SDN/NFV-enabled Satellite Communications: Ground Segment Network Architecture for 5G Integration

R. Ferrus[1)], H. Koumaras[2)], O. Sallent[1)], T. Rasheed[3)], R. Riggio[3)], N. Kuhn[4)], P. Gélard[4)], T. Ahmed[5)]

[1)]Universitat Politècnica de Catalunya, Spain; [2)]National Centre for Scientific Research "Demokritos", Greece; [3)]Center for Research and Telecommunication Experimentation for Networked communities, Italy; [4)]Centre National d'Etudes Spatiales, France; [5)]CNRS-LaBRI, University of Bordeaux, France

***Abstract*— The satellite industry is clearly committed to revisit and revamp the role of satellite communications within the 5G ecosystem. Central technologies being adopted in 5G networks such as Software Defined Networking (SDN) and Network Function Virtualization (NFV) are also anticipated to become key technological enablers for improved and more flexible hybridization of both satellite and terrestrial segments. This paper describes a novel architecture for SDN/NFV-enabled satellite ground segment systems that is conceived to facilitate the integration of the satellite component within 5G systems so that ubiquitous, highly available and reliable connectivity can be better supported.**

Keywords—Satellite network; Network Function Virtualization; Software-Defined Networking; Satellite gateway virtualization; Combined satellite-terrestrial networks

I. Introduction

The unique wide-scale geographical coverage of satellite networks, coupled with its inherent broadcast/multicast capabilities and highly reliable connectivity, anticipates new opportunities for the integration of the satellite component in the upcoming 5G systems. Several recent industry white papers reference the satellite-terrestrial cooperation as part of the mobile networks of 2020 and beyond [1][2], as there is a growing consensus on the idea that satellite responds efficiently to a number of usage/connectivity/traffic scenarios and complements nicely terrestrial 5G network components for many verticals (e.g. transportation, energy, media & entertainment, emergency communications). Indeed, the 3rd Generation Partnership Project (3GPP) is actually considering several use cases for 5G connectivity using satellites [3].

A huge increase in satellite capacity is underway as new High Throughput Satellites (HTS) in Geostationary Earth Orbit (GEO) come online, reducing the cost of the satellite capacity and achieving throughput rates that are magnitudes higher than previous satellites. Moreover, technological evolutions in satellites and the fruition in the forthcoming years of a range of disruptive initiatives envisioning the use of Low Earth Orbit (LEO) constellations with a large number of low-cost micro-satellites [4][5] might lead to further cost reduction as well as improvements in other Quality of Service (QoS) metrics such as latency. However, the evolutions in satellite ground segment network architectures (satellite hubs, satellite terminals and networking equipment within the satellite networks) can hardly be identified, since they are rarely publicly documented and implementations may not follow existing standards. Functionalities are thus deployed on vendor-specific network appliances, which execute specific functions. This leads to network infrastructure settings quite prone to vendor locking, complicated to manage since they use specific management protocols and proprietary systems that cannot operate together: even suppliers following the DVB-S2/RCS2 standards cannot inter-operate.

In this context, the introduction of Software Defined Networking (SDN) and Network Function Virtualization (NFV) technologies within the satellite ground segment networks (referred simply to as satellite networks in the following) is anticipated to be a necessary step in their evolution [6][7]. SDN and NFV technologies can bring greater flexibility to Satellite Network Operators (SNOs), reducing both operational and capital expenses in deploying and managing SDN/NFV-compatible networking equipment within the satellite networks. In addition, the adoption of SDN/NFV into the satellite networks can eventually pave the way for a more flexible and agile integration and operation of combined satellite and terrestrial networks [8].

This paper describes an innovative architecture for SDN/NFV-enabled satellite networks. The proposed architecture improves flexibility and reconfigurability in the delivery of satellite network services by supporting virtualization (i.e. softwarisation) of key satellite network functions together with network abstraction and resource control programmability. Moreover, the proposed architecture supports multi-tenancy to facilitate virtual network operator models and federation capabilities for the multi-domain orchestration of network functions and SDN-based control and management across terrestrial and satellite domains.

The rest of the paper is organized as follows. Section 2 briefly describes current satellite network architectures and discusses on the feasibility of virtualizing part of the satellite network functionality. Section 3 points out the expected benefits that the integration of a SDN/NFV-enabled satellite component could bring into two compelling scenarios: mobile backhauling and hybrid access. On this basis, Section 4 describes the proposed architecture for SDN/NFV-enabled satellite networks and Section 5 extends the architecture to cover the case of integrated satellite-terrestrial networks. Finally, main conclusions are drawn in Section 6.

II. Virtualization of Satellite Networks

A. *Current satellite network architectures*

Fig. 1 illustrates a general reference model for a multi-gateway satellite ground segment for satellite broadband communications [9][10]. It is structured in three main subsystems:

-The access subsystem, commonly referred to as the satellite access network. This includes the satellite gateways (GWs) and the satellite terminals (STs), which are interconnected through the resource of one or several channels (transponders) of a communication satellite.

-The core subsystem, commonly referred to as the satellite core network. This is an aggregation network that interconnects different satellite GWs located in the same or different satellite hub/teleport facilities as well as the network nodes located in some Points of Presence (PoPs) to interconnect with other operators, corporations and Internet Service Providers (ISPs).

-The control and management subsystems, composed of network elements such as the Network Control Centre (NCC) and the Network Management Centre (NMC), the former providing real-time control of the satellite network (e.g. connection control including the signaling necessary to set up, supervise and release connections) and the latter in charge of the management of the system elements of the satellite network (e.g. fault, configuration, accounting, performance, and security management).

A satellite GW typically comprises: the Out-Door Unit (ODU), composed of the antenna and radio head units; the Satellite Baseband Gateway (SBG) subsystems, composed of the Forwarding Link (FL) subsystem and the Returning Link (RL) subsystem for satellite access and transmission; and a set of Satellite Network Functions (SNF), in charge of the L2/L3 interconnection with the satellite core network as well as of different Performance Enhancing Proxy (PEP) functions to improve the higher layer protocols performance.

B. *Virtualization of satellite gateways*

Given their central role in the satellite network, the satellite GW is the most crucial component. Key drivers for the virtualization of satellite GWs are similar to those behind the virtualization of mobile radio access networks (e.g. Cloud Radio Access Network and virtualization of small cells). The ultimate aim is to enable the creation of an environment with fully virtualized capabilities allowing multi-tenancy, flexible instantiation, orchestration and management of resources and functions. In this regard, the concept of Satellite Cloud RAN (Sat-Cloud-RAN) is defined to refer to the applicability of NFV techniques to satellite GWs so that most of their functions can be run as one or more Virtual Network Functions (VNFs) on general-purpose compute platforms, leaving only very specific functionality to be run on specific hardware appliances for the sake of performance.

Fig. 2 provides a more detailed view of the main data and control plane functions that are generally integrated within a typical GEO satellite GW. For a LEO constellation, the functional GW model would be similar, including only a few other specific additionnal control functions such as the management of handovers. This architecture is based on the authors' interpretation of the DVB-S2 and DVB-RCS2 normative documents. Three potential variants for the split between VNFs and Physical Network Functions (PNFs) are illustrated in Fig. 2 by red-dotted lines. For each variant, the processes below the red-line would be implemented as PNFs (i.e. embedded within specialized hardware), while the ones above the red-dotted line would be supplied as VNFs (i.e. executed in a NFV Infrastructure Point of Presence [NFVI-PoP] with generic hardware). The relevance of selecting a variant mostly depends on the fronthaul link characteristics and the interaction between (1) the functions that could be centralized in one or several network entity (2) and those that are distributed in the satellite gateways. Without being conditioned to any particular variant, in the following the VNF implementation of the SNFs shown in Fig. 2 is generically denoted as SNF-VNF. Likewise, the VNF implementation of part of the SBG is denoted as SBG-VNF. And the non-virtualized part of the SBG is denoted as SBG-PNF. More information on the suitability of the different potential decompositions can be found in [11].

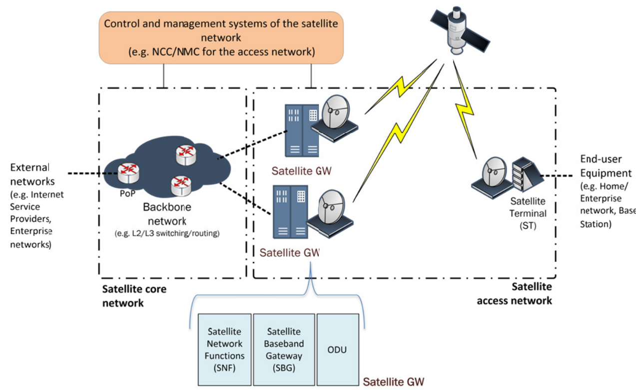

Fig. 1. Reference architecture for a typical multi-gateway satellite network

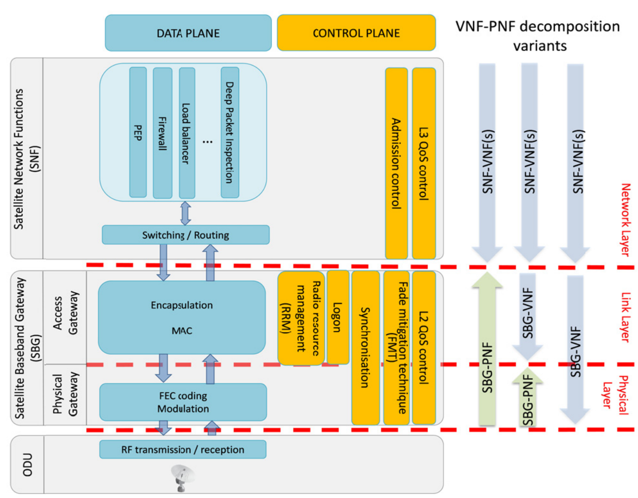

Fig. 2. Main functions within the data and control planes of a satellite GW and possible VNF-PNF decomposition variants

III. Integration Scenarios

Two compelling scenarios that will benefit from the integration of satellite and terrestrial networks through SDN/NFV-based technologies are described in the following.

A. 4G/5G satellite backhauling services

In addition to service extension in remote or hard to reach areas, a tighter integration of satellite backhauling services in 4G/5G mobile networks can be instrumental to facilitate more efficient traffic delivery to radio access network (RAN) nodes (e.g. the satellite link can be used to offload multicast/broadcast traffic such as TV live streams addressed to multiple cell sites), increased resilience and support for fast, temporary cell deployments and moving cells [12][13].

Building on the enhanced flexibility (e.g. bandwidth on demand) and satellite network service customization (e.g. selectable set of satellite VNFs) capabilities brought by SDN/NFV-enabled satellite networks, MNO's are expected to improve the level of control and management of satellite backhauling services through programmable interfaces for resource management and control. This must allow the MNO to simplify integration and management of satellite network services to satisfy its time- and location-dependent backhauling needs. This must also allow the MNO to be able to dynamically and flexibly provision and configure satellite network services with specific network functions (e.g. PEP, firewalling, etc.). From the SNO side, this scenario could also lead into an extended role of the SNO that, in addition to providing satellite connectivity, could be also participating in the value chain of Mobile Edge Computing (MEC) services and cellular access capacity provisioning through the operation of neutral/wholesale RAN shared nodes (e.g. multi-tenant small cells bundled with satellite connectivity).

B. Satellite-terrestrial hybrid access services

Hybrid access networks are those combining a satellite component and a terrestrial component in parallel [10]. Such a combination can improve service delivery in areas where QoS/QoE delivered by terrestrial access alone may be not satisfactory (e.g. higher speed broadband Internet access in low density populated areas with limited xDSL or fiber coverage [14]).

One promising approach to address the integration of satellite and terrestrial networks for hybrid access is federation. Federation refers to the pooling of network resources from two or more domains in a way that slices of network resources distributed across the different domains can be created and used as one logical domain enabling easier control of the resources [15]. Federation of network resources in heterogeneous and multi-domain scenarios is currently being addressed in several EU research projects (e.g. FELIX, FI-PPP XIFI, and FP7-NOVI). The expected development of federation capabilities in satellite communications is regarded as pivotal for providing additional resources, features and services by SNOs to customers.

Reconfigurability, evolvability and programmability are three key characteristics that can facilitate the achievement of the federation challenge, while SDN and NFV are the most promising enabling technologies. By embracing SDN, the satellite network can expose a vendor-neutral, universally supported open interface, enabling unified management with terrestrial networks. Similarly, the NFV techniques simplify the provision of value-added networking services in the satellite communications systems, by expanding the terrestrial NFV management framework to satisfy the needs of the satellite domain as well. This is in line with the 5G vision, which encompasses federation of heterogeneous access networks in a transparent manner [16]. Federation could also create a new market, where the federation from a business perspective is supported by a third party e.g. a broker, which offers added value federated network services supported by the underlying federated networks.

IV. Architecture of SDN/NFV-enabled Satellite Networks

A high-level view of the proposed architecture for SDN/NFV-enabled satellite ground segment systems is given in Fig. 3 and explained in the following.

A. Physical network infrastructure

As depicted in Fig. 3, the physical network infrastructure is assumed to consist of the following elements:

- NFVI-PoP(s) for SNF-VNFs. This infrastructure might not be necessarily located close to the satellite hub premises. The main resources in this NFVI-PoP are network, computing (CPU) and storage. Additionally, certain VNFs may require specific NFVI resource requirements, such as hardware accelerators (e.g. IPSec specific hardware).

- NFVI-PoP(s) for SBG-VNFs. This represents the virtualization infrastructure over which the satellite baseband gateway functions would be deployed. This infrastructure is likely to be located in or close to the satellite hub premises due to distance limitations that might impose the fronthaul network in terms of latency and bandwidth between SBG-VNFs and SBG-PNFs.

- One or several SBG-PNFs. These elements host the non-virtualized part of the satellite gateway. A SBG-PNF is directly connected to an ODU.

- Transport network between the several NFVI-PoPs (backhaul) and between the NFVI-PoP where the SBG-VNFs are run and the location that hosts SBG-PNFs (fronthaul).

B. Virtualized satellite network

On top of the above described physical network infrastructure, one or several virtualized satellite networks could be deployed, as illustrated in Fig. 3. A Virtualized Satellite Network (VSN) is conceived here as a satellite network in which most of their functions are supplied as software components running in one or several NFVI-PoPs of the SNO physical network infrastructure. The operation of each VSN could be undertaken by the SNO itself or by another company that will therefore play the role of SVNO. Each of the VSNs may include a variety of different entities (e.g. PEP, VPN, etc.). In particular, as illustrated in Fig. 3, the following entities could form part of a given VSN:

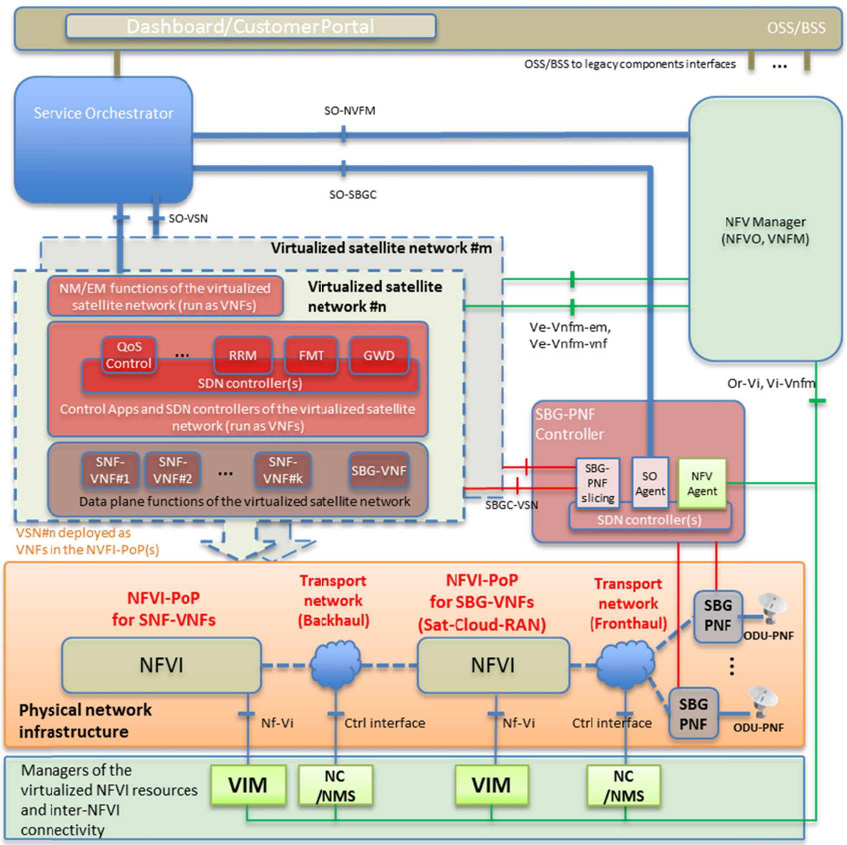

Fig. 3. Architecture reference model of the SDN/NFV-enabled satellite ground segment

- One or several SNF-VNFs and one or several SBG-VNFs. All these functions are part of the data plane processing of the VSN.

- Control applications and SDN controllers (all running as VNF instances) for the control and management planes of the VSN. SDN controllers provide the programmatic languages and abstraction models while the ultimate control logic is within the control applications. Control applications and SDN controllers interact with the data plane VNFs through different protocols (e.g. openflow, netconf, proprietary solutions). As illustrated in Fig. 3, potential control applications are RRM (i.e. dynamic bandwidth allocation to satellite terminals), FMT (i.e. dynamic selection of modulation and coding schemes according to satellite link quality) and GWD (i.e. gateway diversity). It's worth noting that an SDN abstraction of the SBG-PNF functions for control and management purpose is made available to the control programs through the PBG-Controller entity (explained below).

- Network Management (NM) and Element Management (EM) functions of the VSN. This provides a package of functions (to be used by the operator of a particular VSN) for the management of the satellite network (e.g. FCAPS management). These NM/EM functions could be supplied as VNFs or Virtual Machines on top the same NFVI-PoP where data and control plane VNFs are instantiated. Indeed, it is assumed that the VNFs that form part of the VSN (SNF-VNFs, SBG-VNF and control applications/SDN controllers) should be managed in the same manner as entities implemented with non-virtualization options, to the extent possible.

C. *Management components*

The creation and management of the lifecycle of the VSNs is realized through a set of functional entities within the SNO domain. In particular, VSNs can be instantiated, terminated, monitored, and modified (e.g. scaled up/down, VNFs added/removed, satellite carriers added/removed, etc.) through the following management entities:

- Service Orchestrator (SO). Decides on the composition and capabilities of the VSN. The decision-making logic for network composition can be fully supported within this element or distributed across a number of service orchestrators through federation capabilities (as described later in section 5). Once a network service is defined, the SO provides the necessary deployment templates (e.g. network service descriptor [NSD]) to the NFV management infrastructure. In parallel, the SO allocates and configures the required resources in the SBG-PNFs that will be used by the VSN (e.g. forward and return frequency channels). Once VNFs of the VSN are boarded to the NFVI-PoPs, the SO takes over and interacts with each of the deployed virtualized satellite networks through management interfaces (SO-VSN). In particular, the SO takes care of further (re-)configuration of the VNFs that form part of the VSN at runtime, dynamically and on-demand, to fulfil customer-specific services (e.g. configuration using Netconf/Yang protocols and data models). Therefore, the SO is able to monitor the components of a VSN once operational and take action in case of violation of rules (e.g. SLAs). Triggering conditions could come from both the NFV Manager as well as from the NM/EM functions that form part of the VSN. - NFV management entities. Comprised of the NFV Manager, the Virtual Infrastructure Managers (VIMs) for each involved NFVI-PoP and the Network Controllers (NC)/Network Management Systems (NMS) in charge of the connectivity between the NFVI-PoPs and between NFVI-PoPs and SBG-PNFs. NFV configuration management includes the configuration of VNF application specific parameters (satellite network service related) and the configuration of VNF deployment specific parameters (non-satellite network service related). In addition to initial deployment of the VNFs, some runtime actions such as scaling, updating and healing might also involve the NFV management entities.

- SBG-PNF-Controller. This element hosts a set of control programs and a SDN controller to manage the pool of SGB-PNFs. Through a SO agent application, the SO can request the allocation of SGB-PNFs resources (e.g. forward/return channels) for a given VSN. Therefore, the SBG-PNF-Controller will be in charge of slicing the resources of the SBG-PNF so that a logically isolated portion of those resources is allocated to a particular VSN. Through a NFV agent, the SBG-PNF-Controller will also provide support to the NFV Manager for the chaining of the resources sliced within the PNF and the resources (e.g. SBG-VNF) running within the NFVI-PoPs of the SNO physical network infrastructure (e.g. network ports/labels/tags). In addition, the SBG-PNF-Controller provides a SDN abstraction of the allocated resources (i.e. virtualized view of the PBGW resources and functions) so that control and management of these resources can be integrated within the VSN.

- SNO's OSS/BSS components such as dashboards/customer portals that the customers of the SNO can use to order the provisioning of VSNs and related SLA management.

V. Integrated Satellite-Terrestrial Networks

Fig. 4 depicts an extension of the previous described architecture for a scenario that involves a SDN/NFV-enabled satellite ground segment infrastructure, owned and operated by a SNO, and a terrestrial network infrastructure, such as a mobile or fixed communication network, owned and operated by a Terrestrial Network Operator (TNO). The delineation of the two infrastructures is depicted in Fig. 4 as SNO and TNO domains.

A key added feature to the proposed architecture is the support for multi-domain service orchestration capabilities through federation managers and agents, which will be part of the SO entities within each domain. Federation manager/agent will interact to establish the end-to-end network service settings and to partition the overall service graph into multiple subgraphs which can be given to each of the domains for further decomposition and instantiation.

Another key feature of the architecture will be the support for multi-domain SDN-based control and management. In this regard, the VSN would expose SDN-based interfaces for enabling unified management when interworked with terrestrial networks for e.g. end-to-end (E2E) Traffic Engineering (TE) and QoS control, as illustrated in Fig. 4.

Several federation models are envisioned (hierarchical centralized, distributed in chain, distributed full-mesh, and hierarchical hybrid), which could even lead to new business cases for third party companies that could play the role of a Federation Broker, as illustrated in Fig. 5.

VI. Conclusions

The role that satellite communications can play in the forthcoming 5G ecosystem is being revisited. In particular, the adoption of SDN and NFV technologies into the satellite domain is a key facilitator to actively hybridize satellite infrastructure within an anticipated multi-layer/heterogeneous 5G network architecture.

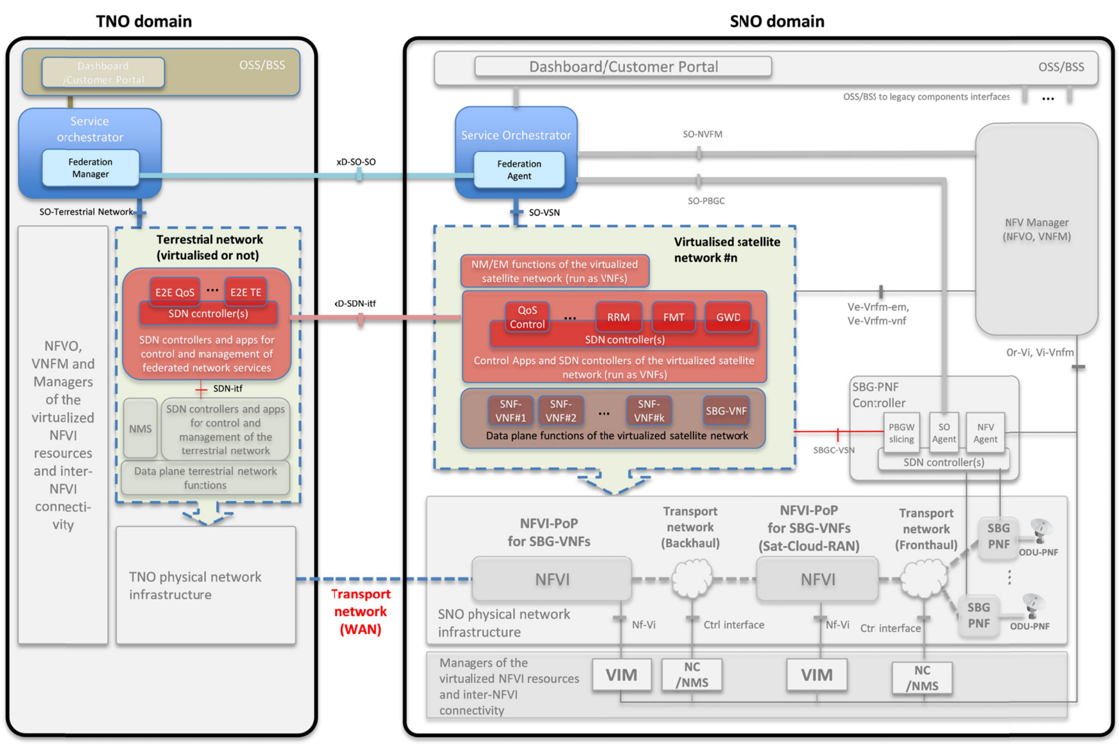

Fig. 4. Architecture reference model for an integrated terrestrial-satellite network with federation functions supported within SNO/TNO domains

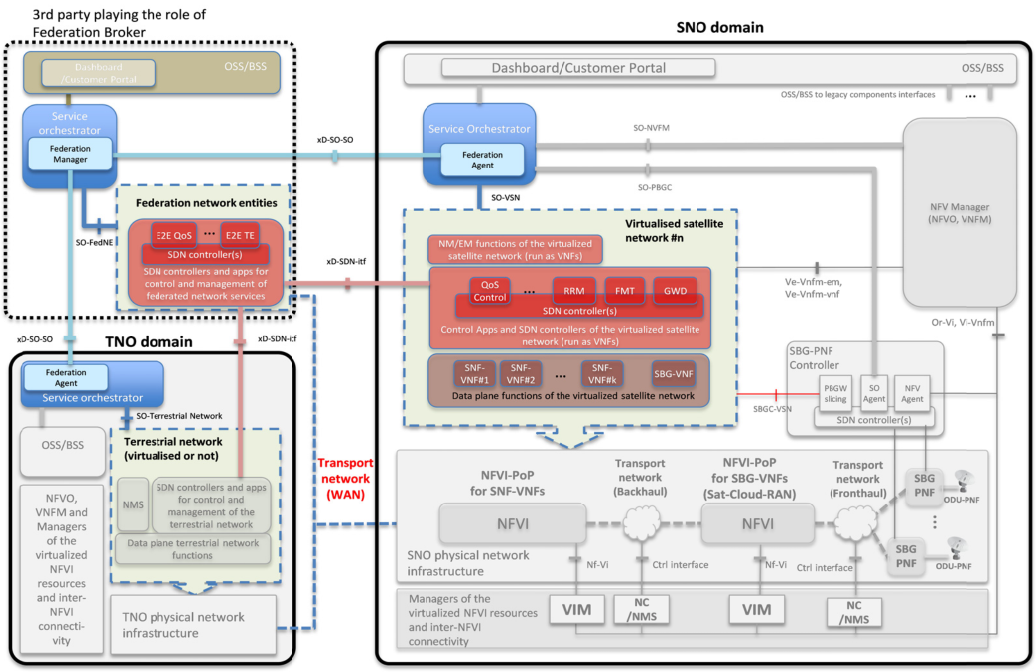

Fig. 5. Architecture reference model for an integrated terrestrial-satellite network with federation functions provided by a 3rd party entity

This paper has described an architecture reference model for SDN/NFV-enabled satellite networks. The proposed architecture is built on (1) the virtualization of satellite core network functions and satellite baseband gateway functions, and on (2) the adoption of SDN principles in the architectural design of the data and control plane components of a virtualized satellite network. The resulting architecture supports multi-tenancy as well as federation capabilities for the multi-domain orchestration of network functions and SDN-based control and management across terrestrial and satellite domains.

Future work will focus on the specification of the functional architecture of a virtualized satellite network, further delineating which control apps actually make sense and what are the interactions between control apps, SDN controllers, data-plane processing VNFs and EM/NM functions. Also, further progress is expected to develop the relevant federation models for multi-domain service orchestration in satellite-terrestrial networks.

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