message to controllers, encapsulated as a PACKET-IN message. The PACKET-IN contains the information about the ingress port the message arrived on, i.e., corresponding to the previously inactive port. The leader replicas process the PACKET-IN by extracting the newly attached switch's MAC address and adding the previously inactive port to the existing tree. If the new switch is connected to the existing network with multiple links, only the first activated port is used. Figure 11 illustrates this scenario.



(a) Initial virtual spanning tree. (b) Addition of a switch with 2 links. (c) Resulting virtual spanning tree.

FIGURE 11: EXEMPLARY NETWORK EXTENSION WITH ONE SWITCH AND TWO LINKS. C) DEPICTS THE RESULTING TREE.

HHC enforces the virtual tree topology together with remaining initial flows, i.e., the spanning tree is (re-)enforced iteratively during the bootstrapping procedure itself. Whenever an element of the tree fails, HHC refreshes the rules with the alternative tree.

4.1.4 FLOW TABLE OCCUPANCY

The proposed bootstrapping scheme enforces a non-negligible number of forwarding rules. The exact flow table occupancy can be pre-determined only for loop-free topologies. In non-loop-free topologies, the flow table occupancy varies depending on the outputs of the used tree computation and routing algorithm.

HHC's flow table occupancy is upper-bounded by F_{HHC}:

$$F_{HHC} \leq 13 + n * 4 + (5 + 3 * |C|) + i * 7 + m * j * 6 + k$$

$$n \in [0, \binom{|C|}{2}]; i \in [1, D_{Tree}]; m \in [0, |C|]; j \in [0, |S| - 1]; k \in \mathbb{N}$$

where |*C*| denotes the number of deployed controllers, *D_{Tree}* is the maximum node degree of the computed spanning tree, and |*S*| is the number of switches. The 13 fixed rules are the pre-configured rules in each switch. The 4 fixed rule types are TCP and ARP rules that allow for controller synchronization. The 5 fixed rules are composed of: ARP, SSH, OpenFlow rules for forwarding incoming traffic from controllers to the LOCAL port; and 2 discovery rules (LLDP, ARP). 3 flow rules (ARP, SSH, OpenFlow) are embedded per controller so to forward local traffic toward the respective controller (ref. Figure 9). Index *i* denotes the degree of a switch in the virtual spanning tree used for network extensions. The 7 fixed rules are the NEXT discovery rules. Index *j* denotes how many resilient paths that start/end in a particular controller traverse a switch. Index *m* denotes the number of controller replicas. The 6 fixed rules are the resilient flow rules (ARP, SSH, OpenFlow) used for traffic relaying, in directions to/from other switches. *k* denotes the number of inactive ports, imposing a discovery rule per port.

4.1.5 COPING WITH BROADCAST STORMS IN HHC

To solve the issues related to Phase 2b where particular flows may initially cause broadcast storms, we rely on rate limiting mechanisms provided by the data plane (e.g., OpenFlow's Metering or Linux's Traffic Control). Namely, we police the following inter-controller flows (ref. Figure 9): i) controller-initiated ARP traffic; ii) TCP SYNs destined for the inter-controller TCP port; ii) TCP SYN ACKs with inter-controller TCP port as source. The rate limit for policers may be configured to a very low value, e.g., we used 1.5Kbps for metering both ARP requests and replies (~ 12 ARP pps). Similarly, a low maximum rate can be chosen for TCP SYN and TCP SYN ACK packets. It suffices to match and rate-limit only TCP SYN and TCP SYN ACK traffic (as only these packets may generate broadcasts) and not the complete TCP flow.

4.2 Pattern Engine

Implementation Status: Developed from scratch for purposes of SEMIoTICS use cases.

The Pattern Engine (PE) module enables the capability to insert, modify, execute and retract patterns at design or at runtime in the SDN controller. PE can be based on a rule engine which is able to express design patterns as production rules. Enabling reasoning, driven by production rules, appeared to be an efficient way to represent SEMIoTICS patterns. For that reason, a rule engine is required to support backward and forward chaining inference and verification. Drools [18] rule engine appeared to be a suitable solution to support design patterns by applying and extending the Rete algorithm [19] and later the Phreak algorithm. The Drools rule engine is based on Maven and, thus, it can support the integration of all required dependencies with the ODL controller, as well as the integration of the entities that interact with the controller to run Drools at design and at runtime. Finally, the PE integrates different subcomponents required by the rule engine such as the knowledge base, the core engine and the compiler.

The PE is able to detect invalid rule configurations by means of component observations – i.e., connectivity-related patterns requiring flow installation will evaluate to False on failure of intermediate network elements (detected by subscribing to network topology events). Thus, the event detection requirement R.GP.4 will be fulfilled by the monitoring component implemented in Pattern Engine. The Pattern Engine additionally exposes a bidirectional interface towards backend, i.e., the Pattern Orchestrator component. On each status change of an active pattern instance, the remote Pattern Orchestrator is notified, so that additional reconfiguration steps can be partaken there. This is in line with Requirements R.GP.5 and R.GP.7

The interaction and placement of the Pattern Engine component in the SEMIoTICS architecture is portrayed in Figure 5.

4.2.1 PATTERN SPECIFICATION NBI

To support insertion, modification and deletion of facts and rules in the knowledge base by administrators or users, suitable northbound interfaces (YANG APIs and the respective REST APIs) are implemented (for more details, please refer to D3.10). Finally, a number of different YANG interfaces are implemented to interact with the different components, including also network components such as switches, service functions and end-hosts, active links and statistics from the controller, as required by the pattern rules.

4.2.2 UPDATED AND FINAL PATTERN ENGINE DESIGN

The main goal of the PE module at the SDN is to verify the connectivity between components and in some cases to establish said connectivity when required. This is accomplished mainly by the Drools rules that are loaded in the Drools Engine, along with some auxiliary classes that were necessary to describe instances of the aforementioned components. Figure 12 shows the basic Drools engine components where it is obvious that Rules and Facts are vital components.

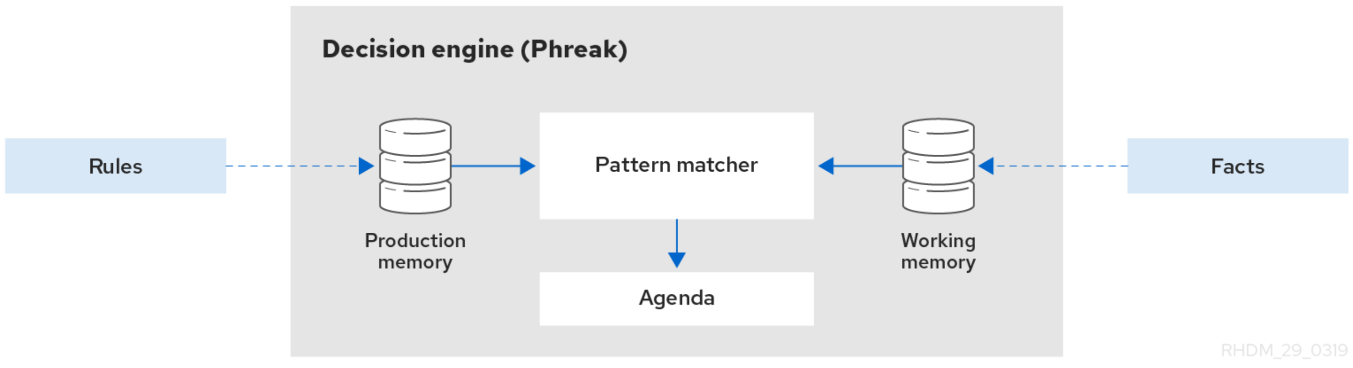


image source: https://docs.jboss.org/drools/release/7.24.0.Final/drools-docs/html_single/#decision-engine-con_decision-management-architecture

FIGURE 12: BASIC DROOLS ENGINE COMPONENTS

Although the Drools engine in Drools had used the Rete algorithm in the previous versions, the version used in PE module (6.5.0) works with a different algorithm. The said version uses the Phreak algorithm for evaluating the rules which has been proven to be more scalable and faster than its predecessors. Figure 13 shows how the Phreak algorithm tackles with the Rule Memory (Production memory). Essentially it is composed of three layers, Node memory, Segment Memory, and Rule Memory.

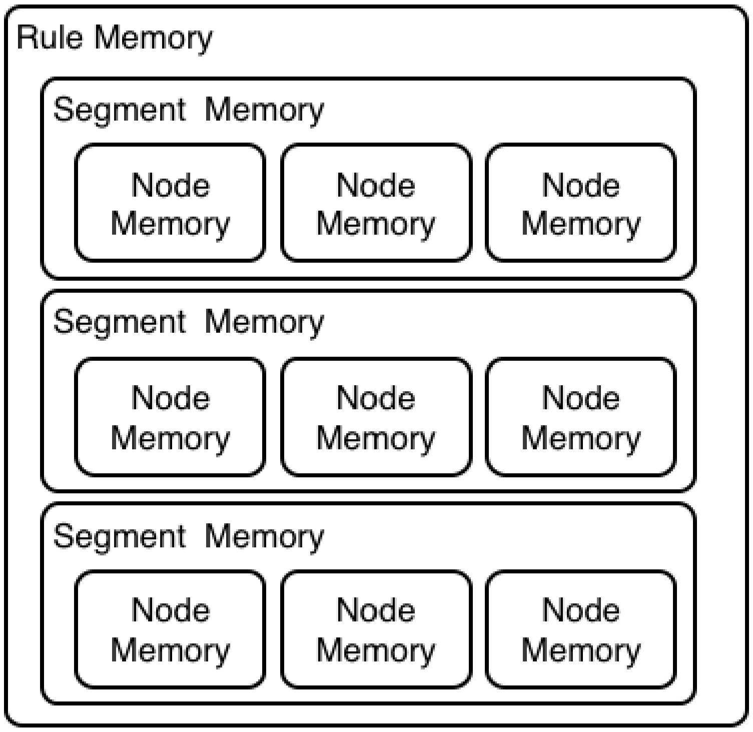
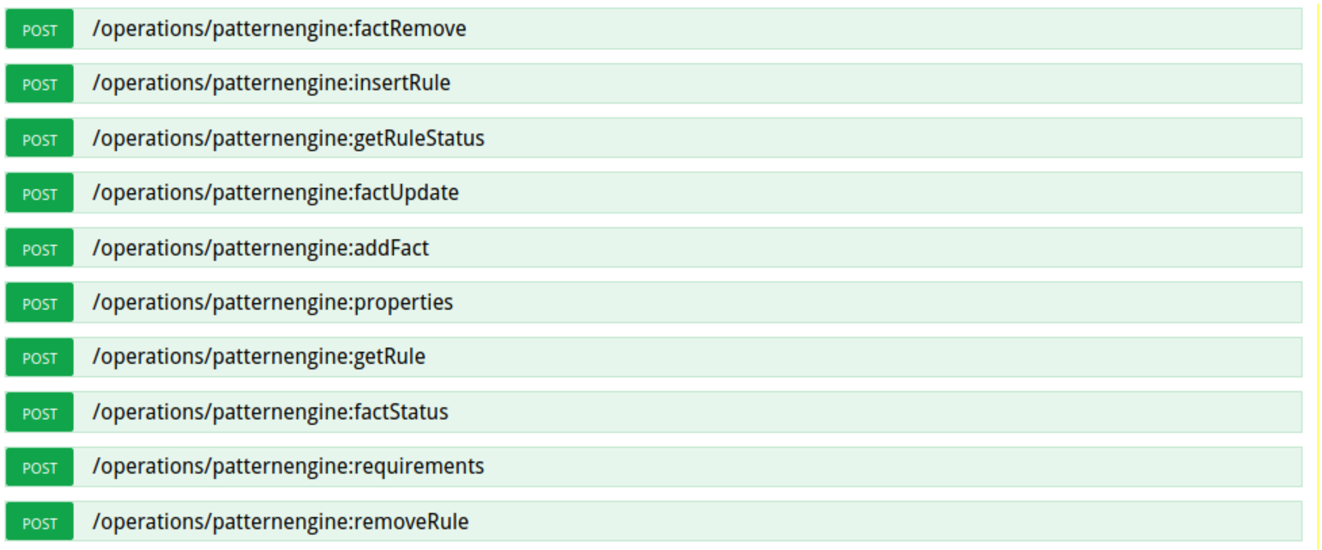


FIGURE 13 PHREAK THREE-LAYERED MEMORY SYSTEM

The Drools Engine evaluates the first Node Memory and the result is propagated to the next child node. This process is terminated when a terminal node is reached. Segments are created for the nodes that are shared by the same set of rules.

The Drools Engine in the PE is not running continuously. On the contrary, it is started only when needed, i.e. when a Fact or a Rule is added/updated/removed. This does not mean that the facts are lost because they are stored outside of the Drools Engine; these are stored locally in the file system where the SSC is installed for debugging purposes. The PE also has the Rules stored locally in the SSC and loads them every time the engine is required to run. These Rules may be pre-installed, but they can also be added during runtime through the corresponding endpoint “insertRule”. Facts are inserted from the Pattern Orchestrator by using the “addFact” endpoint and from an internal monitoring mechanism. The total list of endpoint of the PE is presented in Figure 14 which were defined in YANG in order to use them in SSC.



```
POST /operations/patternengine:factRemove
POST /operations/patternengine:insertRule
POST /operations/patternengine:getRuleStatus
POST /operations/patternengine:factUpdate
POST /operations/patternengine:addFact
POST /operations/patternengine:properties
POST /operations/patternengine:getRule
POST /operations/patternengine:factStatus
POST /operations/patternengine:requirements
POST /operations/patternengine:removeRule
```

FIGURE 14: PATTERN ENGINE MODULE API

The event detection requirement R.GP.4. is tackled by the monitoring mechanism of the PE which is based on existing capabilities of the SDN controller. In particular, data in SSC is tree-based represented and SSC offers interfaces that can monitor/listen changes in the tree. Using that logic, the PE implements two data tree change listeners, one for nodes and one for links. This way the PE is notified of the changes as soon as the SSC is made aware of them.

Figure 15 highlights the interaction of the PE, residing at the SSC, with other modules in the controller as well as with other SEMIoTICS’ components. There are more interactions between the pattern related components that are not depicted, such as the interaction of the Pattern Orchestrator with the PE in the backend layer, however the figure is meant to focus on the PE module at the SDN controller.

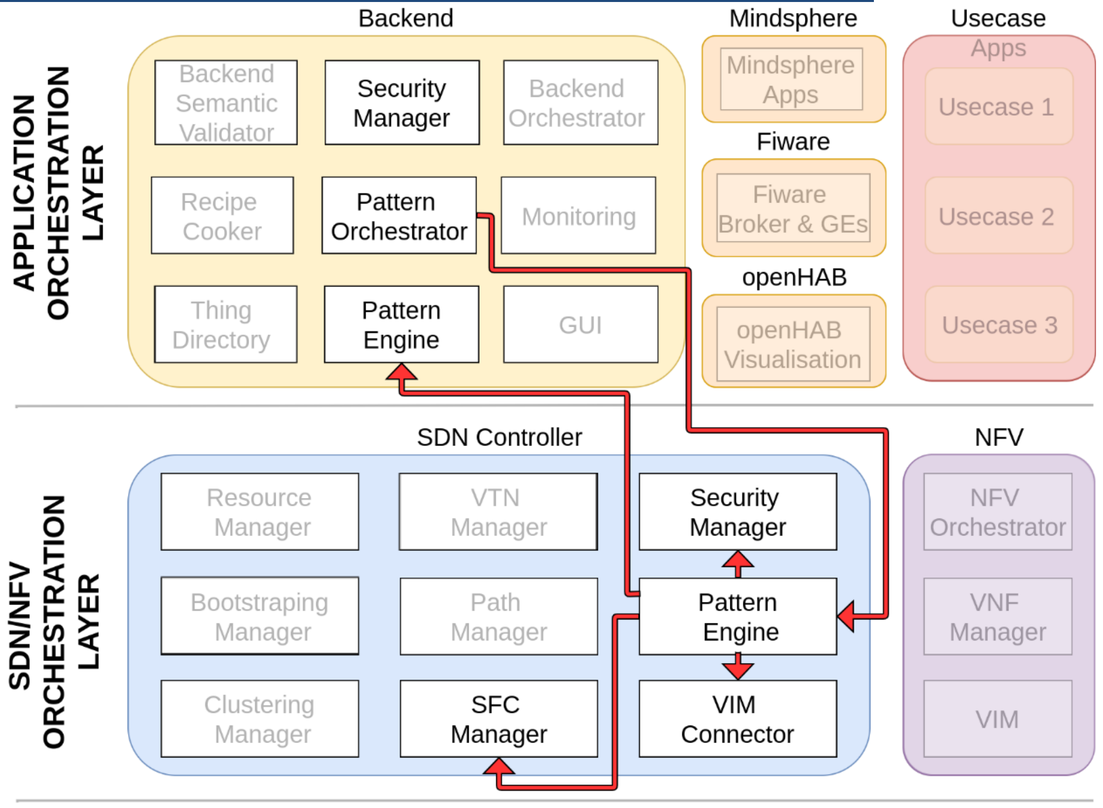


FIGURE 15: PATTERN ENGINE MODULE INTERACTION

The Pattern Orchestrator uses PE endpoints at the SDN controller, to feed facts to PE working memory. The PE will use these facts to trigger Drools Rules to reason with them. After the reasoning has completed, the updated facts are also forwarded as facts to the PE at the Backend layer.

Due to the nature or Drools Rules, the interaction of PE with other components inside the SSC is not limited only to the aforementioned components, but can also be extended to others as well, as it is shown in Figure 15. The ability to add new rules during runtime provides flexibility to interact with existing or future components of the SSC.

For a detailed presentation of the pattern-driven approach in SEMIoTICS, of which the above components are key enablers, please refer to D4.1.

4.3 VTN Manager

Implementation Status: Reused from VirtuWind, but modified for the purposes of SEMIoTICS use cases, as presented in Section 4.3.3.

4.3.1 SPECIFICATION OF VIRTUAL TENANT NETWORKS

VTN Manager is a component of the that provides for a multi-tenancy functionality. It realizes logical slices (“virtual tenant networks”) for per-application mapping and enforcement of isolation of the tenant networks in the infrastructure. VTN Manager’s APIs in SEMIoTICS leverage the logical VTN primitives (VTN definition, vInterface definition, port-mappings, flow-filters and flow-conditions) and exploit YANG/RESTCONF as modelling language and transport protocol. VTN Manager thus allows for creation of tenant networks and translation of pattern requests into path-request calls to Path Manager in scope of its VTN. VTN Manager stores all resulting data structures containing information about reservations and established VTNs in the centralized data store.

VTN Manager isolates individual tenants of the network at Layer 2 level, i.e., unmapped participants deployed in different tenant networks will be unable to interact with each other. Thus, VTN Manager provides network-level security end-point interactions. The VTNs are provisioned by means of a YANG-modeled REST interface, thus providing for R.NL.8 and R.NL.9 requirement support.

The interaction and placement of the VTN Manager component in the SEMIoTICS architecture is portrayed in Figure 5.

4.3.2 AN NBI FOR A MULTI-TENANT CAPABLE NETWORK SERVICE ORCHESTRATION

This SEMIoTICS module provides a north-bound interface API (NBI API). It translates the application’s request into low-level APIs of underlying components (VTN Manager and Security Manager). It provides RESTCONF RPC calls modelled in YANG. Additionally, it verifies the applications authenticity using credentials issued by Security Manager, also it logs application’s requests and responses in the distributed data store.

4.3.3 UPDATED AND FINAL VTN MANAGER DESIGN

The approach partaken in VirtuWind assumed manual creation of VTNs and imperative admission requests to admit new services into established VTNs for each end-to-end service in the system. With SEMIoTICS, a large number of inter-connected infrastructural services must be admitted in order to provide basic infrastructural communication - i.e., an IIoT Gateway must be capable of talking both to sensors / actuators, as well as to industrial backend cloud, using the SDN. Similarly, Pattern Engine must be capable of communicating with SDN controllers, the IIoT Gateway, the VIM / NFVO among others. Manually creating communication requests and admitting these is a large effort. To solve this issue, we have extended and enhanced VirtuWind’s VTN Manager in two regards:

- **Automated Installation of default Virtual Tenant Networks:** We have modified the VTN Manager, so that after bootstrapping of the system, or after a network extension, an additional default slice is automatically installed or extended, respectively. The default slice is installed automatically and encompasses all connected end-hosts of the topology. Its purpose is to host the infrastructural services. It provides no guarantees to the admitted communication services and uses the lowest priority queue. Thus, any misbehaving default services may not impact the QoS-constrained services with high criticality and reliability requirements.

- **Automated admission and installation of basic infrastructural services:** We have enabled a Packet-In listener, that, after a notification is triggered by a detected unknown packet in the data plane, parses the triggering packet, identifies the end-points based on source and destination Layer-2 / Layer-3 addresses of the triggering packet and subsequently triggers path finding and service installation in the basic infrastructural VTN (discussed above). Thus, unknown packets lead to automatic installation of the flows necessary to provide the basic connectivity.

For non-infrastructural services, i.e., the application services that may have high demands on QoS (i.e., bounded end-to-end latency and reserved bandwidth), imperative requests must be made using the Pattern Engine’s interface. These services than use higher-priority queue as decided by the resource planning algorithm in the Path Manager.

4.4 Path Manager

For the guaranteed industrial QoS, i.e. the bandwidth provisioning, flow isolation and worst-case delay

Implementation Status: Path Manager was reused from VirtuWind project, without modifications.

estimation, we have leveraged the Path Manager component. The related project VirtuWind [1] has previously proposed using network calculus, a deterministic mathematical modeling framework for communication networks to enable delay-bound, bandwidth-guaranteeing end-to-end network service [10]. Instead of basing its routing decision on a reactive control loop of network observations, Path Manager provides for real-time

Using the Path Manager, SSC will enable path computation under consideration of different QoS connectivity needs, including the requirement on low latency and reliable communication, thus supporting the platform design requirements across multiple Use Cases: R.GP.3, R.UC1.3, R.UC2.15 and R.UC2.17. The computation of paths is done according to isolation properties, i.e., the individual new reservations will not affect existing flows, thus supporting requirement R.UC1.4. Additionally, Path Manager supports the computation of maximally redundant paths, required to provide resilience in the face of network failures and thus enabled fulfillment of requirement R.UC1.5.

constraints by mechanisms for admission (and rejection) of flows. Namely, by maintaining an accurate model of the network state and service embeddings in the control plane, Path Manager ensures per-flow isolation and worst-case guarantees at all times.

The interaction and placement of the Path Manager component in the SEMIoTICS architecture is portrayed in Figure 5.

4.5 Resource Manager

Implementation Status: Resource Manager was reused from VirtuWind project, without modifications.

Resource Manager is responsible for configuration management and network control tasks, i.e. embedding of L2/L3 OpenFlow flow rules into the network. Resource Manager provides for embedding of: i) real-time flows which require dedicated per-queue flow assignments; ii) best effort flows, without queue considerations; and iii) the meter structures for policing purposes.

Resource Manager is capable of interacting with the infrastructure (switches, routers) etc. using one or multiple of the following interfaces: OpenFlow/OVSDB/SSH. This adheres to the requirement R.GP.6. The SSC controller will be capable of interacting both with virtual and physical OpenFlow switches. Open vSwitch is an exemplary production-ready virtual switch software (R.NL.7), that is to be used in SEMIoTICS Backend Layer for enabling the virtualization infrastructure.

The interaction and placement of the Resource Manager component in the SEMIoTICS architecture is portrayed in Figure 5.

4.6 Security Manager

Implementation Status: Security Manager was reused from VirtuWind project, without modifications.

The SEMIoTICS security management system includes the Security Manager (SM) component which offers support for authentication and accounting services. SM can realize the authentication and accounting services to the rest of the SDN Controller as well as the users and applications that interact with the controller. With respect to authentication, the SM exposes interfaces for the administration of local SDN Controller accounts. The necessary methods for C.R.U.D (Create, Read, Update, Delete) Users, Roles and Domains are developed by the SM exposed them to other controller components as well. Moreover, the SM provides authentication capabilities based on credentials stored by exposing a method which has local credentials as input and its output is an authentication token. Also, it exposes a token validation technique which can be used by the other controller components. It verifies both the validation of the provided token and the bearer of the token if it is the one who he claims to be. Additional APIs are exposed for applications to present their credentials. If these credentials prove valid, the SM can issue an authentication token to the requesting party. The token can then be presented to the Pattern NBI when attempting to interact with the SDN Controller. The Pattern NBI can be responsible for transferring these tokens to the SM internally for validation, so the former can then proceed to evaluate the request (i.e., if it is allowed based on the active policies). The final design of the SDN Security Manager will be evaluated in D4.7.2 after the cross layer security mechanism is finalized.

Depending on the use case, we distinguish two scenarios:

- User/application authentication based on a local set of entered policies / users
- User/application authentication based on an external set of entered policies / users, i.e., using an external LDAP server or similar. In the case of distributed authentication, the SM must present the tokens to the external server for validation.

Every interface to the SDN controller is protected by authentication/authorization mechanisms. Interfaces relevant for SEMIoTICS, including the Security Manager, VTN Manager and Pattern Engine northbound interfaces, are protected by HTTPS digest authentication, thus supporting the R.S.7 requirement. To protect and isolate access to particular internal APIs of the controller, Security Manager enables role-based definition of authorities granted access to the service, thus fulfilling the requirement R.S.2.

The interaction and placement of the Security Manager component in the SEMIoTICS architecture is portrayed in Figure 5.

4.7 High-Availability Controller Clustering

Implementation Status: The clustering design is mostly reused from VirtuWind project. The component was, however, extended to (a) an optional support of Byzantine Fault Tolerance operation in SEMIoTICS; (b) to provide a more scalable operation in Byzantine Fault Tolerance mode. The resulting design is presented in Section 4.7.2

The issue of the controller's single point of failure is resolved by means of state replication and fail-over to one of the backup controllers on failure.
Key features include:

- **Centralized controller state registry:** The Clustering module may handle the controller relationship per-data state in the distributed data-store. The controller state as well as the up-to-date network information can be collected in a single registry shard that is replicated across multiple controller instances.

- **Strong (SC) primitives for update ordering:** Components that have stringent requirements on the data state staleness, such as the Path Manager which makes critical routing and resource reservation decisions, may require serialized updates across all instances of the replicated controller. By serializing the individual updates, we ensure that no data-store updates are applied without having first observed the previous history of the updates made to that state. Such components make use of the controller state distribution based on SC primitives (e.g., using distributed RAFT [20] consensus).

By providing for hot-standby failover in case of controller failures/faults, the HA clustering component enables the industrial-grade high-availability requirement R.UC1.5. The final design of the high availability controller clustering solution for the SDN control plane is presented in the following section.

The interaction and placement of the Clustering component in the SEMIoTICS architecture is portrayed in Figure 5.

4.7.1 ENABLING BYZANTINE FAULT TOLERANT SDN CONTROL PLANE OPERATION

Distributed SDN were introduced as a way to improve the scalability of the control plane and mitigate the problem of single-point-of-failure. However, control plane correctness may be endangered by malicious controllers that enforce incorrect configurations, i.e., as a result of adversary attack or corrupt controller instance state [21] [22].

We have recently proposed MORPH [22], a framework that enables a Byzantine Fault Tolerant (BFT) SDN control plane, by allowing for runtime detection of malicious controllers and their dynamic exclusion from the system configuration, and thus the SEMIoTICS requirements R.UC1.5, R.UC1.6 and R.S.7. MORPH framework's function is based on the working principle that the switch processes all control packets originating from all the controllers in their administration domain, before deciding to apply the configuration.

To cater for tolerating unreliable controller decisions, made by faulty/malicious SDN controllers, we introduce the Byzantine Fault Tolerance extensions, which extend the existing Clustering solution proposed and implemented by OpenDaylight and the VirtuWind project. Furthermore, we extend the related works, by adopting a more scalable approach to control flow handling. Thus, we are able to cover the requirement for reliable control plane, made in R.UC1.6.

In the network phase where no malicious or unavailable controllers are identified, such approach results in a high system footprint and limited scalability, which is an additional requirement of the SEMIoTICS project (refer to requirements R.UC1.7 and R.GP.2). Moreover, the current data plane implementations of SDN-enabled switches do not have the necessary capabilities to process multiple control packets before applying them. If the packet comparison is executed in software, the deployment of a Byzantine Fault Tolerant SDN Control plane would clearly result in a highly loaded switch control plane.

To provide for higher scalability of the proposed solution, and thus fulfillment of R.GP.2 and R.UC1.7, an alternative solution by offloading some of the tasks from the control plane of the switches to their data plane. In order to do so, the switches' data plane is programmed using the P4 language binding, which is a special-purpose language that allows for programming of packet forwarding planes. We decrease the system footprint and enable a higher number of total control flows deployable in the SDN. The final design of the high scalability solution for the distributed SDN control plane is presented in 4.7.2.

4.7.2 UPDATED AND FINAL DESIGN OF A BFT CAPABLE CLUSTERING IMPLEMENTATION IN SEMIOTICS

State-of-the-art failure-tolerant SDN controllers (including the VirtuWind controller) base their state distribution on crash-tolerant consensus approaches. Such approaches comprise single-leader operation, where leader replica decides on the ordering of client updates. After confirming the update with the follower majority, the leader triggers the cluster-wide commit operation and acknowledges the update with the requesting client. RAFT algorithm realizes this approach and is implemented in OpenDaylight (base distribution of SSC) and ONOS controllers. RAFT is, however, unable to distinguish malicious / incorrect from correct controller decisions and can easily be manipulated by an adversary in possession of the leader replica. Recently, Byzantine Fault Tolerance (BFT)-enabled controllers were proposed for the purpose of enabling correct consensus in scenarios where a subset of controllers is faulty due to a malicious adversary or internal bugs [22]. In BFT-enabled SDN, multiple controllers act as replicated state machines and hence process incoming client requests individually. Thus, with BFT each controller of a single administrative domain transmits an output of their computation to the target switch. The outputs of controllers are then collected by trusted configuration targets (e.g., switches) and compared for payload matching for the purpose of correct message identification.

In in-band SDN deployments, where application flows share the same infrastructure as the control flows, the traffic arriving from controller replicas imposes a non-negligible overhead. Similarly, comparing and processing controller messages in the switches' software-based control plane causes additional delays and CPU load, leading to longer reconfigurations.

Moreover, the comparison of control packets is implemented as a proprietary non-standardized switch function, thus unsupported in off-the-shelf devices. With the design proposed in SEMIoTICS, we offload the procedure of comparison of controller outputs, required for correct BFT operation, to carefully selected network switches. By minimizing the distance between the processing nodes and controller clusters / individual controller instances, we decrease the network load imposed by BFT operation.

A P4-enabled pipeline is in charge of controller packet collection, correct packet identification and its forwarding to the destination nodes, thus minimizing accesses to the switches' software control plane and effectively outperforming the existing software-based solutions.

To sum up:

- The proposed design allows for collection of controllers' packets and their comparison in processing nodes, as well as for relaying of deduced correct packets to the destinations.
- It selects the optimal processing nodes at per-destination switch granularity. The proposed objective minimizes the control plane load and reconfiguration time, while considering constraints related to the switches' processing capacity and the upper-bound reconfiguration delay.
- It executes in software, e.g., in P4 switch behavioral model (bmv2), or in a physical, e.g., Netronome Smart-NIC environment. Correctness, processing time and deployment flexibility are validated in both platforms.

4.7.2.1 UPDATED CONTROLLER DESIGN

To tolerate Byzantine controller failures, controllers calculate their decisions in isolation from each other, and transmit them to the destination switch. Control packets are intercepted by the processing nodes (i.e., processing switches) responsible for decisions destined for the target switch. In order to collect and compare control packets, we assume packet header fields that include *the client_request_id, controller_id, destination_switch_id* (e.g., MAC / IP address), the payload (controller-decided configuration) and the optional signature field (denoting if a packet has already been processed by a processing node). Clients must include the *client_request_id* field in their controller requests.

Apart from distinguishing correct from malicious/incorrect messages, we are capable of identification and exclusion of faulty controller replicas. Three entities are assumed in the updated model, each with a distinguished role:

1) **SSC controller replicas** enforce forwarding plane configurations based on internal decision making. For simplification, each controller replica of an administrative domain serves each client request. Each correct replica maintains internal state information (e.g., resource reservations) matching to that of other correct

instances. In the case of a controller with diverged state, i.e., as a result of corrupted operation or a malicious adversary take-over, the incorrect controllers' computation outputs may differentiate from the correct ones.

2) **P4-enabled switches** forward the control and application packets. Depending on the output of *Reassigner's* optimization step, a switch may be assigned the processing node role, i.e., become in charge of comparing outputs computed by different controllers, destined for itself or other configuration targets. A processing node compares messages sent out by different controllers and distinguishes the correct ones. On identification of a faulty controller, it declares the faulty replica to the *Reassigner*. In contrast to [22], our approach enables control packet comparison for packets destined for remote targets.

3) **Reassigner** is responsible for two tasks:

   - Task 1: It dynamically reassigns the controller-switch connections based on the events collected from the detection mechanism of the switches, i.e., upon their detection, it excludes faulty controllers from the assignment procedure. It furthermore ensures that a minimum number of required controllers, necessary to tolerate a number of availability failures F_A and malicious failures F_M, are loaded and associated with each switch. This task is also discussed in our published work on basic BFT provisioning [22].
   - Task 2: It maps a processing node, in charge of controller messages' comparison, to each destination switch. Based on the result of this optimization, switches gain the responsibility of control packets processing. The output of the optimization procedure is the Processing Table, necessary to identify the switches responsible for comparison of controller messages. Additionally, the *Reassigner* computes the Forwarding Tables, necessary for forwarding of controller messages to processing nodes and reconfiguration targets. Given the no. of controllers and the user-configurable parameter of max. tolerated Byzantine failures F_M, *Reassigner* reports to processing nodes the no. of necessary matching messages that must be collected prior to marking a controller message as correct.

4.7.2.2 THE OPTIMIZATION FORMULATION – FINDING THE OPTIMAL PROCESSING NODES

The optimization methodology allows for minimization of the experienced switch reconfiguration delay, as well as the decrease of the total network load introduced by the exchanged controller packets. When a switch is assigned the processing node role for itself or another target switch, it collects the control packets destined for the target switch and deduces the correct payload on-the-fly, it next forwards a single packet copy containing the correct controller message to the destination switch. Consider Figure 16.

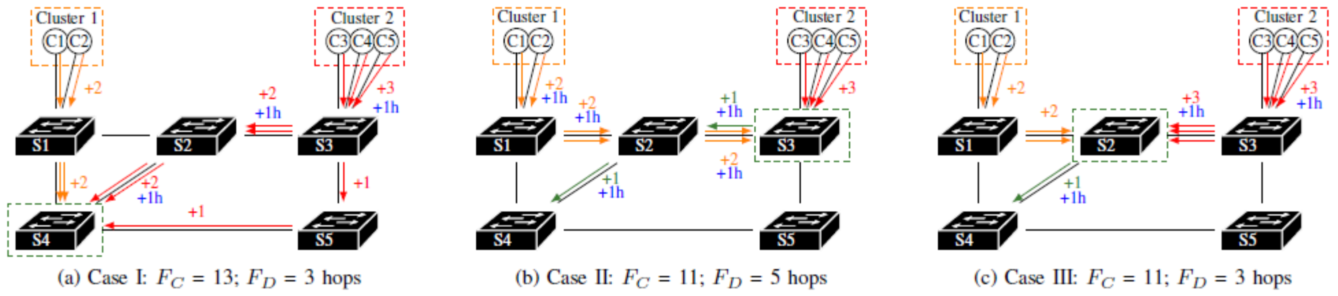

Cluster 1
C1
C2
Cluster 2
C3
C4
C5
S1
S2
S3
S4
S5
+2
+3
+1h
+1
(a) Case I: F_C = 13; F_D = 3 hops
(b) Case II: F_C = 11; F_D = 5 hops
(c) Case III: F_C = 11; F_D = 3 hops

FIGURE 16: MINIMIZATION OF THE COMMUNICATION OVERHEAD AND CONTROL PLANE DELAY USING BFT EXTENSIONS TO THE CONTROL PLANE.

If control packet comparison is done only at the target switch (as in prior works), a request for S4 creates a total footprint of F_C = 13 packets in the data plane (the sum of Cluster 1 and Cluster 2 utilizations of 4 and 9, respectively). This scenario is depicted in Figure 16a). In contrast, if the processing is executed in S3 (as depicted in Figure 16b)), the total experienced footprint can be decreased to F_C = 11. Therefore, in order to minimize the total control plane footprint, we identify an optimal processing node for each target switch, based on a given topology, placement of controllers and the processing nodes' capacity constraints. If we additionally extend the optimization to a multi-objective formulation by considering the delay metric, the total traversed critical path between the controller furthest away from the configuration target would equal $F_D = 3$ in the worst case (ref. Figure 16c)), i.e., 3 hops assuming a delay weight of 1 per hop. Additionally, this assignment also has the minimized communication overhead of $F_C = 11$.

We describe the processing node mapping problem using an integer linear programming (ILP) formulation. Figure 17 summarizes the notation used.

Symbol	Description
$\mathcal{V}: \{S_1, S_2, ..., S_n\}, n \in \mathbb{Z}^+$	Set of all switch nodes in the topology.
$\mathcal{C}: \{C_1, C_2, ..., C_n\}, n \in \mathbb{Z}^+$	Set of all controllers connected to the topology.
$\mathcal{D}: \{d_{i,j,k}, \forall i, j, k \in \mathcal{V}\}$	Set of delay values for path from i to k, passing through j.
$\mathcal{H}: \{h_{i,j}, \forall i, j \in \mathcal{V}\}$	Set of number of hops for shortest path from i to j.
$\mathcal{Q}: \{q_i, \forall i \in \mathcal{V}\}$	Set of switches' processing capacity.
$\mathcal{C}^j \subseteq \mathcal{C}$	Set of controllers connected to the node j.
$\mathcal{M} \subseteq \mathcal{V}$	Set of switches connected to at least one controller.
T	Maximum tolerated delay value.
$x(i,k)$	Binary variable that equals 1 if i is a processing node for k.

FIGURE 17: PARAMETERS USED IN THE ILP MODEL.

Communication overhead minimization objective minimizes the global imposed communication footprint in the control plane. Each controller replica generates an individual message sent to the processing node *i*, that subsequently collects all remaining necessary messages and forwards a resulting single correct message to the configuration target *k*:

$$M_F = \min \sum_{k \in \mathcal{V}} \sum_{i \in \mathcal{V}} (1 \cdot h_{i,k} \cdot x(i,k) + \sum_{j \in \mathcal{M}} |\mathcal{C}^j| \cdot h_{j,i} \cdot x(i,k))$$

Configuration delay minimization objective minimizes the worst-case delay imposed on the critical path used for forwarding configuration messages from a controller associated with node *j*, to the potential processing node *i* and finally to the configuration target node *k*:

$$M_D = \min \sum_{k \in \mathcal{V}} \sum_{i \in \mathcal{V}} x(i,k) \cdot \max_{\forall j \in \mathcal{M}} (d_{j,i,k})$$

Bi-objective optimization minimizes the weighted sum of the two objectives, w_1 and w_2 being the associated weights:

$$\min w_1 \cdot M_F + w_2 \cdot M_D$$

Processing capacity constraint: Sum of messages requiring processing on *i*, for each configuration target *k* assigned to *i*, must be kept at or below *i*'s processing capacity q_i:

$$\text{Subject to:} \quad \sum_{k \in \mathcal{V}} x(i,k) \cdot |\mathcal{C}| \leqslant q_i, \quad \forall i \in \mathcal{V}$$

Maximum delay constraint: For each configuration target *k*, the delay imposed by the controller packet forwarding to node *i*, responsible for collection and packet comparison procedure and forwarding of the correct message to the target node *k*, does not exceed an upper bound *T*:

$$\text{Subject to:} \quad \sum_{i \in \mathcal{V}} x(i,k) \cdot \max_{\forall j \in \mathcal{M}} (d_{j,i,k}) \leqslant T, \quad \forall k \in \mathcal{V}$$

Single assignment constraint: For each configuration target *k*, there exists exactly one processing node *i*:

$$\text{Subject to:} \quad \sum_{i \in \mathcal{V}} x(i,k) = 1, \quad \forall k \in \mathcal{V}$$

Note: The assignment of controller-switch connections for the purpose of control and reconfiguration is adapted from our previous work MORPH [22], and is thus not detailed here as a SEMIoTICS contribution.

4.7.2.3 P4 SWITCH AND REASSIGNER CONTROL FLOW

Processing node data plane: Switches declared to process controller messages for a particular target (i.e., for itself, or for another switch) initially collect the control payloads stemming from different controllers. Each processing node maintains counters for the number of observed and matching packets for a particular (re-)configuration request identifier. After sufficient matching packets are collected for a particular payload (more specifically, hash of the payload), the processing node signs a message using its private key and forwards one copy of the correct packet to its own control plane for required software processing (i.e., identification of the correct message and potentially malicious controllers), and the second copy on the port leading to the configuration target. To distinguish processed from unprocessed packets in destination switches, processing nodes refer to the trailing signature field.

Processing node control plane: After determining the correct packet, the processing node identifies any incorrect controller replicas (i.e., replicas whose output hashes diverge from the deduced correct hash) and subsequently notifies the *Reassigner* of the discrepancy. Alternatively, the switch applies the configuration message if it is the configuration target itself. The switch then proceeds to clear its registers associated with the processed message hash so to free the memory for future requests.

Reassigner control flow: At network bootstrapping time, or on occurrence of any of the following events: a detected malicious controller; ii) a failed controller replica; or iii) a switch/link failure; *Reassigner* reconfigures the processing and forwarding tables of the switches, as well as the number of required matching messages to detect the correct message.

4.7.2.4 P4 TABLES DESIGN

Switches maintain Tables and Registers that define the method of processing incoming packets. Reassigner populates the switches' Tables and Registers so that the selection of processing nodes for controller messages is optimal w.r.t. a set of given constraints, i.e., so that the total message overhead or control plane latency experienced in control plane is minimized (according to the optimization procedure. *Reassigner* thus modifies the elements whenever a controller is identified as incorrect and is hence excluded from consideration, resulting in a different optimization result.

Our approach leverages four P4 tables:

1) **Processing Table:** It holds identifiers of the switches whose packets must be processed by the switch hosting this table. Incoming packets are matched based on the destination switch's ID. In the case of a table hit, the hosting switch processes the packets as a processing node. Alternatively, the packet is matched against the Process-Forwarding Table.

2) **Process-Forwarding Table:** Declares which egress port the packets should be sent out on for further processing. If an unprocessed control packet is not to be processed locally, the switch will forward the packet towards the correct processing node, based on forwarding entries maintained in this table.

3) **L2-Forwarding Table:** After the processing node has processed the incoming control packets destined for the destination switch, the last step is forwarding the correctly deduced packet towards it. Information on how to reach the destination switches is maintained in this table. Contrary to forwarding to a processing node, the difference here is that the packet is now forwarded to the destination switch.

4) **Hash Table with associated registers:** Processing a set of controller packets for a particular request identifier requires evaluating and counting the number of occurrences of packets containing the matching payload. To uniquely identify the decision of the controller, a hash value is generated on the payload during processing. The counting of incoming packets is done by updating the corresponding binary values in the register vectors.

4.7.2.5 MEASUREMENTS OF BYZANTINE FAULT TOLERANT DISTRIBUTED CONTROL PLANE PROPOSED BY SEMIOTICS

Figure 18 depicts the packet load improvement in the approach introduced in SEMIoTICS over the existing reference solutions for randomly generated topologies with average node degree of 4. The footprint improvement denotes the ratio between the total incurred packet footprint as per our optimization procedure, compared to the footprint imposed by existing reference works.

Packet load improvement of our design is over the reference work MORPH [22] for 5000 randomly generated network topologies per scenario, with 7 controllers distributed into 3 disjoint and randomly placed clusters. In addition to the 100% coverage where each node may be considered a processing node, we include scenarios where only the random [1, 25%, 50%, 75%] nodes of all available nodes in the infrastructure are P4-enabled. Thus, even in the topologies with limited programmable data plane resources, i.e., in brownfield-scenarios involving OpenFlow / NETCONF + YANG non-P4 configuration targets, we offer substantial advantages over existing state of the art.

Our approach outperforms the state-of-the art as each of the presented works assumes an uninterrupted control flow from each controller instance to the destination switches. We, on the other hand, aggregate control packets in the processing nodes that, subsequently to collecting the control packets, forward a single correct message towards the destination, thus decreasing the control plane load.

Footprint efficiency of the BFT approach in SEMIoTICS generally benefits from the higher number of controller instances. This relationship is presented in Figure 19. Controller clusters, on the other hand, aggregate replicas behind the same edge switch. With the higher number of disjoint clusters, the degree of aggregation and the total footprint improvement decreases.

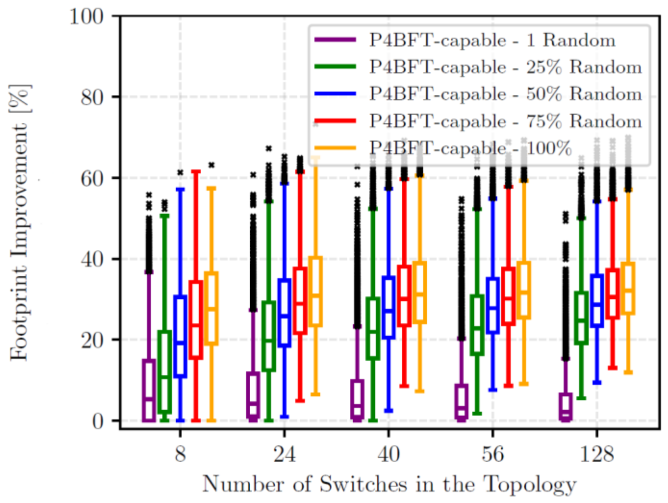


FIGURE 18: PACKET LOAD IMPROVEMENT OF OUR BFT DESIGN OVER THE REFERENCE WORKS

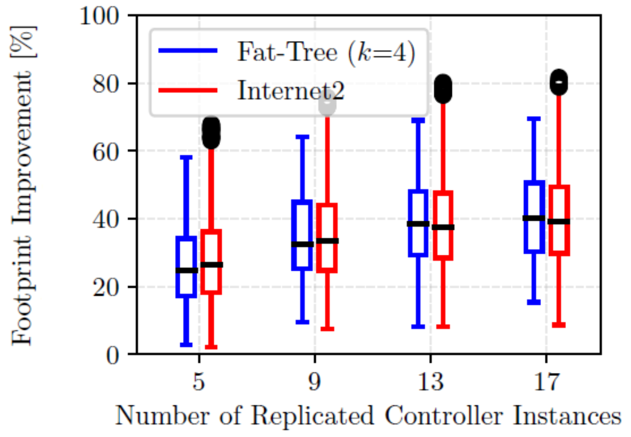


FIGURE 19: THE IMPACT OF CONTROLLERS ON THE CONTROL PLANE LOAD FOOTPRINT IN INTERNET2 AND FAT-TREE (K = 4) FOR 5000 RANDOMIZED CONTROLLER PLACEMENTS.

Implementation Status: SFC Manager is reused from VirtuWind project and subsequently adapted as required to support the interactions with the Pattern Engine of the SDN Controller, so to support orchestrated SFC deployment in Use Case 2 scenario (see Section 6).

4.8 SFC Manager

The SFC Manager (SFCM) component of OpenDaylight is able to handle service function chaining of network functions. An SFC determines an abstract set of service functions and their ordering constraints that should be applied to packets and/or frames selected as a result of classification. Additionally, the implied order could not be a linear progression, due to the fact that the architecture allows for nodes which copy to more than one branch; also, the architecture allows for cases where there is flexibility in the order in which services need to be applied.

In the SEMIoTICS use cases, service instances may include Firewall, IDS, DPI, and HoneyPot. These services may be the physical appliances or virtual machines running in network function virtualization infrastructures. They may be composed of one or multiple instances. At the Management and Control planes, the SFCM is responsible for administrating the services chains, i.e., for mapping the operator's/tenant's/ application's requirements into service chains. SEMIoTICS has identified the benefit of incorporation the NFV and SDN world in order to bring the best of both worlds related to network setup, configuration and management together. For that reason, the SFCM is enhanced to handle the interactions between the SDN controller and the MANO, in order to receive networking information about instantiated VMs, as well as to provide information about possible paths fulfilling the requirements of the SFC.

The interaction and placement of the SFC Manager component in the SEMIoTICS architecture is portrayed in Figure 5.

4.8.1 AN NBI ENABLING SFC ORCHESTRATION

The SFC Manager exposes a number of NBI interfaces that various components can use to provide and receive information about service chains. Information such as SFC required, which tenants want to use them, which destinations are being accessed, what applications the traffic pertains to and about the service instances of the network functions can also be supported. That includes the exposure of both an administration interface through the controller's NBI, which is also used by NFV MANO, and a login interface for the applications through the development of suitable YANG and RESTful interfaces.

4.8.2 UPDATED AND FINAL SFC MANAGER DESIGN

The final design of the SFC Manager does not include any major updates regarding the described component in the SSC controller. However, the main updated functionality of the SFC manager is the capability to interact with the Backend Pattern Engine (see D4.1). In this case, the Pattern Engine can request by the SFC manager through the exposed REST APIs to retrieve existing chains stored on it. In case of non-existence of the requested chain, the Pattern Engine can request the running VNFs by the NFV Mano that should be included in the chain. When all the requested VNFs are up and running, the Pattern Engine will send the requested chain to be inserted in the SFC manager. A more detailed description is already provided in the D2.5, D5.2 and D5.3. The procedure regarding the instantiation of the VNFs through the NFV Orchestrator will be described in D3.8 and the required patterns to provide such approach will be provided in D4.8. Finally, the concept will be evaluated in the Use Case 2 and the respective deliverables in T5.5.

4.9 NFV MANO/VIM Connector

Implementation Status: The VIM Connector is reused from OpenDaylight project. In particular, the ML2 connector was used without changes.

Within ETSI's standardized NFV Architecture (see Figure 6), the Management and Orchestration (MANO) components are those responsible for hardware resources abstraction (VIM), VNF lifecycle management (VNFM), and orchestrator (NFVO). Each one of these expose services (or functions) through well-defined interface abstractions (usually REST APIs), which in turn are used by other MANO components (e.g.: for instantiating a Network Service), or external elements (e.g.: for gathering information about VNFs).

The SEMIoTICS SDN Controller is an external component to the reference NFV MANO framework of Figure 6. That is, the management of virtual network resources (e.g.: VTN, VNF), and the control of the underlying physical network are tasks handled by the SEMIoTICS SDN Controller. This brings benefits in terms of outage/saturation resilience, primarily due to the isolation of network services to separate hosts. But also allows for joint optimization of both overlay and physical network paths/resources, which could help satisfy SEMIoTICS's UC requirements/constraints.

The interaction and placement of the NFV MANO/VIM Connector in the SEMIoTICS architecture is portrayed in Figure 5.

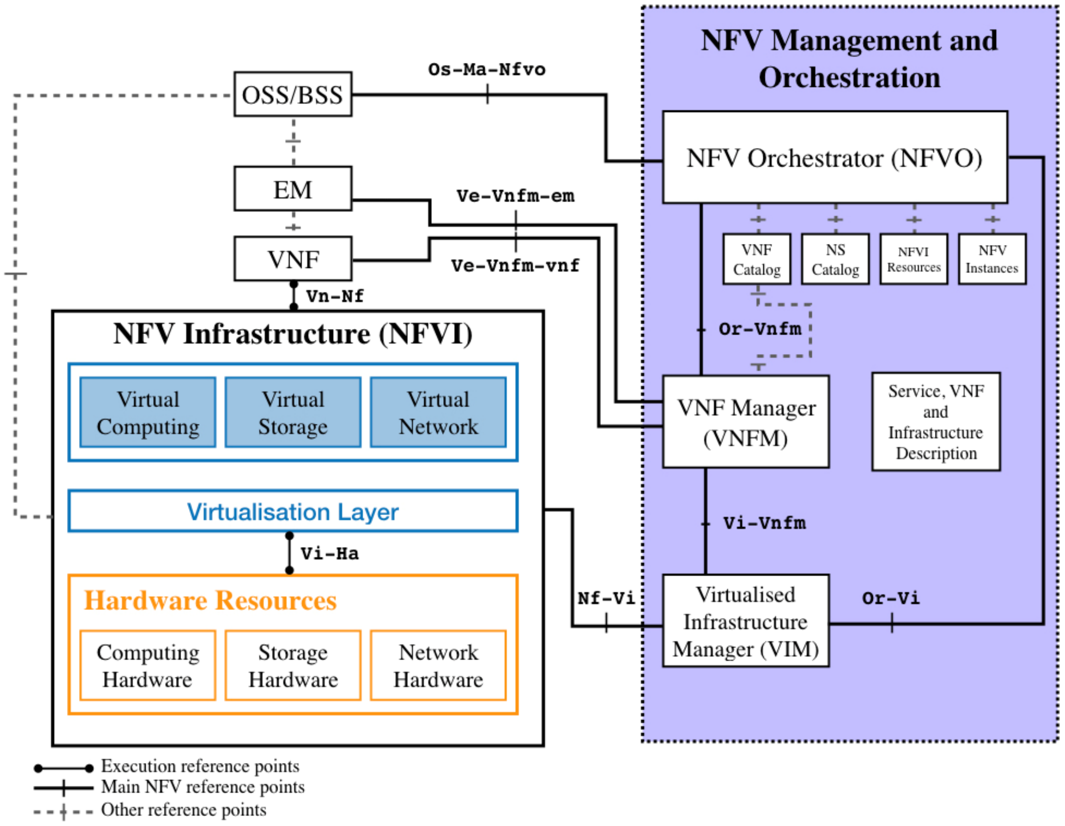


FIGURE 6: FUNCTIONAL BLOCKS OF AN NFV PLATFORM [11]

For the instantiation of an end-to-end service, the NFVO requests a “Network as a Service” through the corresponding exposed interfaces at the VIM (realized through the ***Or-Vi*** reference point shown in Figure 6). Then, through well-defined interfaces (e.g.: ML2 plugin [23]) the VIM exchanges the tenant’s network policy with the SDN Controller (realized through the ***Nf-Vi*** reference point shown in Figure 6), which in turn may request the instantiation of VNFs and other virtual network resources to complete the network service instantiation.

Other relevant information exchange occurring through relevant NFV MANO reference points are [12]:

- **Or-Vi**
  Orchestrator-VIM communication reference point. It is used for:
  - Resource reservation and/or allocation requests by the Orchestrator.
  - Virtualized hardware resource configuration and state information exchange.

  The ***Os-Ma-Nfvo*** reference point (see Figure 6) can be used by OSS/BSS (or other entity such as SEMIoTICS global pattern orchestrator) to gather information of the NFVI and trigger the creation/modification of a NS; but is the ***Or-Vi*** reference point the one that enables direct communication between MANO and VIM in order to realize such service by allocating resources from the infrastructure.
- **Nf-Vi**
  This reference point is used for NFVI-VIM communication. Particularly:
  - Assignment of virtualized resources after an allocation request.
  - Forwarding of virtualized resources state information.
  - Hardware resources configuration, information exchange and events capture.
  - Information exchange with external SDN Controllers.
- **Os-Ma-Nfvo**

It realizes Operations Support System/Business Support System (OSS/BSS)-NFV Management and Orchestration communication. It is used for:

- Request for network service lifecycle management.
- Requests for VNF lifecycle management.
- Forwarding of NFV related state information.
- Policy management exchanges.
- Data analytics exchanges.
- Forwarding of NFV related accounting and usage records.
- NFVI capacity and inventory information exchanges.

It is valid to assume the use of this reference point to software other than OSS/BSS. That is, any authorized software external to NFV could use this reference point for gathering information of the physical/virtualized infrastructure, as well as signaling the intention to create a network service via the NFVO.

4.10 Licensing Aspects

Components of the SEMIoTICS architecture, in their final implementation, are distributed and licensed under the following terms:

- Bootstrapping Manager - Eclipse Public License 2.0 (EPL-2.0)
- Pattern Engine - Proprietary / Not Distributed
- VTN Manager - Eclipse Public License 2.0 (EPL-2.0)
- Path Manager - Eclipse Public License 2.0 (EPL-2.0)
- Resource Manager - Eclipse Public License 2.0 (EPL-2.0)
- Security Manager - Eclipse Public License 2.0 (EPL-2.0)
- Registry Handler (HA Clustering) - Eclipse Public License 2.0 (EPL-2.0)
- BFT-enabled Registry Handler – Proprietary / Not Distributed
- SFC Manager - Eclipse Public License 2.0 (EPL-2.0)
- NFV MANO/VIM Connector - Eclipse Public License 2.0 (EPL-2.0)
- UI - Eclipse Public License 2.0 (EPL-2.0)

5 INTERACTIONS WITH DATA-PLANE DEVICES

In this section, we discuss the selection of data plane forwarding technologies in SEMIoTICS and OpenFlow as the preferred control plane channel to configuring the forwarding devices.

5.1 OpenFlow as Enabler of the SDN Data Plane

5.1.1 OPENFLOW FOR CONTROL PLANE INTERACTIONS

SDN decouples data and control planes, concentrating control information of the whole network at the SDN Controller. In this paradigm shift, network devices obey to whatever forwarding instructions the SDN Controller dictates. For instance, when a packet arrives at an SDN-enabled forwarding device, it checks if there are any matching entries in its local forwarding table. If it fails to find one, it queries the SDN Controller through the control plane and waits for a reply containing the instructions on how to handle such flow.

The most widely used protocol for forwarding table modifications and SDN Controller-forwarding device communication, is Open Network Foundation (ONF) OpenFlow (OF) [2]. It works as a standard interface SDN Controllers use to interact with the forwarding table of network devices.

OF spurs from an initiative to promote innovation in networking (originally aimed to campus networks), where there was almost no practical way of experimenting and testing new protocols on networks with real traffic. Instead of hoping for hardware vendors to provide an open and programmable interface to their routers and switches (which may threaten companies with undesired competition), OpenFlow exploits a common set of functions related to flow tables, simply requiring a minimum set of actions[12].

An SDN-enabled forwarding device (or VNF) relies on the SDN Controller for updating its flow table and to determine all forwarding decisions. This is done exclusively using protocols such as OpenFlow messages through a separate control channel. The following summarizes relevant terminology related to OpenFlow:

- Open flow tables: a collection of flow rules, each one composed of:
    - Match fields: specific packet header information that can be used to filter flows. A flow is said to match a rule if its constituent packets have the same characteristics as specified on the match fields of the rule.
    - Actions: to be executed once a flow is matched.
    - Statistics: e.g.: keep track of the number of packets and bytes that matched a flow rule.
- A secure channel towards the Controller: often referred to as the control channel.
- OpenFlow Agent: running the OpenFlow protocol on SDN-enabled devices, thus realizing the communication between the SDN Controller and network devices' flow tables.

The most recent OpenFlow version, for example, defines up to 45 matching fields per flow rule [24]. That is, a particular forwarding decision taken at the Controller can be based on a wider criterion than that employed in traditional routing and switching; for instance, using the source and destination transport layer port numbers, protocol type, or a combination. Furthermore, OpenFlow network devices can be queried by the SSC in order to retrieve physical ports state information, or flow table statistics; widening even more the criteria upon which forwarding strategies could be defined.

The SEMIoTICS SDN Controller (SSC) is equipped with an OpenFlow module, which acts as Southbound Interface (SBI) for configuring OF-enabled devices' (physical or virtual) forwarding decisions.

5.1.2 OVSDB/NETCONF/YANG FOR MANAGEMENT PLANE INTERACTIONS

[12] E.g.: **Forward** packets to a given port, **Encapsulate and forward** first packet in a new flow to Controller, or **Drop**. Nevertheless, other actions are available, like: pushing new VLAN tags, TTL reduction, set a header field, among others.

From SEMIoTICS SDN Controller's perspective, there are southbound interfaces specifically used for device configuration [7].
NETCONF [3] is an XML-based protocol used as a southbound interface for remote configuration or communication with (physical) devices. Additionally, it could be employed as a northbound interface of the SDN Controller in the form of NETCONF servers to:

- Spawn, reconfigure or destroy SDN Controller's modules or applications.
- Read, write remote procedure calls (RPC, or functions provided by SEMIoTICS SDN Controller).

OVSDB [25] is another popular southbound protocol used for managing Open vSwitch-enabled (OVS) physical or virtual switches. It enables the SDN Controller to view, create, modify, and delete OVS objects such as bridges, tunnels, and ports. Reference SDN Controllers, such as ODL, implement an OVSDB module which, among other things, offers:

- Network virtualization.
- Southbound plugin for configuring OVS devices.
- Library for encode/decode OVSDB protocol.
- REST interfaces for configuring OVS devices.

The semantic modelling and data organization of NETCONF configuration data, notifications, and SDN Controller's RPCs are developed using YANG. It directly maps XML, allowing fast prototyping and modification of configurations. It supports several programming language-like statements such as leaf (single value, no children), leaf-lists (one value, no children, multiple instances), containers (no value, holds related children), must, list (like hashes or dictionaries), and more. Furthermore, it contains built-in types like integrals, strings, binary data, bit fields, references, or other. All of these features allow the deployment/consumption of SDN Controller applications from YANG models guaranteeing API contracts.

5.2 Evaluation of Wireless Field Technologies

In this section, we analyze existing wireless communication technologies that will and could be used for communication with the IoT devices in the different SEMIoTICS use cases defined in D2.2.

While the wireless technologies, i.e., radio access points are not to be managed through SDN, we nevertheless give an overview of technologies deployed in the prototypical Use Case deployments, due to D3.1/D3.7 being the only network-focused deliverables in the project. The final selection of the wireless technologies in the project are summarized in Section 5.3.

The selected technologies were chosen due to their applicability in the SEMIoTICS use cases and availability in commodity hardware. Nevertheless, the deployment of SEMIoTICS architecture, and in particular the gateway solution is not limited to combining with these wireless technologies only. Hence, for completeness, we next provide the description of alternative wireless technologies applicable to SEMIoTICS field layer:

Wireless Technology	**Description**	**Applicable for use in Use Cases**
IEEE 802.11 Wireless LAN	Frequency bands: ▪ 900 MHz (802.11ah) ▪ 2.4 GHz (802.11b/g/n/ax) ▪ 3.65 GHz (802.11y) ▪ 5.0 GHz (802.11j) WLAN ▪ 5 GHz or 5.8 GHz (802.11a/h/j/n/ac/ax) ▪ 5.9 GHz (802.11p) ▪ 60 GHz (802.11ad/ay) Data rates:	Use Case 1 (802.11ac/b/g/n for backend communication and 802.11ah for long-range communication, i.e., to / between offshore turbines). Use Case 2 (as discussed) Use Case 3 (as discussed)

	1 Mbps up to a theoretical limit of 1Gbps (802.11ac)	
IEEE 802.15.4	Frequency bands: 868/915/2450 MHz Data Rate: 250kbps (WirelessHART)	Use Case 1: N/A Use Case 2: Home Gateway to Home appliances Use Case 3: IHES Sensing nodes to IHES supervisor
WiMAX	Frequency bands: 2.5 and 3.5 GHz (requires license), 5.8 GHz (license-free) Data rates: Up to 1Gbps for fixed stations	Use Case 1: As an alternative to LTE deployment for internet/backend connectivity. Use Case 2: As an alternative to LTE deployment for remote call center connectivity. Use Case 3: As an alternative to LTE deployment for mobility web services connectivity.
Xbee PRO	Frequency bands: 868/915 MHz Data rates: 250kbps	Use Case 1: N/A Use Case 2: Home Gateway to Home appliances Use Case 3: IHES Sensing nodes to IHES supervisor
LoRaWAN	Frequency bands: 433/868/915 MHz Data rates: Up to 50kbps	Use Case 1: N/A Use Case 2: Home Gateway to Home appliances Use Case 3: IHES Sensing nodes to IHES supervisor
SIGFOX	Frequency band: 868 MHz Data rate: Up to 100bps	Use Case 1: N/A Use Case 2: N/A Use Case 3: N/A
Narrowband-IoT	Frequency bands: 1800/900/800 MHz Data rate: 250kbps	Use Case 1: As an alternative to LTE deployment for remote call center connectivity. Use Case 2: Home Gateway to Home appliances or/and as an alternative to LTE deployment for remote call center connectivity. Use Case 3: IHES Sensing nodes to IHES supervisor or/and as an alternative to LTE deployment for remote call center connectivity.
Public Cellular (HSPA & LTE)	Frequency bands: 850/900/1800/1900/2900 MHz Data rate (LTE): ~1200 Mbit downstream, ~225 Mbit upstream	Use Case 1: As described above. Use Case 2: As described above. Use Case 3: As described above.
Satellite Communications	Frequency bands: 137 MHz – 150 MHz or 1,6 GHz Data rate:	Use Case 1: Alternatively, for interconnection of local site to backend in case of off-shore / rural deployments. Limited applicability due to reliability/availability constraints.

	2400bps (Iridium), 15 kbps upstream / 60kbps downstream (ACeS)	Use Case 2: N/A Use Case 3: Alternatively, for interconnection of IoT Gateway to backend in case of off-shore / rural deployments. Limited applicability due to reliability/availability constraints.

5.2.1 IEEE 802.11 WIRELESS LAN

The IEEE 802.11 Wireless LAN (WLAN) is one of the most prevalent wireless communication standards. The technology is mature and stable, and mass production has driven hardware module prices down. WLAN is not only limited to the 2.4 GHz and the 5 GHz ISM bands, as changes in the firmware can allow the usage of neighboring frequencies. One example of this is the case with the 5.9 GHz spectrum reserved for communication on Intelligent Transport Systems. Some countries allow additional frequencies, as is the case of the IEEE 802.11j amendment, which allows the operation of WLAN in the 4.9 GHz to 5 GHz band. Yet another example is the IEEE 802.11y amendment, which enables high power data transfer equipment to operate on the 3650 to 3700 MHz band in the United States of America.

An additional approach, which is not limited to WLAN or to unlicensed frequency bands, is remixing the analog signal from a standard device into another frequency using analog radio equipment. The new signal will have the same bandwidth of the original signal, but will have a different center frequency.

The data rate of WLAN goes from 1 Mbps up to a theoretical limit of 480 Mbps, depending on the modulation used. The current draft of the IEEE 802.11ac aims to achieve data rates over 1 Gbps. As a general rule, the larger the range, the slower the data rate that can be achieved; an exception is on data rates below 12 Mbps, in which the faster orthogonal frequency-division multiplexing (OFDM) modulated data can be transmitted farther than the slowed direct sequence spread spectrum (DSSS) modulation.

Several installations exist worldwide using the 2.4 GHz band, which achieve more than 1 km of range. However, most, if not all of them, have a direct line-of-sight, bridging a building and a mountain installation using high-gain directional antennas. For the first scenario as defined above, the limited range will not allow using the 2.4 GHz band. For the second scenario, the communication range of WLAN is sufficient to fulfill the distance as well as the data rate.

In the 5 GHz band, there is the possibility of sending up to 1000 mW of power (+30 dBm, 1 Watt), which can easily exceed one kilometer. This sending power is permitted in the USA when using the 5.725 GHz – 5.875 MHz ISM band without any further restrictions. In the USA and Europe, the 5.250 MHz - 5.725 MHz permits this sending power only when employing dynamic frequency selection (DFS) so that any potential interference with airport radar equipment operating in the vicinity can be detected and avoided. It should be mentioned that the specific frequency requirements as defined by the Federal Communications Commission are undergoing an overhaul; the exact changes haven't been defined yet.

5.2.2 IEEE 802.15.4

The IEEE 802.15.4 is a standard for low-rate personal area networks (PAN), which defines the physical layer and the media access control. The basic IEEE 802.15.4 is the foundation of ZigBee and WirelessHART and uses mainly three frequency bands: 868.0-868.6MHz (Europe), 902-928 MHz (North America), 2400-2483.5 MHz (Worldwide). There are additional frequency bands for specific countries, for example 950-956 MHz for Japan (IEEE 802.15.4d) and 314-316 MHz, 430-434 MHz, 779-787 MHz for China (IEEE 802.15.4c).

WirelessHART has been specifically designed for industrial wireless sensor networks. Siemens has products available for the WirelessHART [26] standard in the SITRANS product line, including temperature and pressure sensors. WirelessHART allows for the use of multihop technology, effectively increasing the range of coverage. There is a maximum hop count of five and the base data rate of 250 kbps reduces with the number of hops.

5.2.3 IEEE 802.15.4K

In general, the channel modulation used by the basic IEEE 802.15.4 combined with the permitted radiated power in Europe of 100 mW (in the USA 200 mW) in the 2.4GHz band makes it a challenge to achieve 3 km of range. Hence, there are many amendments from which to choose from, and one of them, IEEE 802.15.4k, has proven to communicate at such distances.

The IEEE 802.15.4k Low Energy Critical Infrastructure Monitoring (LECIM) achieves the required range with commercial off-the-shelf hardware. Using an extremely slow, direct sequence spread spectrum modulation, the transmitters are in operation for extended periods of time, before the receiver can understand the signal. The company onRamp Wireless is, at the moment of writing this report, the only manufacturer of IEEE 802.15.4k LECIM hardware. Their hardware achieves a range of several kilometers and their endpoints can work on batteries. Their radio modules have the advantage of working on the 2.4GHz ISM frequency band and have a channel bandwidth of 1MHz. The center frequency can be determined by the user in a 1 MHz raster.

The radio modules have -141dBm receiver sensitivity, providing for a very large link budget, which will allow for large transmission ranges. The typical transmission power in Europe is 10mW EIRP. The modules use 600mW of power while transmitting and 350mW while receiving. Most of the times the modules will be in deep sleep using just 15µW. Using very low duty cycles of a few messages per day, such a radio module can operate for 10 years on battery power.

Access points use 15W-20W of power and have to be always on. Due to the duty cycle constraints and the use of a very slow ‘direct sequence spread spectrum’ (DSSS), any communication will have a delay of up to 45 seconds.

The OnRamp system uses a star topology, and every access point will require a 128 kb/s uplink to a network control center, which is managed by OnRamp Wireless. This presents an important limitation as the communications system cannot provide a simple point-to-point or point-to-multipoint connection. Endpoints cannot communicate with each other directly and the endpoints cannot communicate to each other over an access point directly, as all communications have to be managed by the centralized equipment.

5.2.4 WIMAX

The IEEE 802.16 Worldwide Interoperability for Microwave Access (WiMAX) communications standard concentrates on metropolitan area networks and in its latest version can provide connection speeds of up to 1 Gbps. Channel bandwidth depends on the specific profile used and goes between 1.25 MHz and 20 MHz Specified to work in just about any frequency between 2 to 66 GHz, hardware is available for the following spectrum profiles: 700 MHz, 1.5 GHz, 1.9 GHz, 2.3 GHz, 2.5 GHz, 2.8 GHz, 3.3 GHz, 3.5 GHz, 3.7 GHz, 4.9 GHz, 5.2 GHz, 5.4 GHz, 5.8 GHz and 5.9 GHz. Communications range can run up to 50 km using the lowest data rate and very high sending power. Independent tests confirm that WiMAX is more energy efficient than GSM, UMTS and LTE mobile communication when compared under similar conditions (data rate, communications range, and ambient temperature).

The major disadvantages are similar to mobile communication. They require a licensed band and additional backend components to support simple point-to-point communication. The requirement for a licensed band means that a frequency must be acquired from the government authorities, in each country in which operation is desired. This is typically linked with very high costs.

5.2.5 XBEE PRO 868

Instead of using the 2.4 GHz frequency band, going to a lower frequency will help achieve the required range for the same amount of power. This led to the usage of the 868 MHz unlicensed band, e.g., utilized by the XBee-PRO 868, from the company Digi International, which uses a proprietary protocol. The data sheet quotes a distance of 40km, which has also been proven under line-of-sight conditions (+25dBm sending power,

+2.1dBi antenna gain). Independent tests show good results for 10.6km (+14dBi Antenna, Line-of-Sight, sending telemetry data from a model airplane). The same data sheet quotes a range of 550m for indoor and urban environments. As the range with line-of-sight is very good, an alternative for non-line-of-sight would be to position one or two nodes as repeaters to forward the information.

The XBee product is not compatible with IEEE 802.15.4, using a proprietary protocol instead. The 868MHz frequency band is an SDR band in Europe, providing operation free of charge. The equivalent frequency for Region 1 (Americas) is 915MHz, which use is also free of charge.

5.2.6 RF MESH / MULTIHOP

RFmesh, also called multihop, is a networking concept in which nodes that are member of a network can relay the information to other nodes, so that data can be propagated along the network. Using multihop, the basic communications range can be extended several times, at the cost of an increase in latency and power usage, and the decrease of data throughput rate. An important advantage is the self-healing mechanisms that include the communication protocols used. If a network node fails, the traffic is routed around the problem.

Many of the technologies analyzed in this document allow for a multihop communication. One common example is WLAN, which in the IEEE 802.11s amendment to the standard supports multihop. Another example is the IEEE 802.15.4. Together, these two represent almost all the available RF mesh devices available on the market. They work in the ISM frequency bands that permit for a license-free operation in any region in the world.

5.2.7 LPWAN

The low-power wide-area network (LPWAN) is a type of wireless communication technology. LPWAN is wide area network designed to allow long range communication at a low bit rate among remote and energy constrained objects. It is an umbrella for different specific technologies, as described below.

5.2.8 LORAWAN

Long Range Wide Area Network (LoRaWAN) is a communications standard in the 868/915MHz SRD frequency band. Due to the relatively low frequency, relatively high sending power (20dBm) and good receiver sensitivity (-148dBm), devices have been reported to achieve a typical range of 2km (with a theoretical maximum range of 16km).

LoRaWAN is the network on which LoRa operates and can be used by remote and unconnected industries. LoRaWAN is a media access control (MAC) layer protocol. It is a network layer protocol for managing communication between LPWAN gateways and end-node devices as a routing protocol, maintained by the LoRa Alliance. Under the network architecture demanded by LoRa, each client device requires a logical connection to one or more LoRa gateways to achieve a connection; the protocol does not allow clients to talk to each other directly. The devices use less power than cellular mobile communication, and they have low data rates, which go from 0.3kbps up to 50 kbps.

The standard is driven by the LoRa Alliance, with Cisco, IBM, Semtech and Gemalto among its members.

5.2.9 SIGFOX

Sigfox uses the 868MHz/915MHz license-free frequency band to enable a business model similar to mobile network operators. As of October 2018, the Sigfox IoT network has covered a total of 4.2 million square kilometres in a total of 50 countries and is on track to reach 60 countries by the end of 2018[13]. Sigfox provides cost effective communication (1€ - 5€ per device per year) for devices which don't need a fast connection.

This system has a channel bandwidth of 200kHz and a slow connection speed (100bps). The communication latency is of 4s for a typical message, and 60s maximum. Moreover, it has to be taken into account that this

[13] https://www.electronicsweekly.com/news/products/rf-microwave-optoelectronics/sigfox-iot-network-reaches-50-countries-2018-10/

technology allows to exchange 140 messages per day as a maximum which is expected to be an exclusion criterion for most scenarios even if low bandwidth is needed.

Many manufacturers of Sigfox clients can be found on the market, including Atmel and Texas Instruments.

Before Sigfox is selected as the preferred communications technology, special attention has to be paid to the network coverage in the area of use, as today (October 2015) it covers only one city in Germany (Munich).

5.2.10 NB-IOT

Narrowband IoT (NB-IoT) is developed by 3GPP to enable a wide range of cellular devices and services. It aims to address the needs of very low data rate devices (often powered by batteries) that need to connect to mobile networks. As a cellular standard, the goal of NB-IoT is to standardize IoT devices to be interoperable and more reliable. The 3GPP standard is currently in Release 13 (LTE Advanced Pro). It defines the device receiving bandwidth as 180 kHz with a download/upload rate of 250 kbits and a latency of 1.6s–10s.

5.2.11 SATELLITE COMMUNICATION

An interesting option is using satellite data communication in the bands of 137 MHz – 150 MHz or 1,6 GHz. Some of the current satellite systems available allow usage of a simple and relatively small rod antenna. Examples are Iridium and Orbcomm in Low Earth Orbit (LEO), as well as Globalstar and Inmarsat in geosynchronous orbit (GEO). Modules for machine-to-machine communication (M2M) are available on the market.

Using satellite communication has the disadvantage of generating running costs. However, it has the advantage of not requiring any infrastructure for a long-range communication. Unfortunately, such systems have a significant latency when delivering the data. As an example, Orbcomm announces that 2% of all the data have a delay of over 15 minutes, while Iridium defines waiting times between 1-8 minutes as possible.

5.2.12 PUBLIC CELLULAR NB (GPRS, GSM): MHZ & BB (HSPA, LTE)

Mobile communication allows the possibility of packet switched digital data communication using GPRS, EDGE, Evolved EDGE and HSPA. If the field components which require communication are all in range of a mobile communications network, then a very simple solution would be to provide the elements with communication over GSM/UMTS. These wireless technologies work in the bands of 850/900/1800/1900/2900 MHz.

As this is not always the case, an alternative is the setup of a local microcell. For a microcell, a low power cellular base station providing mobile communication coverage over a few kilometers, standard GSM/UMTS modules can be used. It should be noted that this microcell would require a connection to the backbone systems of the mobile network operator, as a cellular base station is going to require different resources located there, i.e., the home location register and the base station controller.

Different manufacturers offer such microcell products, for example Huawei and Alcatel-Lucent. The communications module can be obtained from many manufacturers, including Qualcomm, CSR and SIMCom. License to the appropriate frequency band will run by the mobile network operator.

5.3 Deployment Selection in SEMIoTICS Use Cases

Use Case 1 relies heavily on OpenFlow 1.3 to implement to packet matching and actions (forwarding and packet policing), as well as to realize the bootstrapping and signaling of the data plane. The heavy reliance on OpenFlow for control plane initialization is discussed in Bootstrapping Manager component description in Section 4.1. In addition to OpenFlow, Use Case 1 relies on OVSDB for initial device configuration and setup of the forwarding devices. NETCONF/YANG were not used for control plane <-> data plane interactions in SEMIoTICS due to the unavailability of commercial forwarding devices that implement the feature set necessary to realize QoS-constrained forwarding. Use Case 1, on the other hand, does not rely on wireless technologies and instead assumes a completely cabled setup, typical for industrial wind park deployments. An LTE router deployment is available for providing internet connectivity in the setup in non-wired environment (but only for the purpose of demonstrator showcase).

Use Case 2 leverages IEEE 802.11 Wireless LAN and IEEE 802.15.4 in the field layer, in particular:

- The four SARA hubs (i.e. User Mobile Phone, Robotic Rollator, Robotic Assistant and Home Gateway) communicate via IEEE 802.11 Wireless LAN
- The User Mobile Phone uses also cellular connectivity (LTE/HSPA depending on availability, to communicate with remote call center)
- The Home Gateway communicates with appliances and home automation via 802.15.4 ZigBee

Use Case 3 field devices, i.e., the IHES Sensing nodes are connected to the IoT Gateway hosting the IHES supervisor service using 802.11 Wireless LAN. From IoT gateway on, the connection is assumed to be cabled one. The final use case demonstrator is connected to relevant web services in mobility exploiting a HSPA/LTE router connection (but this is required only to allow the demo more portable and does not present a design constraint).

6 SDN IN THE CONTEXT OF THE SEMIOTICS USE CASES

The SSC with the majority of its functions will be deployed in Use Cases 1 and 2 as the main network connectivity enabler. Both Use Case 1 and Use Case 2 will deploy complete SSC function set, i.e., including all modules of Figure 5. Nevertheless, the two use cases will highlight different individual features of the SEMIoTICS architecture. More details per use case are presented in the following subsections.

6.1 Use Case 1

SEMIoTICS Use Case 1 comprises multiple programmable logic controllers, IIoT gateway, network routers (internet gateway) and SCADA application instances, interacting for purpose of field level monitoring, actuation and reporting of observed system state values to MindSphere platform in the backend. All interactions require basic field-layer and internet network connectivity, enabled by the SDN controller in automated and reliable manner. Furthermore, field layer services, such as: (i) the wind park controller-to-turbine actuation; (ii) updating of threshold values by SCADA in the turbine controller, with goal of per-turbine frequency and voltage optimization in energy production, as well as; (iii) proactive/reactive actuation in case of failure (i.e., stopping the turbine in case of oil/grease detection and outlier sound samples); require QoS-constrained interaction between the observing instance and the actuator.

To this end, SSC enables QoS-constrained network flows, fulfilling the individual latency, bandwidth requirements of the service, and will demonstrate:

(I) The initial automated bootstrapping of the network (focuses on Bootstrapping Manager)

(II) Instantiation of Virtual Tenant Networks in the field-layer (focuses on using Security Manager for authentication/authorization in SSC's UI and the VTN Manager for VTN enforcement).

(III) Providing best-effort flows for interconnecting infrastructural components in scope of the established VTN (focuses on interaction between Path Manager, Bootstrapping Manager, VTN Manager and Resource Manager components).

(IV) Providing QoS-constrained flows for interconnecting critical components (i.e., Programmable Logic Controller-to-Monitoring App connection). This workflow will require interaction between Path Manager, Pattern Engine, VTN Manager and Resource Manager, but will also necessitate the reservation state updates in Clustering Manager).

6.2 Use Case 2

The second use case of SEMIoTICS focuses on an ambient assisted living scenario. It encompasses a complex environment, requiring support for integration of heterogeneous devices and communication protocols, high degrees of interoperability and support for distributed services and applications (each with its own set of intrinsic requirements), while guaranteeing the safety of the patient and the security and privacy of her patient data. There is a significant motivation to leverage the flexibility provided by Service Function Chaining (SFC; as detailed in deliverable D3.2), to define specific service chains for each type of traffic in this scenario. With the functionality of each individual service functions in the chains being in line with the details presented in deliverable D3.2 (Section 2, in specific), we foresee the enablement of following SFCs:

- Chain 1 – Mobile Phone: Firewall -> Header Enrichment -> IDS -> Output
- Chain 2 – Robotic Rolator: Firewall -> IDS -> Load Balancer -> Output
- Chain 3 – Smart Home: Firewall -> IDS -> Output
- Chain 4 – Robotic Assistant: Firewall -> Load Balancer -> Output
- Chain 5 - Malicious: Firewall -> Honeypot

SSC will enable the Service Function Chaining, i.e., the configuration of paths fulfilling the forwarding of matched traffic through the VNF chains, as required by the above SFCs. To this end, VIM will interact with the SFC Manager of the SSC to request the according translation of SFC graph into the resulting network configuration and will showcase SSC's enablement of connectivity in backend layer using the VIM connector API of the SSC.

6.3 Use Case 3

While in principle SDN could be deployed in an extension of Use Case 3 scope, the aim of this use case is to highlight other components of the SEMIoTICS architecture, mainly focusing on the field layer.

7 CONCLUSIONS

This deliverable, being the final output of Task 3.1 ("Software defined Aggregation, Orchestration and cloud networks"), presented the purpose, architecture placement and the final design of the SEMIoTICS SDN Controller (SSC) solution. To this end, details on the design of all building blocks comprising the SSC were presented herein. The implementation and the description of SSC provided in D3.1 and D3.7 contributes to the achievement of project KPIs KPI-5.1, KPI-5.2 and KPI-6.3.

The presented SSC provides a means to dynamically and flexibly provision, monitor and evict virtual tenant networks and network services at per-application granularity, both during the engineering phase (pre-planned services) and at runtime. The flexibility in deployment of services comes from the wide gamut of specifiable and guaranteed properties associated with the provisionable network services, including but not limited to the end-to-end delay, bandwidth and redundancy properties.

Compared to existing industry standard, OpenDaylight and VirtuWind SDN controllers, SEMIoTICS has extended the platform by multiple controller components and component extensions, resulting in simplified network deployment, under consideration of strict constraints on control and data plane availability and reliability, unique to industrial domains and its mission-critical applications.

The SSC and the bulk of its functions will be deployed in Use Cases 1 and 2, as the main network connectivity enabler of SEMIoTICS. Furthermore, the deliverable covered the currently available wireless technologies for connecting (low-powered) sensor/actuator at large scale and long distance for industrial use cases, also including a mapping of selected wireless technologies on the individual Use Cases.

Compared to the initial version of the deliverable (i.e., D3.1), we have extended the contents of the implementation descriptions, with particular focus put on the newly developed mechanisms. To this end, D3.7 has focused on descriptions of the SEMIoTICS-specific contributions to the following designs and implementations:

- Byzantine Fault Tolerant SSC design.
- Automated in-band SDN bootstrapping for bootstrapping industrial SDN networks.
- The Pattern Engine for pattern-based interactions with the remainder of SEMIoTICS architecture.

We have additionally discussed the extensions made to VTN Manager, necessary in order to support the SEMIoTICS use cases. The newly developed designs have been evaluated, peer-reviewed and accepted in various high-ranking ACM and IEEE scientific conferences: ACM SIGCOMM 2019, ACM SOSR 2020 (Symposium on SDN Research), IEEE GLOBECOM 2019 etc. The design for in-band bootstrapping presented here was published as open-source on Github: https://github.com/ermin-sakic/sdn-automated-bootstrapping

REFERENCES

[1] T. Mahmoodi, V. Kulkarni, W. Kellerer, P. Mangan, F. Zeiger, S. Spirou, I. Askoxylakis, X. Vilajosana, H. J. Einsiedler and J. Quittek, "VirtuWind: virtual and programmable industrial network prototype deployed in operational wind park," *Transactions on Emerging Telecommunications Technologies,* no. 27-9, pp. 1281-1288, 2016.

[2] N. McKeown, T. Anderson, H. Balakrishnan, G. Parulkar, L. Peterson, J. Rexford, S. Shenker and J. Turner, "OpenFlow: enabling innovation in campus networks," *ACM SIGCOMM Computer Communication Review,* vol. 38, no. 2, pp. 69-74, 2008.

[3] R. Enns, M. Bjorklund, J. Schoenwaelder and A. Bierman, "RFC 6241: Network Configuration Protocol (NETCONF)," June 2011. [Online]. Available: http://www.rfc-editor.org/info/rfc6241. [Accessed 23 October 2018].

[4] M. Bjorklund, "YANG-a data modeling language for the network configuration protocol (NETCONF). No. RFC 6020.," 2010.

[5] E. Sakic, C. Bermudez Serna, E. Goshi, N. Deric and W. Kellerer, "P4BFT: A Demonstration of Hardware-Accelerated BFT in Fault-Tolerant Network Control Plane," in *SIGCOMM Posters and Demos '19: Proceedings of the ACM SIGCOMM 2019 Conference Posters and Demos*, Beijing, China, 2019.

[6] E. Sakic, N. Deric, E. Goshi and W. Kellerer, "P4BFT: Hardware-Accelerated Byzantine-Resilient Network Control Plane," in *2019 IEEE Global Communications Conference (IEEE GLOBECOM 2019)* , Waikoloa, HI, USA, 2019.

[7] R. Toghraee, Learning OpenDaylight: The art of deploying successful networks, Birmingham: Packt Publishing Ltd., 2017.

[8] OpenDaylight, "OpenDaylight Lithium," [Online]. Available: https://www.opendaylight.org/what-we-do/current-release/lithium. [Accessed January 2019].

[9] T. L. Foundation, "Open vSwitch," [Online]. Available: https://www.openvswitch.org/. [Accessed January 2019].

[10] J. W. Guck, A. Van Bemten and W. Kellerer, "DetServ: Network models for real-time QoS provisioning in SDN-based industrial environments," *IEEE Transactions on Network and Service Management 14.4,* pp. 1003-1017, 2017.

[11] ETSI, "ETSI.org: Network Functions Virtualisation (NFV); Architectural Framework (ETSI GS NFV 002 V1.2.1)," February 2014. [Online]. Available: https://www.etsi.org/deliver/etsi_gs/NFV/001_099/002/01.02.01_60/gs_NFV002v010201p.pdf. [Accessed November 2018].

[12] ETSI, "ETSI.org: Network Functions Virtualisation (NFV); Management and Orchestration (ETSI GS NFV-MAN 001)," December 2014. [Online]. Available: https://www.etsi.org/deliver/etsi_gs/NFV-MAN/001_099/001/01.01.01_60/gs_NFV-MAN001v010101p.pdf. [Accessed November 2018].

[13] OpenStack, "Compute API," [Online]. Available: https://developer.openstack.org/api-guide/compute/.

[14] OpenStack, "OpenStack Docs: Block Storage," [Online]. Available: https://developer.openstack.org/api-ref/block-storage/v3/.

[15] OpenStack, "OpenStack Docs: Networking API v2," [Online]. Available: https://developer.openstack.org/api-ref/network/v2/.

[16] OpenDaylight, "OpenStack and OpenDaylight," [Online]. Available: https://wiki.opendaylight.org/view/OpenStack_and_OpenDaylight.

[17] "YangTools Project," [Online]. Available: https://github.com/opendaylight/yangtools.

[18] " Drools Business Rules Management System (BRMS)," [Online]. Available: https://www.drools.org.

[19] R. Charles Forgy, "A Fast Algorithm for the Many Pattern/Many Object Pattern Match Problem," *Artificial Intelligence,* vol. 19, p. 17–37, 1982.

[20] H. Howard, M. Schwarzkopf, A. Madhavapeddy and J. Crowcroft, "Raft refloated: do we have consensus?," *ACM SIGOPS Operating Systems Review,* vol. 49, no. 1, pp. 12-21, 2015.

[21] K. ElDefrawy and T. Kaczmarek, "Byzantine fault tolerant software-defined networking (SDN) controllers," *Computer Software and Applications Conference (COMPSAC), 2016 IEEE 40th Annual,* pp. 208-213, 2016.

[22] E. Sakic, N. Djeric and W. Kellerer, "MORPH: An Adaptive Framework for Efficient and Byzantine Fault-Tolerant SDN Control Plane," *IEEE Journal on Selected Areas in Communications,* vol. 36, no. 10, pp. 2158-2174, 2018.

[23] OpenStack, "ML2 plug-in," [Online]. Available: https://docs.openstack.org/newton/networking-guide/config-ml2.html. [Accessed January 2019].

[24] O. N. F. (ONF), "OpenFlow Switch Specification: version 1.5.0 (Protocol 0x06)," 2014. [Online]. Available: https://www.opennetworking.org/images/stories/downloads/sdn-resources/onf-specifications/openflow/openflow-switch-v1.5.0.noipr.pdf. [Accessed 2018].

[25] B. Pfaff and B. David, "The open vSwitch database management protocol," *RFC 7047,* 2013.

[26] J. Song, S. Han, A. Mok, D. Chen, M. Lucas, M. Nixon and W. Pratt, "WirelessHART: Applying wireless technology in real-time industrial process control," *IEEE real-time and embedded technology and applications symposium,* pp. 377-386, 2008.

[27] OpenStack, "OpenStack Docs: Server concepts," [Online]. Available: https://developer.openstack.org/api-guide/compute/server_concepts.html.