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

Luca Boero[1], *Student Member, IEEE,* Roberto Bruschi[2], *Senior Member, IEEE,* Franco Davoli[1,2], *Senior Member, IEEE,* Mario Marchese[1], *Senior Member, IEEE,* and Fabio Patrone[1], *Member, IEEE*

[1]Department of Electrical, Electronics and Telecommunication Engineering, and Naval Architecture (DITEN)
University of Genoa, Via All'Opera Pia 13, 16145, Genoa, Italy

[2]CNIT, S3ITI Federated National Laboratory, Genoa, Italy

E-mail: [1]{luca.boero@edu., franco.davoli@, mario.marchese@, f.patrone@edu.}unige.it
[2]roberto.bruschi@cnit.it

***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 Key Performance Indicators (KPIs). Anyway, 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 - namely, Software Defined Networking (SDN) and Network Functions Virtualization (NFV) - can change this perspective. In this respect, this paper 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 the light of the network slicing concept by 5G virtualization, along with a possible roadmap including different network virtualization levels. The yet unsolved problems are evidenced toward the development and deployment of a complete integration of satellite components in the 5G ecosystem.**

***Index Terms*—5G, Satellite Networks, Software Defined Networking, Network Functions Virtualization, Network Slicing.**

I. INTRODUCTION

THE upcoming 5th generation of mobile networks (5G) 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 the 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 the 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 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 towards vertical industries and Over-The-Top (OTT) players, the 3rd 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 (BSS/OSS) 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 sub-networks 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 such 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, aircrafts, vessels, trains, or 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 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 in the order of 1-2 hundred milliseconds. 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, as for 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 paper is dedicated, virtualization and multi-tenancy are key aspects. Despite satellite technologies are well known to provide advanced network virtualization means, since they allow the dynamic management of multi-point 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 paper 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 the integration in the 5G environment (Section II). Then, the still open challenges are described to highlight the need of further research before proceeding with the deployment phase (Section III). An architectural paradigm and a possible road-map to identify the next steps of the satellite network virtualization and integration process within the 5G architectural framework are proposed in Section IV. Section V contains the conclusions.

II. SDN/NFV ENABLED SATELLITE NETWORKS

A. 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: 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; Control Plane, aimed at computing and enforcing forwarding rules to a number of data forwarding nodes in order to properly route traffic flows; 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 possible to run such functions on general-purpose servers which could be deployed in network operators' datacenters. In this way, a 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;
- decrease in energy consumption, by virtualizing the functions performed by the ground segment of the satellite infrastructure and consolidating/activating/deactivating them on remote datacenters;
- 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 are investigated in [4]. This has been one of the first studies to include a vision of how SDN and NFV concepts could be employed in satellite networks. The authors propose a network architecture based on GEO satellite communications. Reconfigurable broadband satellite networks are also the focus of the research work in [5], where a strategy is developed to deal with the problem of resource management based on a functional architecture composed of virtualized functions distributed throughout the network. [6] proposes 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 is 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 datacenters and Satellite Gateways (SGWs). The Data Plane is also divided into space and terrestrial parts and is composed of MEO and LEO satellites, SGWs, and other intermediate terrestrial nodes, such as SDN switches.

B. Research Projects

The European H2020 SANSA (Shared Access Terrestrial-Satellite Backhaul Network Enabled by Smart Antennas) [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, to reduce the energy consumption of the current mobile networks and to ease their deployment. To these purposes, the project proposes the use of smart antennas to set up a novel end-to-end system architecture composed by 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 VITAL (VIrtualized hybrid satellite-TerrestriAl systems for resilient and fLexible future networks) brings NFV into the satellite domain and enables SDN-based resource management in hybrid terrestrial-SatCom networks. A framework named Satellite Cloud Radio Access Network (SatCloudRAN) [9] is defined. Its main principle is to virtualize a DVB (Digital Video Broadcasting) - 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, MAC layers 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 ODUs are physical layer frames (I/Q symbols). This framework could allow a full virtualization of the satellite delivery chain and its provision "*as-a-Service*" to multiple tenants contributing to the Satellite Network-as-a-Service (SatNaaS) 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.
- Federated Manager, representing the interface toward each orchestrator, as well as the interface toward final users.

III. 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 lifecycle 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, i.e. 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, such as pico, nano, micro, etc. For these reasons, their communication capabilities are differentiated, in terms of transmission frequency bands, transmission rate, and number of on-board 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 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 Control and Management Planes enforcing 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, owing to LEO and MEO satellites motion. As a consequence, there is the need of 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 satellite NFV services may be needed, in order to avoid service interruption. Checking the impact of satellite mobility on virtualization and on the creation of logical virtual networks *as-a-Service* dedicated to given use cases (slices) is indeed a challenging task.

Another open challenge is related to the problem of the gateway diversity. The ground infrastructure may be composed of a set of satellite gateways linked together through the terrestrial network. Therefore, they offer different points of access to the space segment, which are geographically distributed in a wide area. This network topology, if really exploited, implies the application of strategies to choose the best satellite gateway for the forward links [13], [14]. The spectrum frequency bands used by satellite transponders are high, which increases the achievable transmission rates but also the attenuation due to atmospheric phenomena, such as rain. This means that the access to the space segment may be, in a given period of time, more convenient from one point with respect to another, both from the performance and from the energy viewpoint. Selecting the gateway may give practical advantages, if properly orchestrated. A real-time change of the satellite gateway for the ongoing transmissions due to the extreme attenuation of the forward link of the currently selected satellite gateway is a possibility; however, on one side, it should be transparent for OTT players using slices, and, on the other side, it should be dynamically managed by the network control plane in an agile and flexible fashion. For example, slice internal elements (i.e. slice subnetworks) might be reconfigured to route traffic towards the new gateways.

Other open issues regard real-time monitoring and resource constraints, which are not limited to the widely investigated GEO and LEO scenarios. Since the past few years, new kinds of satellites, such as CubeSats, have been attracting the attention of a large number of industries and universities, thanks to their lower costs and shorter deployment. The size and weight of these satellites are much lower if compared to GEO and LEO, but they suffer from very strict constraints about, for example, available energy, storage capacity, and computational power. These variables, among others regarding the status of the satellites in contact with the satellite gateways, should be monitored and controlled in the resource allocation process. At the same time, they make the provision of slices more time-dependent. To cope with the dynamic satellite features, slice provision and adaptation should be performed along with real-time monitoring of performance parameters and resource availability.

IV. Proposed Solutions

With reference to the 3GPP, ETSI NFV Management and Orchestration (MANO, http://www.etsi.org/technologies-clusters/technologies/nfv/open-source-mano) and ETSI Multi-access Edge Computing (MEC, http://www.etsi.org/technologies-clusters/technologies/multi-access-edge-computing) architectural frameworks, we can refer to the architectural elements depicted in Fig. 1 to highlight the main points connected with the deployment of satellite-related functionalities and their embedding as full-fledged slice components. Current satellite networking elements can be seen as PNFs, providing long-haul connectivity. To be integrated and orchestrated as slice components by an NFV-Orchestrator (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 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 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 make a practical example. A vertical service request may be monitoring and controlling remote installations such as oil and gas pipelines through SCADA (Supervisory Control and Data) 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 quality of service in terms of delay, loss, and jitter (if requested). To provide the assured quality the satellite network may need to operate 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 medium access control and physical layer (e.g., MAC using SIC - Successive Interference Cancellation -, adaptive coding and modulation, etc.) in the Satellite Dependent part. These operations may be performed in a VIM by one or more datacenters, not necessarily located nearby 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 I.

TABLE I
Matching between challenges and Architectural Elements

Challenges	Involved Architectural Elements
SDN Planes 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	SS/NFVO/WIM
Resource and Performance Constraints issues	OSS/NFVO/VIM/WIM/MEC

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

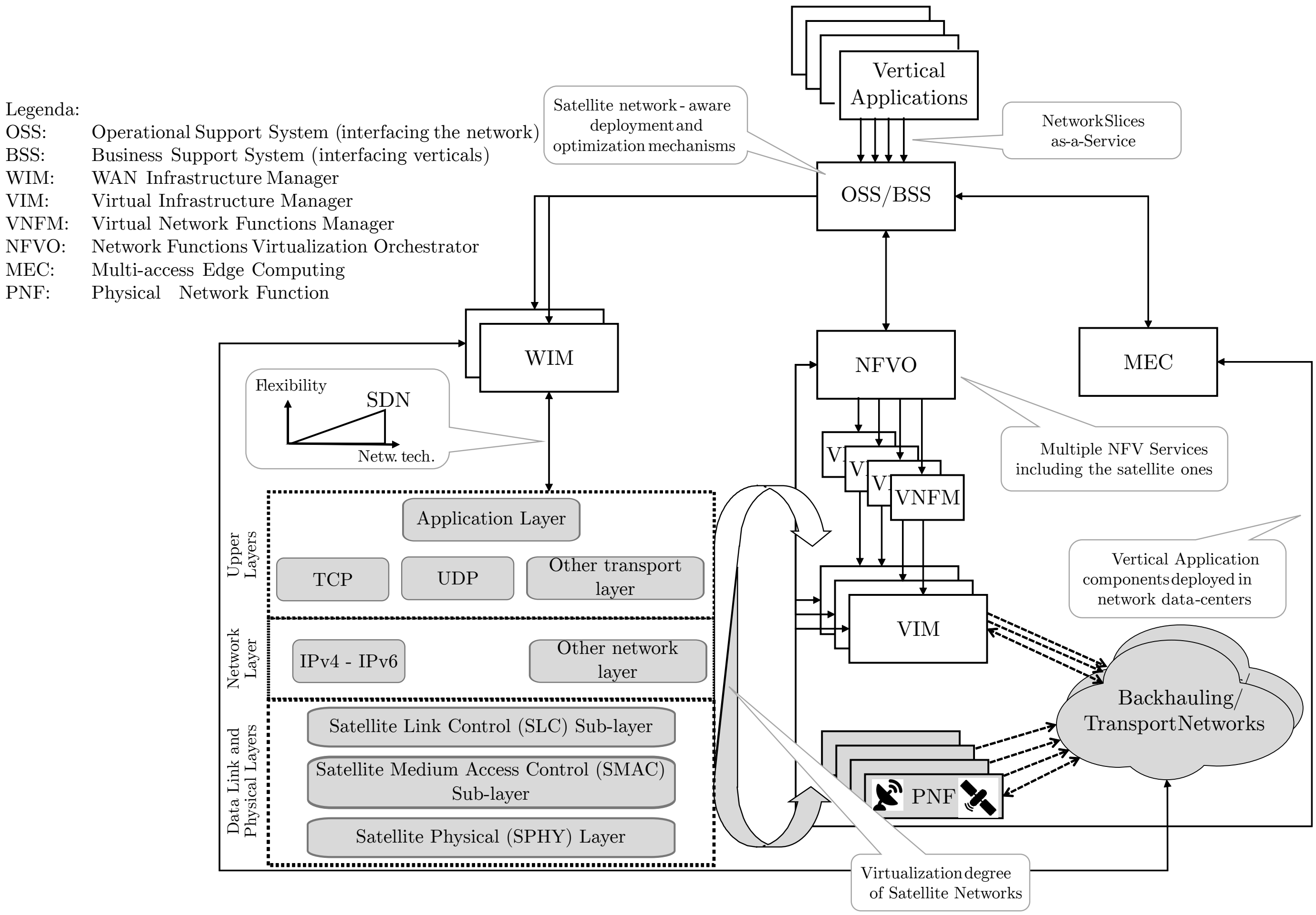

Fig. 1. Architectural Framework

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 on-board technologies.

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

(a) *Ground Infrastructure*, physically composed of SGWs (i.e., the nodes interfacing satellite portions and ground infrastructure, which include ODUs), Network Control Center (NCC) and 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 datacenter 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 SDN Management and Control Planes, such as user

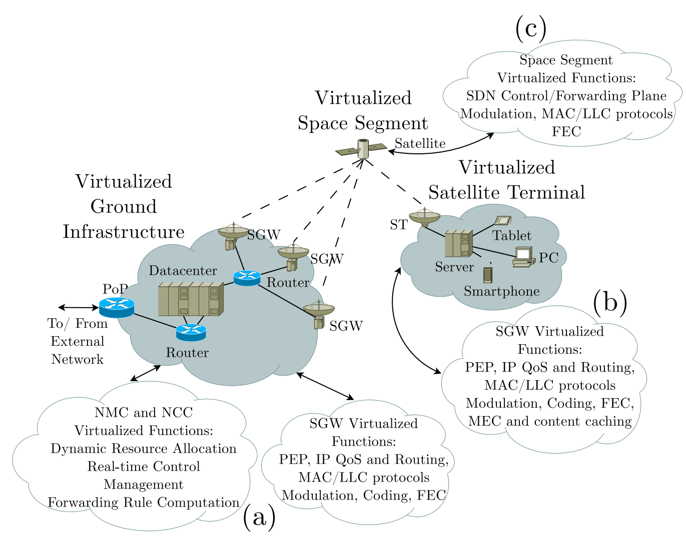

Fig. 2. Road-map for an SDN/NFV-enabled satellite network

policies management and forwarding rules computation. The functions performed by SGWs can be virtualized and remotely located in one or more datacenters, reducing the specific-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 a SGW, depending on the virtualization "depth": only network and upper layers functions, such as PEP and VPN (Virtual Private Network); 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.

(b) *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 that are 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.

(c) *Satellites*. The final step could involve the addition of virtualized functions on board satellites. Considering the different kinds of satellites and the various possible satellite constellations, both SDN Control and Data Planes functions could be implemented on-board satellites. Satellite communication functions could be virtualized in order to better exploit limited available resources. This point, however, requires a careful analysis of the on-board available resources, both in terms of performance and energy consumption and implementation costs.

V. 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 in particular in cases of emergency and critical missions, service continuity and multimedia distribution. However, their integration with 5G terrestrial networks is a non-trivial task and entails evolutions 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 networks 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 flexible management of service lifecycle operations, including the real-time monitoring of performance and other 5G KPIs.

This paper has surveyed the outputs of some 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 road-map including a set of possible future steps to allow a gradual virtualization starting from the satellite ground infrastructure up to on-board functionalities have been proposed.

Acknowledgment

This work was partially supported by the European Union's Horizon 2020 research and innovation programme under the 5G-PPP MATILDA project (grant agreement no. 761898).

References

[1] J. Ordóñez-Lucena, P. Ameigeiras, D. Lopez, J. J. Ramos-Muñoz, J. Lorca, and J. Folgueira, "Network Slicing for 5G with SDN/NFV: Concepts, Architectures, and Challenges," *IEEE Communications Magazine*, vol. 55, no. 5, pp. 80–87, May 2017.

[2] *3GPP TS 23.501:"Technical Specification Group Services and Systems Aspects; System Architecture for the 5G system; Stage 2"*.

[3] Z. Ma, Z. Zhang, Z. Ding, P. Fan, and H. Li, "Key techniques for 5G wireless communications: network architecture, physical layer, and MAC layer perspectives," *Science China Information Sciences*, vol. 58, no. 4, pp. 1–20, Apr 2015. [Online]. Available: \url{https://doi.org/10.1007/s11432-015-5293-y}

[4] L. Bertaux, S. Medjiah, P. Berthou, S. Abdellatif, A. Hakiri, P. Gelard, F. Planchou, and M. Bruyere, "Software Defined Networking and Virtualization for Broadband Satellite Networks," *IEEE Communications Magazine*, vol. 53, no. 3, pp. 54–60, 2015.

[5] M. Sheng, Y. Wang, J. Li, R. Liu, D. Zhou, and L. He, "Toward a flexible and reconfigurable broadband satellite network: Resource management architecture and strategies," *IEEE Wireless Communications*, vol. 24, no. 4, pp. 127–133, 2017.

[6] J. Liu, Y. Shi, L. Zhao, Y. Cao, W. Sun, and N. Kato, "Joint placement of controllers and gateways in SDN-enabled 5G-satellite integrated network," *IEEE Journal on Selected Areas in Communications*, vol. 36, no. 2, pp. 221–232, Feb 2018.

[7] T. Li, H. Zhou, H. Luo, and S. Yu, "Service: A software defined framework for integrated space-terrestrial satellite communication," *IEEE Transactions on Mobile Computing*, vol. 17, no. 3, pp. 703–716, 2017.

[8] Z. Georgios, P. Georgia, N. José, B. Jorge, M. Isaac, T. Christos, M. Sina, S. S. Krishna, A. Maha, and C. Symeon, "SANSA-hybrid terrestrial-satellite backhaul network: scenarios, use cases, KPIs, architecture, network and physical layer techniques," *International Journal of Satellite Communications and Networking*, vol. 35, no. 5, pp. 379–405. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/sat.1207

[9] T. Ahmed, E. Dubois, J.-B. Dupé, R. Ferrús, P. Gélard, and N. Kuhn, "Software-defined satellite cloud RAN," *International Journal of Satellite Communications and Networking*, vol. 36, no. 1, pp. 108–133, 2018.

[10] R. Ferrús, H. Koumaras, O. Sallent, G. Agapiou, T. Rasheed, M.-A. Kourtis, C. Boustie, P. Gélard, and T. Ahmed, "SDN/NFV-enabled satellite communications networks: Opportunities, scenarios and challenges," *Physical Communication*, vol. 18, pp. 95–112, 2016.

[11] G. Gardikis, H. Koumaras, C. Sakkas, and V. Koumaras, "Towards SDN/NFV-enabled satellite networks," *Telecommunication Systems*, vol. 66, no. 4, pp. 615–628, 2017.

[12] B. Yang, Y. Wu, X. Chu, and G. Song, "Seamless handover in software-defined satellite networking," *IEEE Communications Letters*, vol. 20, no. 9, pp. 1768–1771, 2016.

[13] T. Ahmed, R. Ferrús, R. Fedrizzi, O. Sallent, N. Kuhn, E. Dubois, and P. Gélard, "Satellite gateway diversity in SDN/NFV-enabled satellite ground segment systems," in *Communications Workshops (ICC Workshops), 2017 IEEE International Conference on*. IEEE, 2017, pp. 882–887.

[14] M. Mongelli, T. De Cola, M. Cello, M. Marchese, and F. Davoli, "Feeder-link outage prediction algorithms for SDN-based high-throughput satellite systems," in *Communications (ICC), 2016 IEEE International Conference on*. IEEE, 2016, pp. 1–6.

Luca Boero got his B.Sc. in Telecommunication Engineering in 2012 and his M.Sc. in Multimedia Signal Processing and Telecommunication Networks at the University of Genoa with a thesis on Software Defined Networking (SDN), developed at the Satellite Communications and Networking Laboratory (SCNL) in March 2015. He is currently a Ph.D. Student at the SCNL, and his main research activity concerns SDN, in particular Routing and Resource Allocation algorithms and Network Security for SDN Networks.

Roberto Bruschi (M'08, SM'13) received his Ph.D. degree in Electronic Engineering from the University of Genoa in 2006. He is currently a researcher of the National Inter-University Consortium for Telecommunications at the S3ITI Federated National Laboratory. He has co-authored over 100 papers in international journals, book chapters and international conference proceedings. He was the recipient of the best paper award at the 2009 IEEE ICC conference, at the 2010 IEEE GreenCom workshop, and of the best demonstration award at the 2017 IEEE/IFIP IM conference. Roberto has been the coordinator of the European H2020 INPUT project and of the Italian FiR GreenNet project (access rate 3%). He also served as project manager in the European FP7 ECONET Project, and currently serves as WP leader in the H2020 5G-PPP MATILDA project. He is Associate Editor for the IEEE Journal on Selected Areas in Communications - Series on Green Communications and Networking, for the IEEE Transactions on Green Communications and Networking, and for the IEEE Communications Magazine. His current main research interests include green networking, 5G, NFV, SDN, and edge computing.

Franco Davoli (M'90, SM'99) is Full Professor of Telecommunication Networks at the University of Genoa, Department of Electrical, Electronic and Telecommunications Engineering, and Naval Architecture (DITEN), currently serving as Coordinator of the Study Council in Telecommunications Engineering. His current research interests are in dynamic resource allocation in multiservice networks and in the Future Internet, wireless mobile and satellite networks, multimedia communications and services, and in flexible, programmable and energy-efficient networking. On these and other aspects he has co-authored over 350 scientific publications in international journals, book chapters and conference proceedings. He is currently the Head of the federated CNIT National Laboratory of Smart, Sustainable and Secure Internet Technologies and Infrastructures (S3ITI), based in Genoa, Italy, and the coordinator of the 5G-PPP project MATILDA.

Mario Marchese (S'94, M'97, SM'04) was born in Genoa, Italy in 1967. He got his "Laurea" degree cum laude at the University of Genoa, Italy in 1992, and his Ph.D. (Italian "Dottorato di Ricerca") degree in "Telecommunications" at the University of Genoa in 1997. From 1999 to January 2005, he worked with the Italian Consortium of Telecommunications (CNIT), by the University of Genoa Research Unit, where he was Head of Research. From February 2005 to January 2016 he was Associate Professor at the University of Genoa. Since February 2016 he has been Full Professor at the University of Genoa. He authored/co-authored more than 300 scientific works, including international journals, international conference proceedings and book chapters. His main research activity concerns: Networking, Quality of Service over Heterogeneous Networks, Software Defined Networking, Satellite DTN and Nanosatellite Networks, Network Security.

Fabio Patrone got his B.Sc. and his M.Sc. in Telecommunication Engineering in 2010 and 2013 at the University of Genoa. He got his Ph.D. at the Satellite Communications and Networking Laboratory (SCNL) with a thesis on routing and scheduling algorithms in Satellite Delay and Disruption Tolerant Networks (DTNs). He is currently a Post-Doc research fellow at the SCNL. His main research activity concerns Satellite Networks, with particular regard to the design of Routing, Scheduling, and Congestion Control algorithms.