

Satellite Networking Integration in the 5G Ecosystem: Research Trends and Open Challenges

Luca Boero, Roberto Bruschi, Franco Davoli, Mario Marchese, and Fabio Patrone

ABSTRACT

The envisioned 5G ecosystem will be composed of heterogeneous networks based on different technologies and communication means, including satellite communication networks. The latter can help increase the capabilities of terrestrial networks, especially in terms of higher coverage, reliability, and availability, contributing to the achievement of some of the 5G KPIs. However, technological changes are not immediate. Many current satellite communication networks are based on proprietary hardware, which hinders the integration with future 5G terrestrial networks as well as the adoption of new protocols and algorithms. On the other hand, the two main paradigms that are emerging in the networking scenario — software defined networking (SDN) and network functions virtualization — can change this perspective. In this respect, this article presents first an overview of the main research works in the field of SDN satellite networks in order to understand the already proposed solutions. Then some open challenges are described in light of the network slicing concept by 5G virtualization, along with a possible roadmap including different network virtualization levels. The remaining unsolved problems are related to the development and deployment of a complete integration of satellite components in the 5G ecosystem.

INTRODUCTION

The upcoming fifth generation (5G) of mobile networks is specifically conceived to provide extreme flexibility levels by design to support services and applications with highly heterogeneous requirements in terms of performance, scalability, and deployment scenarios. To cope with these challenging objectives, the current specification of 5G can be considered as “a network of networks,” since it will allow the adoption and combination (as needed by the overlying applications) of different and alternative network stacks and communication technologies. The “virtualization” paradigm is the key crosscutting enabler of 5G design. It will pervade the 5G architecture at any layer in order to provide the related resources “as a service.”

Clear and tangible examples of this process are the network functions virtualization (NFV), software defined networking (SDN), and software

defined radio (SDR) technological frameworks, which together constitute the “virtualization” engine of the 5G architecture [1]. Such technological frameworks fully decouple hardware infrastructures from network protocols and functions, and introduce advanced multi-tenancy capabilities such as the possibility of creating multiple isolated “virtual” domains over the same infrastructure, where multiple tenants can build and run their customized network services. To fully exploit these new capabilities and expose them toward vertical industries and over-the-top (OTT) players, the Third Generation Partnership Project (3GPP) and Next Generation Mobile Networks (NGMN) Alliance are radically redesigning northbound interfaces of telecommunication platforms, by adopting “network slicing” [1] as a base service model. The business/operational support systems (BSSs/OSSs) of upcoming 5G network platforms are meant to expose “customized” and isolated virtual projections of the mobile network (i.e., network slices) to vertical industries and OTT players, so as to enable them to run their applications and services on top of these network slices. To this end, a network slice is composed of a number of logical subnetworks that can have different roles and configurations. Such subnetworks can be instantiated as “private” network projections inside the slice, or shared among multiple slices (e.g., to attach multiple slices to the same radio access network).

The potential role of satellite networking in this ecosystem becomes manifest if referred to this slicing model, within which satellite resources can be embedded, either as physical network functions (PNFs) when considered in their current deployment, or, with much greater relevance, by including their virtualized operational components as manageable entities in the 5G architectural framework. Thanks to their intrinsic ubiquity and broadcasting capabilities, satellite networks can play multiple roles in 5G. The satellite can act as a main single backhaul segment for rural areas, aircraft, vessels, and trains; as additional backhaul means to opportunistically provide additional connectivity/bandwidth resources, also improving service continuity; or as a pure transport subnetwork.

The integration and use of satellite technology within the 5G ecosystem obviously poses new architectural and service requirements/limitations. For instance, on one side, it is reasonable to

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In order to enable this deep integration between satellite and 5G, a number of actions should be undertaken to bring state-of-the-art satellite technologies closer to the virtualization paradigm used within the 5G architecture. Many issues are related to physical layer aspects.

assume that satellite subnetworks can be directly applied to those traffic flows (e.g., mission-critical data) that are associated with 3GPP 5G [2] quality of service (QoS) indicators (5QI) allowing delays on the order of 100–200 ms. On the other side, satellite subnetworks can be adopted to facilitate and make more effective the deployment and operations of other intermediate 5G subsystems such as edge computing nodes needed to cope with tighter and more challenging 5QI levels like augmented reality applications. In the edge computing scenario, satellite interconnectivity may be exploited for the unicast/multicast/broadcast geographical distribution of video, audio, and application software binaries to a large number of terminals simultaneously.

In order to enable this deep integration between satellite and 5G, a number of actions should be undertaken to bring state-of-the-art satellite technologies closer to the virtualization paradigm used within the 5G architecture. Many issues are related to physical layer aspects; quoting [3]: “non-orthogonal multiple access (NOMA), massive multiple input and multiple output (MIMO), cooperative communications and network coding, full duplex (FD), device-to-device (D2D) communications, millimeter wave communications, automated network organization, cognitive radio (CR).” Nevertheless, from the networking viewpoint, to which this article is dedicated, virtualization and multi-tenancy are key aspects. Despite satellite technologies being well known to provide advanced network virtualization means, since they allow the dynamic management of multipoint QoS-guaranteed links, these capabilities should be exposed “as a service” to multiple concurring tenants. In this respect, the potential impact of architectural frameworks based on NFV, SDN, and SDR might be more than relevant.

This article offers a review of the main research studies and projects aimed at investigating how the network infrastructure of satellite networks will evolve embracing the virtualization principle in order to allow integration in the 5G environment. Then the still open challenges are described to highlight the need for further research before proceeding with the deployment phase. An architectural paradigm and a possible roadmap to identify the next steps of the satellite network virtualization and integration process within the 5G architectural framework are then proposed. The final section contains the conclusions.

SDN/NFV ENABLED SATELLITE NETWORKS

STATE OF THE ART

The physical and hardware separation between control and data forwarding nodes is one of the main principles behind the SDN paradigm. Its implementation is based on three different functional planes: the management plane, whose purpose is to compute resource allocation strategies to provide each user with the required QoS,

depending on the user’s policies and current status of the network; the control plane, aimed at computing and enforcing forwarding rules to a number of data forwarding nodes in order to properly route traffic flows; and the data plane, composed of the nodes of the underlying network infrastructure, whose only purpose is to forward the incoming traffic flows by following the given rules.

The aim of NFV is to decouple network functions from dedicated physical devices, making it possible to run such functions on general-purpose servers that could be deployed in network operators’ data centers. In this way, more precise hardware resource allocation and sharing can be achieved, implementing virtual network functions (VNFs) on virtual machines and assembling and chaining VNFs to create services.

These new concepts can also be employed in satellite communication networks, allowing:

- Intelligent delivery and deployment of new services in a flexible and programmable way
- Decreased energy consumption, by virtualizing the functions performed by the ground segment of the satellite infrastructure and consolidating/activating/deactivating them on remote data centers
- Capital expenditure (CAPEX) decrease by exploiting general-purpose hardware components to deploy virtualized functions
- Last but not least, the flexible embedding of satellite networking functionalities in the creation and dynamic adaptation of network slices, along with the required resource provisioning at the level of the satellite network operator (SNO)

SDN and virtualization for broadband satellite networks were investigated in [4]. This was one of the first studies to include a vision of how SDN and NFV concepts could be employed in satellite networks. The authors proposed a network architecture based on geostationary Earth orbit (GEO) satellite communications. Reconfigurable broadband satellite networks were also the focus of the research work in [5], where a strategy was developed to deal with the problem of resource management based on a functional architecture composed of virtualized functions distributed throughout the network. Reference [6] proposed a joint placement of controllers and gateways in an SDN-enabled 5G-satellite integrated network.

An SDN/NFV-based framework for integrated satellite-terrestrial communication networks called SERVICE was considered in [7], which exploits the centralized control of SDN to suggest a strategy to distribute the three planes of the SDN paradigm in the various network nodes of a multi-layer satellite network. The management plane acts as the orchestrator of the overall network in the satellite network management center (SNMC). The control plane is divided into two parts: the space part, dealt with by the space controller in GEO satellites, and the terrestrial part, in charge of the terrestrial controllers implemented inside data centers and satellite gateways (SGWs). The data plane is also divided into space and terrestrial parts, and is composed of medium Earth orbit (MEO) and low Earth orbit (LEO) satellites, SGWs, and other intermediate terrestrial nodes, such as SDN switches.

The European H2020 Shared Access Terrestrial-Satellite Backhaul Network Enabled by Smart Antennas (SANSA) [8] project has the objective of increasing the performance of mobile backhaul networks in order to meet the 5G requirements. Specific goals are to increase the capacity of the backhaul network trying to meet the predicted traffic demand of 5G, to improve the network resilience against link failure and congestion along with the spectrum efficiency in the Ka band, and to reduce the energy consumption of the current mobile networks and to ease their deployment. For these purposes, the project proposes the use of smart antennas to set up a novel end-to-end system architecture composed of both terrestrial and satellite nodes. Flexibility in the network is achieved through a hybrid network manager (HNM), which includes configuration, event, and topology management functionalities.

The European H2020 project Virtualized Hybrid Satellite-Terrestrial Systems for Resilient and Flexible Future Networks (VITAL) brings NFV into the satellite domain and enables SDN-based resource management in hybrid terrestrial-Sat-Com networks. A framework named the satellite cloud radio access network (SatCloudRAN) [9] is defined. Its main principle is to virtualize a digital video broadcasting (DVB) – satellite second generation (DVB-S2)/DVB – return channel satellite second generation (DVB-RCS2) ground infrastructure onto a centralized cloud-based processing platform. Three different virtualization levels are identified: network layer functions, medium access control (MAC) layer functions, and physical layer ones up to the radio frequency front-end of SGW outdoor units (ODUs). In detail, in the first level network functions such as performance enhancing proxy (PEP), admission control strategies, and QoS policies' management are performed in a centralized hub. IP packets are sent to the SGW. In the second level, the uncoded DVB-S2 frame (called BBFRAME) is created remotely and then sent to the physical gateway. In the last level, data packets forwarded to the ODU are physical layer frames (I/Q symbols). This framework could allow full virtualization of the satellite delivery chain and its provision as a service to multiple tenants, contributing to the satellite network as a service (Sat-NaaS) paradigm [10].

ARTES 1 CLOUDSAT aims to determine the applicability of SDN and NFV technologies in order to define and validate integrated virtualized satellite-terrestrial architectures [11]. The network architecture is composed of the following subsystems:

- Infrastructure, including the virtualization-capable equipment on which network services are deployed: switches and routers of the satellite terminals and gateways
- Infrastructure management entities, based on distributed management paradigms, such as virtualized infrastructure management (VIM) entities for the SDN/NFV enabled segments and the satellite segment, and a wide area management (WAN) entity
- Orchestrators, in charge of the deployment of services and resource allocation within each network segment

Despite the research efforts performed to fill the gap between the current satellite communication networks and their envisioned network virtualization evolution, we have identified some open challenges, which require being further investigated and solved.

- The federated manager, representing the interface toward each orchestrator, as well as the interface toward final users.

OPEN CHALLENGES

Despite the research efforts performed to fill the gap between the current satellite communication networks and their envisioned network virtualization evolution, we have identified some open challenges, which require being further investigated and solved before proposing a stable and standardized network architecture. All these issues have a strong impact on the future integration of satellite technologies into the 5G ecosystem; for instance, on how a satellite network may be included in a slice subnetwork, and how it may support dynamic life cycle operations such as instantiation, de-instantiation, and tuning, as discussed in the next section.

The first issue to be tackled is how to distribute the different layer functionalities that compose the SDN architecture, that is, in which nodes to locate the three SDN planes. This problem involves different factors, such as the high propagation delays of satellite links and the processing power capabilities of the considered components. Satellite networks may use different types of satellites acting at different altitudes (GEO, MEO, LEO) and characterized by different sizes (e.g., pico, nano, micro). For these reasons, their communication capabilities are differentiated in terms of transmission frequency bands, transmission rate, and number of onboard antennas that can be installed. All these variables can lead to different choices about SDN planes positioning, and consequently to different satellite network architectures.

Another concern in the design of an SDN satellite network is the implementation of the communication protocol between the data and control planes. In traditional SDN networks, this protocol is identified in the de facto standard OpenFlow. It enables the collection and processing of the network status information in order to allow the control and management planes to enforce policies and forwarding rules about current traffic flows. In a satellite network there is the need to collect network status information that may be insignificant in terrestrial networks, such as network topology changes due to satellite movements, satellite current available energy, and storage space. To allow this, some extensions of the OpenFlow protocol may be required.

As already mentioned, the network topology may change during the network lifetime due to LEO and MEO satellites' motion. As a consequence, there is the need for a handover procedure to keep the flow tables of the data plane nodes updated, performing new rule computations when needed. Another situation in which handover is required is when a satellite terminal, served by a given satellite, loses its visibility and has to switch to another one [12]. Even in this case, a change of the flow rules inside the involved switches and possibly reconfiguration of

(NFVO), upon requests coming from the OSS to satisfy the requirements of vertical applications, the functionalities of SGWs and satellite terminals (STs) need to be virtualized except for the ODU, which remains a PNF, basically conforming to the SatCloudRAN paradigm. To better highlight such functionalities and their mapping to VNFs, in Fig. 1, we have included the representation of a satellite network protocol stack that can implement either standard protocols such as TCP/UDP and IP or dedicated protocols indicated as “Other transport/network solution,” with the intention to include proprietary architectural elements aimed at performance optimization such as PEP and header compression. With the desired flexibility, satellite components (physically and/or virtually implemented in VIMs) can then be employed by the WIM in the backhaul whenever needed to support applications whose key performance indicators (KPIs) are compatible with their characteristics, or even to create transport links or subnetworks toward the Enhanced Packet Core (EPC). The role of SDN here becomes instrumental to allow fast reconfiguration and interconnection of attachment points for the functional components. In the MEC framework, in the presence of otherwise isolated terminals, the satellite virtual network may be the only means to deploy application components close to their users and to provide them with caching at the edge in order to satisfy stringent application requirements.

Let us take a practical example. A vertical service request may be monitoring and controlling remote installations such as oil and gas pipelines through supervisory control and data acquisition (SCADA) or, alternatively, tracking assets like containers. Remote installations, as well as containers when on board vessels, may be networked only through satellites, but vertical applications may ignore this technical need and deliver the service request to the BSS. The OSS checks multiple NFV services exposed by the NFVO and selects the satellite transport providing a given QoS in terms of delay, loss, and jitter (if requested). To provide the assured quality, the satellite network may need to perform specific actions, from the transport layer (e.g., PEP, TCP optimization) and network layer (e.g., IP DiffServ/IntServ, IP routing), within the satellite-independent layers, down to link and MAC and physical layer (e.g., MAC using successive interference cancellation [SIC], adaptive coding and modulation) in the satellite-dependent part. These operations may be performed in a VIM by one or more data centers, not necessarily located near the satellite Earth station, connected to each other by the WIM.

Open challenges identified in the previous section may be mapped over the architectural elements in Fig. 1 as also shown in Table 1.

The integration of terrestrial and satellite networks in 5G through the virtualization of network functions, the provision of slices, and the use of general-purpose instead of ad hoc hardware will not be immediate. Moreover, the investments required to design and deploy a GEO/LEO satellite communication network are huge, so current satellite operators cannot replace costly hardware components before the end of the scheduled network lifetime, especially concerning onboard technologies.

Challenges	Involved architectural elements
SDN plane positioning	WIM/PNF
SDN communication protocol issues	WIM/PNF/VNFM
Gateway selection	OSS
Real-time monitoring	OSS/NFVO/PNF
Impact of satellite motion on virtualization	OSS/NFVO/WIM
Resource and performance constraints issues	OSS/NFVO/WIM/WIM/MEC

TABLE 1. Matching between challenges and architectural elements.

Before implementing a complete operative case such as the one used in the previous practical example, gradual virtualization would be recommended to facilitate a preliminary integration in the near future. We have identified three possible incremental virtualization levels, as shown in the clouds of Fig. 2a, 2b, and 2c, respectively:

Ground Infrastructure: Physically composed of SGWs (i.e., the nodes interfacing satellite portions and ground infrastructure, which include ODUs), the network control center (NCC), and the network management center (NMC). The first step could be to virtualize network control and management functions previously performed inside the NCC and NMC, which would be virtually implemented inside a data center rather than on ad hoc nodes. These functions include dynamic network resource allocation, real-time control, and non-real-time management of the overall network, and could include the actions related to the SDN management and control planes, such as user policies management and forwarding rules computation. The functions performed by SGWs can be virtualized and remotely located in one or more data centers, reducing the special-purpose hardware components of the SGWs, which could be limited to the ODUs, excluded from the virtualization. As described in [9], there may be three different variants for the virtualization of an SGW, depending on the virtualization “depth”: only network and upper layers functions, such as PEP and virtual private network (VPN); network and upper layers + encapsulation MAC functions; network and upper layers + encapsulation MAC + physical layer functions, such as adaptive forward error correction (FEC), coding, and modulation, giving access to satellite links.

Satellite Terminals: The second step could be to virtualize the functions performed by the STs. Considering their role, the virtualized functions could be the same as for the SGWs except for the scheduling task that the SGW has to perform across many STs sharing the same resources. In this case the SGW has to coordinate different STs with different demands, QoS profiles, and channel conditions, whereas the STs do not have to deal with this task. Moreover, additional functionalities related to the MEC and content caching paradigms can be implemented inside remote servers to help reduce the latency.

Satellites: The final step could involve the addition of virtualized functions onboard satellites. Considering the different kinds of satellites and the various possible satellite constellations, both SDN control and data plane functions could be

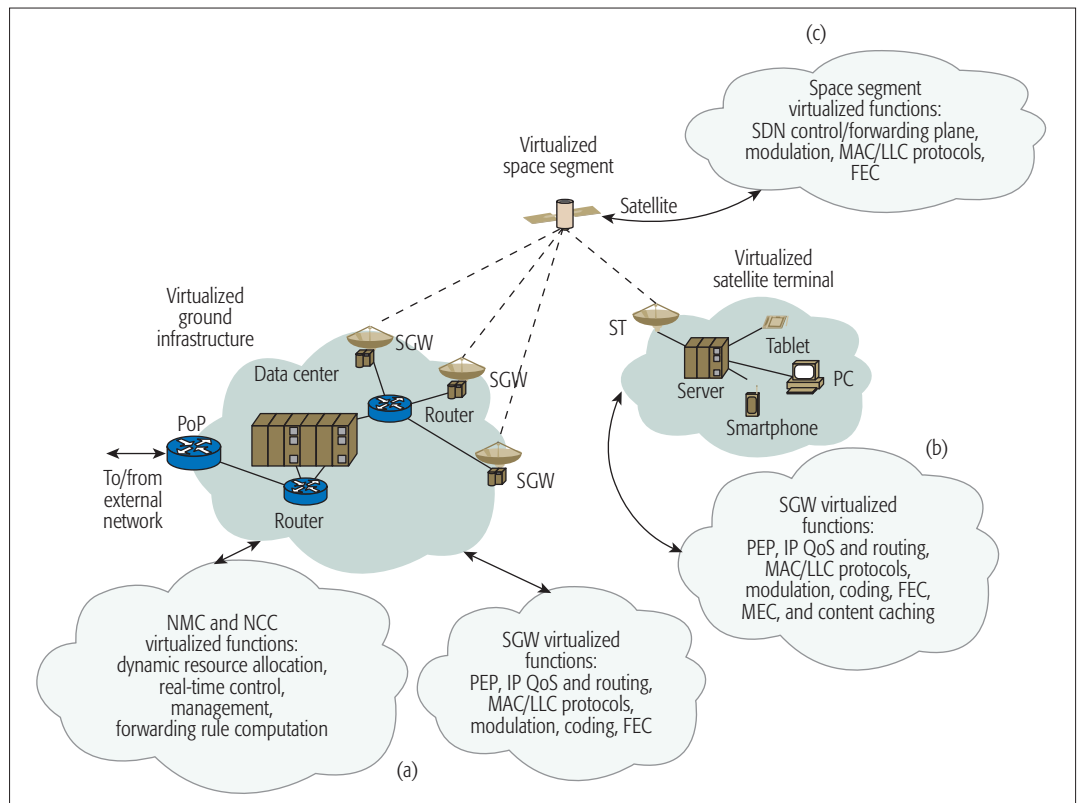


FIGURE 2. Roadmap for an SDN/NFV-enabled satellite network.

Satellite communication networks are going to play a crucial role in the 5G ecosystem, which can take advantage of their high coverage and broadcast capability to increase the number of networked users, and to improve the reliability and availability of the overall network.

implemented onboard satellites. Satellite communication functions could be virtualized in order to better exploit limited available resources. This point, however, requires a careful analysis of the onboard available resources, in terms of both performance and energy consumption and implementation costs.

CONCLUSIONS

Satellite communication networks are going to have a crucial role in the 5G ecosystem, which can take advantage of their high coverage and broadcast capability to increase the number of networked users, and to improve the reliability and availability of the overall network, particularly in emergency and critical missions, service continuity, and multimedia distribution. However, their integration with 5G terrestrial networks is a nontrivial task and entails evolution of the current structures. From the networking viewpoint, network virtualization is a concept that will bring benefits in terms of lower costs, higher flexibility, and tailored service provision. The adoption of SDN and NFV technologies into the satellite domain is seen as a key element to accomplish satellite and mobile terrestrial network integration, allowing the creation of a heterogeneous 5G network architecture and the provision of dedicated slices. In this vision, satellite network architectures should be augmented with autonomous and flex-

ible management of service life cycle operations, including the real-time monitoring of performance and other 5G KPIs.

This article has surveyed the outputs of some of the main research projects and studies about the integration of satellite networks in the 5G environment, with the purpose of highlighting the current status of the research in this field. Different architectures have already been proposed and tested, even though there are still some open challenges. We have described the open issues to be investigated before defining and standardizing an SDN/NFV-based solution for satellite networks. Considering the difficulties of virtualizing these networks, an architectural framework and a possible roadmap including a set of possible future steps to allow gradual virtualization starting from the satellite ground infrastructure up to onboard functionalities have been proposed.

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