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Software-defined satellite cloud RAN

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SUMMARY

This paper provides an assessment study on the virtualization of a Digital Video Broadcasting - Satellite - Second Generation (DVB-S2)/ Digital Video Broadcasting - Return Channel Satellite - Second Generation (DVB-RCS2) satellite ground infrastructure and proposes a framework, named Satellite Cloud Radio Access Network (SatCloudRAN), that aims to ease the integration of satellite components in forthcoming 5G systems. Special attention is given to the design of SatCloudRAN by considering the split and placement of virtualized and nonvirtualized functions while taking into account the characteristics of the transport links connecting both type of functions. We assess how virtualization and softwarization technologies, namely, network function virtualization and software-defined networking, can deliver part of the satellite gateway functionalities as virtual network functions and achieve a flexible and programmable control and management of satellite infrastructure. Under the network function virtualization paradigm, building virtual network function blocks that compose a satellite gateway have been identified, and their interaction exhibited. This paper also gives insights on how the SatCloudRAN approach can allow operators to provide software-defined networking-based (1) bandwidth on demand, (2) dynamic Quality of Service, and (3) satellite gateway diversity. Copyright © 2017 John Wiley & Sons, Ltd.

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1. INTRODUCTION

5G is not only about increasing the throughput or reducing the latency. The objectives behind this initiative are much wider and aim at providing Internet service anywhere, anytime, and with any device [1]. To achieve this goal, the various access technologies shall be inter-operable, but each component should fulfill its own role, to provide ubiquitous seamless coverage. The role of the satellite in 5G is deeply discussed in [2]: It is mainly driven by its inherent strengths in terms of large coverage complementing the terrestrial coverage, the resilience that is necessary in critical telecom missions and the broadcast capabilities. In this context, it is necessary to evaluate and assess the feasibility of solutions for the integration of a satellite component in future infrastructures to benefit from their natural advantages.

Satellite bidirectional access networks are of interest for many markets to (1) provide reasonable Internet access in rural areas, where commercially viable broadband service may hardly be realized, (2) provide services anywhere and anytime including coverage to wide areas, and (3) provide broadcast service to millions of users. The interest in more cooperative interactions between satellite and terrestrial networks is not new [3–6], and some access providers start offering broadband bundles that conjointly use satellite and terrestrial resources such as the National Broadband Network initiative.[‡]

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Despite these initiatives, satellite networks are harsh to integrate for a terrestrial operator because of the lack of common interfaces for resource management and control of terrestrial and satellite networks, emphasized by the absence of convergence in their management planes. Moreover, the satellite ground segments exploit rather specialized functions such as tuned Transmission Control Protocol (TCP) proxies for satellite networks [7] or specific low-layer mechanisms for the Digital Video Broadcasting - Satellite - Second Generation (DVB-S2)/Digital Video Broadcasting - Return Channel Satellite - Second Generation (DVB-RCS2) [8].

Anticipating flexible and standard control of satellite network resources will not only help toward a seamless convergence between satellite and terrestrial segments, but may also result in an increased service innovation and business agility. To reach this objective, recent years have witnessed a major shift toward the adoption of software-defined networking (SDN) [9] and network function virtualization (NFV) [10]. These technologies are only identified as necessary key technical components in 5G [1] so that 5G's requirements on flexibility and performance can be fulfilled. The introduction of SDN and NFV technologies within the satellite ground infrastructure along with the terrestrial network could pave the way for a fully unified control plane that would allow operators to efficiently manage and optimize the operations of their terrestrial and satellite networks. We have analyzed, in our previous work [11], the opportunities and the challenges of using SDN and NFV in satellite networks. In particular, we have presented three scenarios that could provide some improvement areas through the introduction of SDN and NFV in the satellite ground infrastructure. The SDN and NFV technologies can considerably improve the support of network sharing and multi-tenancy, that is, to let multiple tenants share an opened satellite ground segment infrastructure [11]. This approach can be seen as offering wholesale access to satellite network resources along with customizable control and management of equipment as well.

In general, network virtualization involves the implementation of network functions in software that can run on a range of industry standard hardware [12]. Ubiquitous, convenient, and on-demand access to a shared pool of configurable computing resources (e.g., networks, servers, storage, and services) can be rapidly provisioned and released with minimal management effort or service provider interaction. Virtualizing some functions that currently take place within the satellite gateways would improve the flexibility and the reconfigurability in the delivery of satellite network services. In the light of the increasing adoption of SDN and NFV technologies within terrestrial networks and the promised flexibility that would induce more interest in using satellite networks, this paper fills a gap in analyzing how to realize both (1) the virtualization of the satellite gateway and the satellite core network functions and (2) the management and control of a virtualized satellite ground infrastructure.

The main contribution of this paper is a novel framework named Satellite Cloud Radio Access Network (SatCloudRAN) that leverages cloud-based infrastructure and SDN-enabled network virtualization to deliver cost efficient, high-level resources availability and flexible resources sharing. Based on a thorough analysis of the DVB-S2 and the DVB-RCS2 normative documents[8, 13–16], we provide a detailed analysis of (1) how the control functions are currently implemented, (2) how they can be virtualized, and (3) how their management can be enhanced. Even if this analysis does not include a quantitative discussion of the advantages of SDN-control and NFV, we believe that it provides a valuable basis for a qualitative discussion. Indeed, it can be used to identify the aspects that have to be carefully considered in the virtualization process of a satellite gateway.

The rest of this paper is organized as follows. Section 2 describes (1) a reference architecture for satellite networks, (2) important functions that take place in the satellite core network, and (3) the functions that are integrated in a satellite gateway. We propose in Section 3 a discussion on the roadmap toward the feasibility of virtualizing the processes within the satellite network. In Section 4, we determine how the functions of a satellite gateway can be decomposed in a set of functions that could run as virtualized network functions and another set that would remain embedded in legacy hardware appliances. In the light of what processes can be isolated from each other, we assess the feasibility of virtualizing them in Section 5. Section 6 discusses the SDN control of a satellite core network with examples of controlled functions, such as bandwidth on demand or dynamic Quality of Service (QoS). We conclude this paper in Section 7.

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2. FUNCTIONAL ANALYSIS OF SATELLITE NETWORKS FOR BROADBAND ACCESS

Currently, satellite Internet access is mainly provided through geostationary orbit (GEO) broadband satellites, which ground segments systems are mainly proprietary. They follow nonetheless the spirit of the normative documents described in the DVB-S2 and DVB-RCS2. Our analysis has been based on published DVB-S2 and DVB-RCS2 documents [8, 13–16].

It is worth pointing out that our analysis can be extrapolated to other systems, such as Low Earth Orbit constellations. Indeed, some control functions are inherent to the use of satellite Internet access. As one example, error correction codes and specific modulations are required to cope with the challenging satellite channels. Moreover, there are control functions essential to monitor the way the resource is shared.

After a brief description of the main components found in a GEO broadband system, this section provides a description of the data, control, and management plane functions that form part of a typical satellite gateway. Table I presents the requirements for a GEO broadband system and the functions that are detailed in the rest of this section.

The rationale is to clearly describe the key processes candidate for virtualization that will be further analyzed throughout this paper.

2.1. Main components in a geostationary orbit broadband system

In the context of satellite broadband access for fixed communications, a general reference model for a multi-gateway satellite ground segment is structured in several main subsystems, as depicted in Figure 1.

The ‘Satellite Radio Access Network’ includes the satellite gateways and the satellite terminals, which are interconnected through the resource of one or several satellite channels. It can use a variety of network topology (star, multi-star, mesh, or hybrid star/mesh) and provide a variety of types of connectivity.

The ‘satellite core network’ is an aggregation network that interconnects different satellite gateways and includes the network nodes located at international point of presence to interconnect with other operators, corporations, and Internet service provider. Typically, the satellite core network is built

Table I. Requirements for a geostationary orbit broadband system.

Requirement	Rationale	Featured functions to fulfill the requirement
Optimized spectrum efficiency	Expensive satellite resource	Fade Mitigation Techniques Adaptive Coding Modulation Physical layer recovery mechanisms
Connect terminals	Strong requirement for bi-directional access	Log-on procedure Service Level Agreement
Share the capacity	Multiple terminals access	Synchronization Access gateway Quality of Service Channel access methods
Enable and improve an end-to-end connectivity	Network connectivity between components	Aggregation between multiple gateways (Quality of Service) Connectivity to Broadband Network Gateway (Ethernet, ipv4/6, etc.) Performance Enhancing Proxy Security, etc.
Manage the network	Network management [15]	Fault management Configuration management Accounting management Performance management Security management

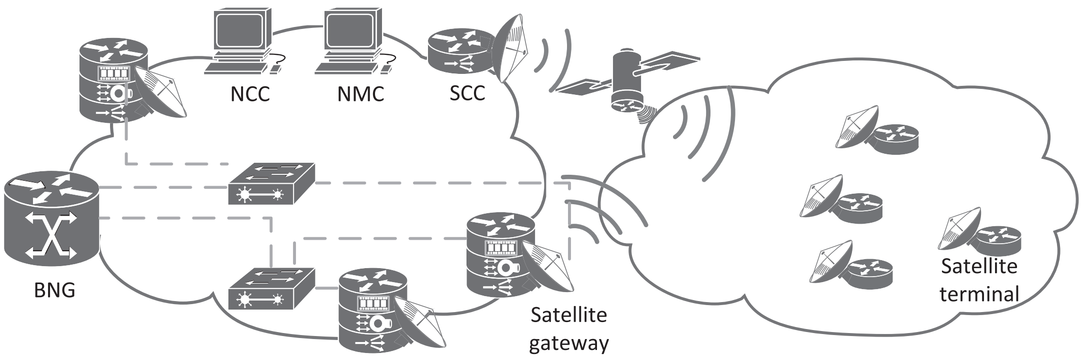

Figure 1. Satellite network architecture - source [17].

around an optical backbone with switching and routing equipment nodes based on Internet Protocol (IP)/MultiProtocol Label Switching or carrier-grade Ethernet technologies. The BNG can also form part of the satellite core network if the satellite operator is a network service provider.

The 'control and management subsystems' are composed of the Network Control Centre and Network Management Center. The Network Control Centre is used for real-time control of the connections and associated resources allocated to terminals that constitute one satellite network. The Network Management Center is used for non-real-time management functions related to a single satellite network. In addition, a Satellite Control Center is used to manage the satellite in-orbit platform and the satellite payload.

The reference architecture of a satellite gateway is depicted on Figure 2, which shows the following main elements that compose a typical satellite gateway: (1) an outdoor unit (ODU)*, composed of an antenna and its radio components (block up converter to transmit to the satellite and low-noise block converter to receive from the satellite); (2) a physical gateway, dealing with physical layer-related processes; (3) an access gateway, dealing with media access control (MAC) layer-related processes; and (4) a network connectivity block, dealing with the interface for aggregation network access (IP router, Ethernet switch).

The baseband gateway is the combination of the physical and access gateways. There are various main processes within the baseband gateway. Each process is composed of a set of functionalities that can be later isolated and virtualized when applicable. To support a discussion on their potential virtualization, we review in the rest of this section the main functionalities within each process.

2.2. *Data plane processes*

The data plane encompasses the actual transmission of IP packets on the satellite access network. Data plane functions within the network connectivity block, access gateway, and physical gateway are presented hereafter.

2.2.1. Network connectivity block. A non-exhaustive set of functions that could form part of the network connectivity block is illustrated in Figure 2.

A virtual private network (VPN) [18] securely connects isolated computers or regional networks to each other and the head office. The load-balancing process can be seen as a process that deals with splitting the load over various paths to simultaneously exploit the capacity of different links. As an example, load-balancing techniques can be used to share the load between various carriers, various gateways, or various access technologies (terrestrial/satellite). The performance-enhancing proxy (PEP) provides a combination of compression, caching techniques, and TCP acceleration. Because of TCP performance degradation over satellite links, PEPs are currently the most commonly adopted

*The ODU commonly refers to the satellite terminal; however, in general, it describes the equipment that is located outside of the building. The satellite hub as the place where the ODU is located.

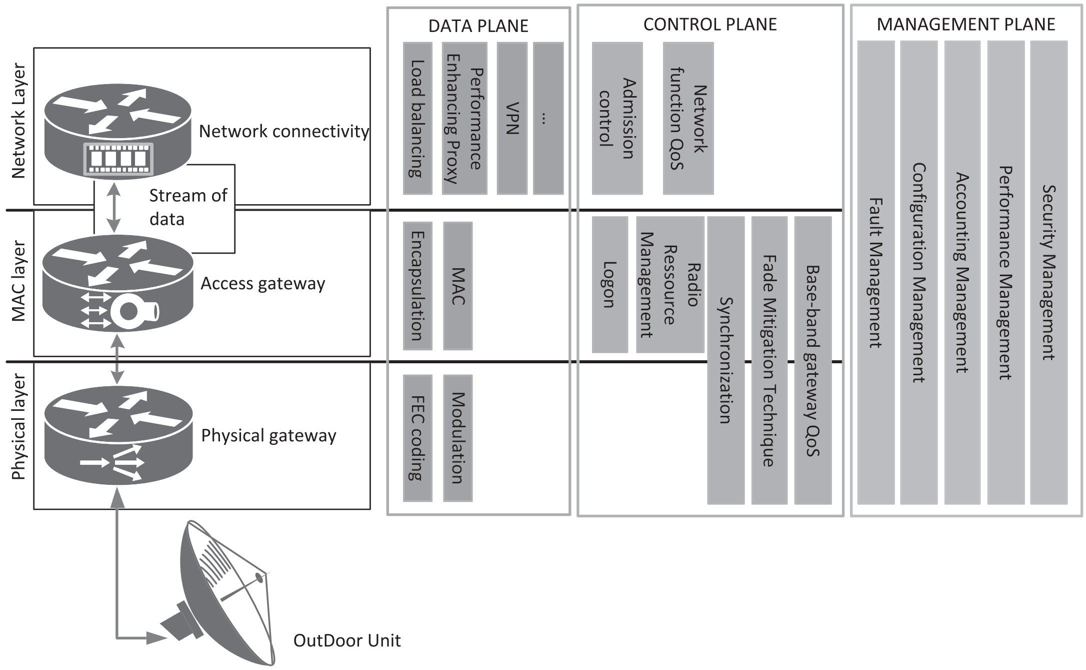

Figure 2. Satellite gateway reference architecture.

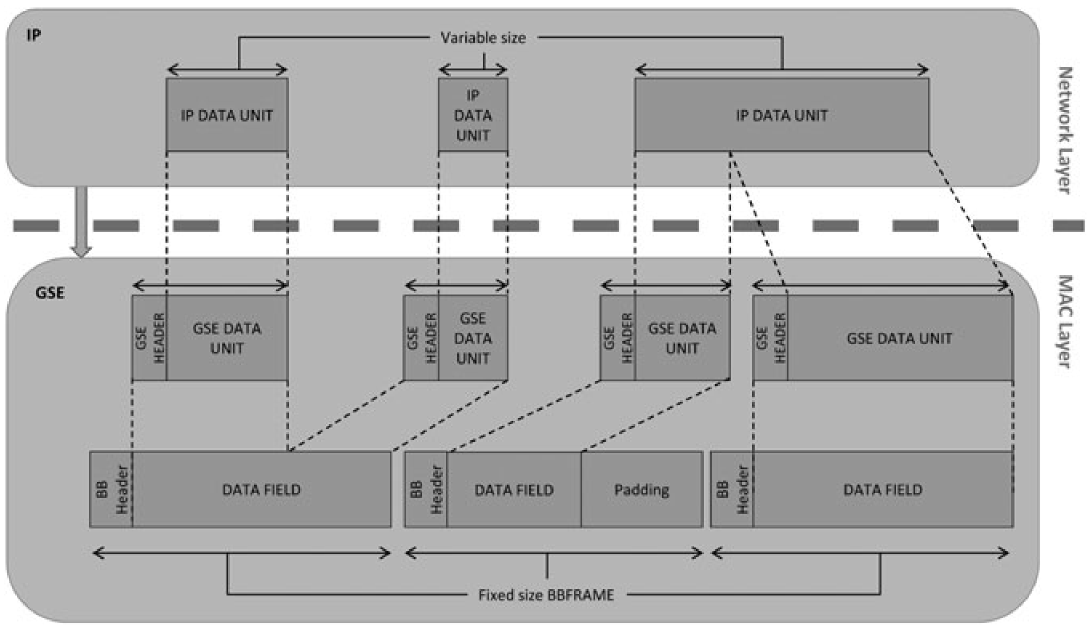

Figure 3. Media access control (MAC) layer data plane architecture on the forward link. BBFRAME, baseband frame.

solution to achieve good transport performance (in terms of link utilization and user experience) whatever the available TCP stack at both ends (clients and servers). The location of PEP terminations in the architecture has important impacts on the overall network design.

Other functions, such as data compression, firewall, or deep packet inspection, could have been considered but have been voluntarily omitted for the sake of clarity.

2.2.2. Access gateway. The protocol stack of the MAC gateway's data plane is given on Figure 3, on the forward link. MAC layer encompasses various functionalities, such as encapsulation and

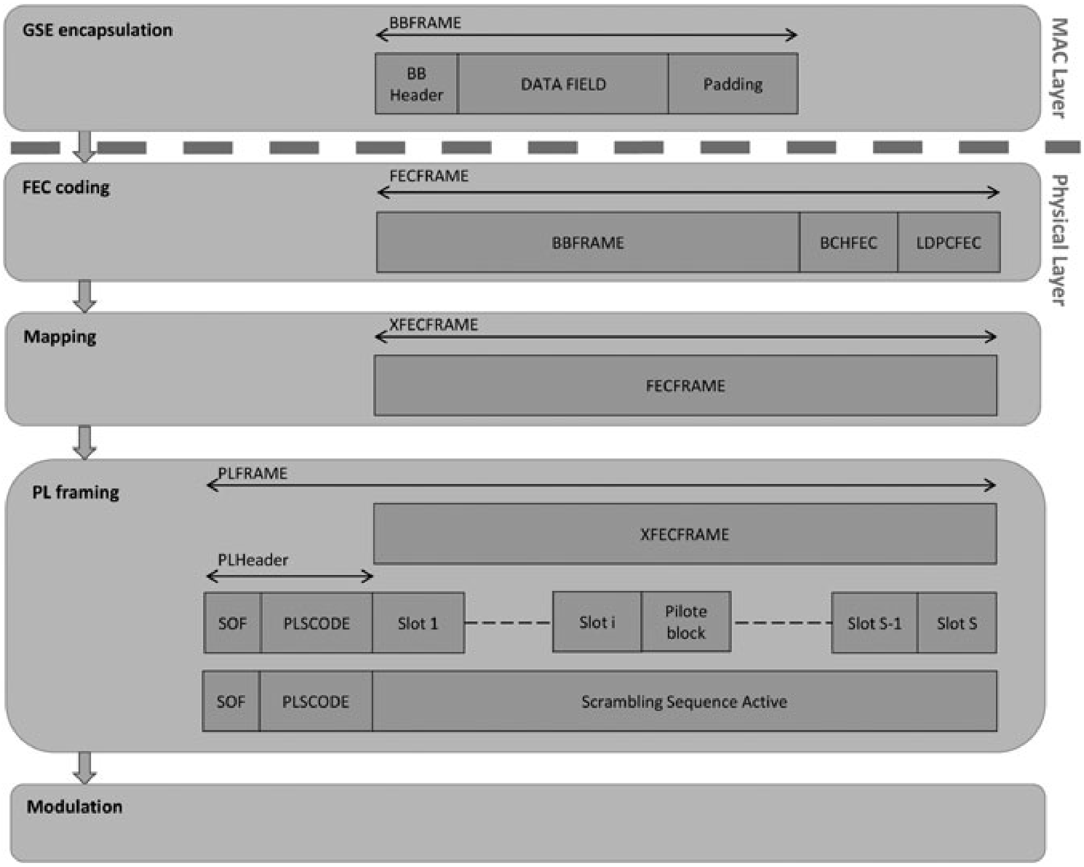

Figure 4. Forward link physical layer data plane architecture. GSE, Generic Stream Encapsulation; MAC, media access control.

fragmentation, medium access control itself, protocol multiplexing, scheduling, QoS, addressing scheme, and errors detection. The present section focuses on the description of the data plane, whereas processes related to the control plane are detailed in Section 2.3.

2.2.3. Physical gateway. The physical gateway is responsible for the actual transmission of baseband frame (BBFRAME)s or reception of return link data units. The architecture of the physical gateway is depicted, for the forward link. Because the process is similar on the forward and return link, we focus here on the former. The physical gateway forwards the 'ready-to-sent' L-Band signal to the ODU with the steps shown on Figure 4.

2.3. Control plane processes

The control plane process includes all the processes that set up the necessary procedure for data to be forwarded across the satellite network. In the routing area, the control plane is responsible for choosing the optimal routes and indicating routers how to actually forward packets from one point to another.

These processes are mostly in the access gateway but can take decisions that will be applied at the physical gateway: The control information can either be carried out along with data packets or through specific interfaces. Control processes mainly deal with deciding the physical gateway parameters that should be used, such as choosing the forward error correction coding rate, the modulation to be used, and the moment at which synchronization messages shall be transmitted. Thus, they parameterize the processes in the data plane that are shown in Section 2.2.

2.3.1. Logon. In order to access the radio resources and request capacity, a terminal has to gather the necessary information to communicate with the gateway.

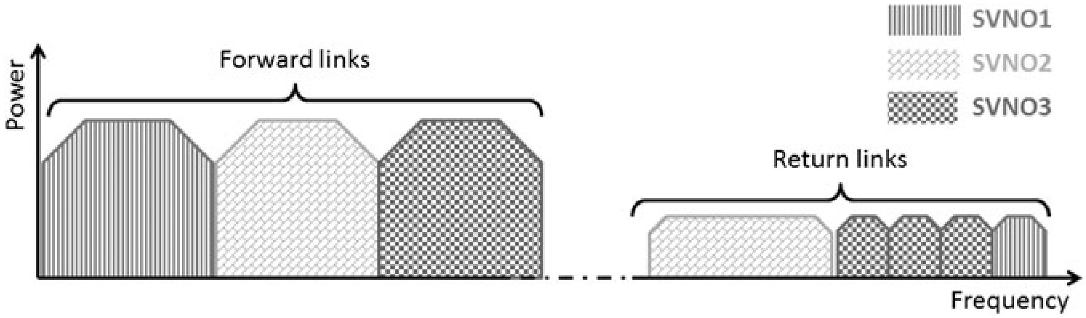

Figure 5. Example of the sharing of the spectrum between Satellite Virtual Network Operators (SVNOs). The way the frequency is shared among the SVNOs is more related to the management process; the scope of this figure is to show how the frequency can be shared between the forward and the return links.

2.3.2. Synchronization. Terminals and the gateway use internal clocks that independently drift over the time. On top of these clock drifts, the global clock synchronization is challenged by the fact that the satellite is moving and terminals are not located at the same place, which results in different jitters and different round-trip time for each terminal.

On the frequency synchronization, the DVB-S2 Forward Link frequency synchronization is dealt by using the pace at which the start-of-frame are received. At the terminal, the directed digital phase locked loops with phase error detection symbols sequence on the received symbols to improve frequency synchronization.

On the temporal synchronization, to achieve a global clock synchronization between the different terminals and the gateway, the gateway frequently transmits a timestamp Network Clock Reference (NCR) that is exploited by all the terminals on the return link. When terminals are able to locate the logon slots accurately, they can send logon requests. Knowing the slot in which the logon burst was sent and its reception time, the gateway can transmit correction messages to the terminal. At the receiver level, the transmission of data burst cannot start until the correction messages are not ‘close to zero’.

2.3.3. Radio resource management. Radio resource management (RRM) encompasses techniques needed to distribute the available frequency bandwidth in order to allow bidirectional communication between the terminals and the gateway. As shown in Figure 5, we illustrate the example of three Satellite Virtual Network Operator (SVNO) sharing the frequency resource that is divided between the forward and the return links. The relevance of this example depends further on the relations between the satellite operator, the bandwidth resellers, and so on.

On the forward link, the gateway uses all the available bandwidth, possibly with several carriers, to communicate with the remote terminals. A carrier is a single time-division multiplexing where packets addressed to terminals are multiplexed within BBFRAME as shown in Figure 3. The carrier settings (frequency bandwidth and symbol rate) are usually set once, and terminals are assigned to a carrier that suits their bandwidth needs. Hence, in terms of RRM, the forward link is mostly static for the assignment of terminals to carriers. The scheduling of data within the forward link is mostly dynamic, and we consider in this article that the scheduling is dealt with the baseband gateway QoS.

On the return link, the goal of the RRM is to distribute the resource between terminals to let them communicate with the satellite gateway. The access method proposed units called Bandwidth-Time Unit. Contiguous Bandwidth-Time Units can be grouped into a timeslot, several timeslots form a frame, and several frames are themselves grouped into a superframe. This hierarchy is described in Figure 6.

Terminals can send periodically to the gateway a traffic request, expressed either in rate (rate-based dynamic capacity) or in volume (volume-based dynamic capacity). The request may be only sent in the SYNC slot, but vendors can also use in-band request. If this update process is done at each superframe, only a subset of all terminals can actually update their requests, in order to minimize the overhead created by the control plan on the return link. At each superframe, the gateway collects all the terminals

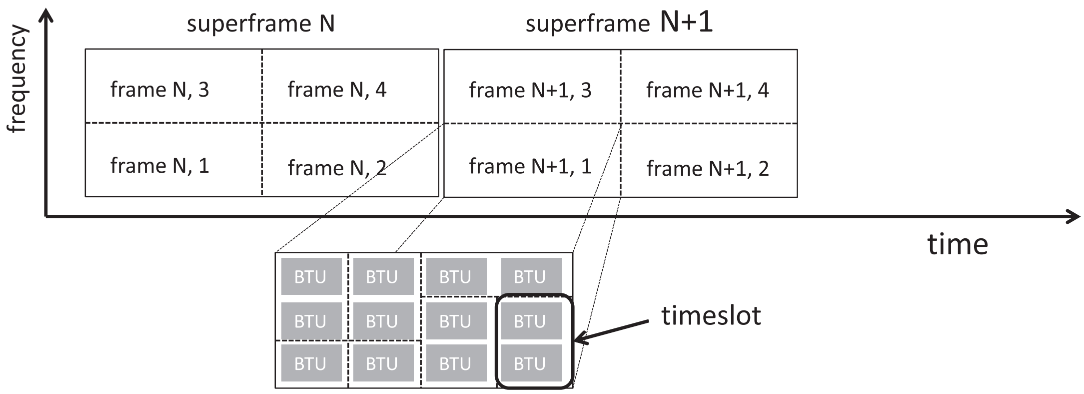

Figure 6. Digital Video Broadcasting - Return Channel Satellite - Second Generation return link hierarchy. BTU, Bandwidth-Time Unit.

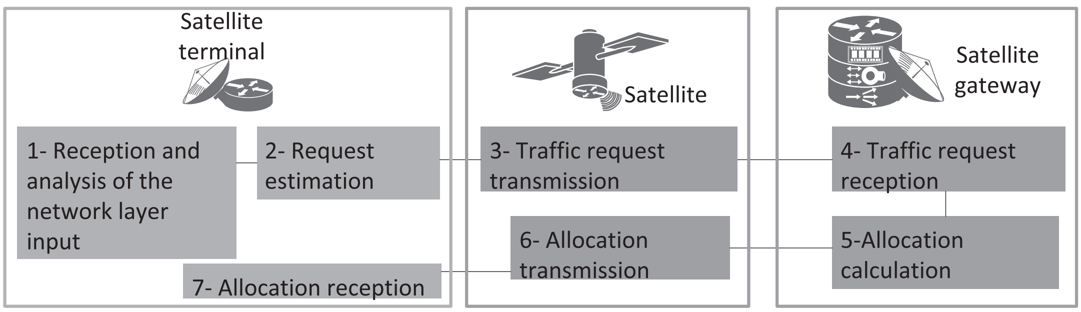

Figure 7. DVB-RCS2Digital Video Broadcasting - Return Channel Satellite - Second Generation allocation process.

requests and allocates the next available superframe to terminals, following their requests. This process is shown, for a single terminal, on Figure 7.

2.3.4. Fade mitigation technique. The first generation of Digital Video Broadcasting - Satellite (DVB-S) systems were designed for a worst-case scenario, where attenuation was considered maximum. The robustness of the transmission toward errors, controlled by both coding rate and modulation order, was adapted to provide a quasi error-free link even in the worst case. It could therefore provide a very high availability (up to 99.6 % of time) but was largely oversized for most of the time. To better utilize the medium, DVB-S2 and DVB-RCS2 systems introduce adaptive modulation and coding schemes that consider the current channel quality.

On the DVB-S2, the key concept of this technique is to monitor link quality in real-time, with the help of known symbols sequences, included along regular packets, on which an estimation of the current signal-to-noise ratio (SNR) can be done. Then, this estimation is sent back to the transmitter who can adapt its coding rate and modulation order to best fit the actual transmission conditions. This process is shown on Figure 8 with focus on the forward link, where it is called Adaptive Coding Modulation (ACM). The ACM process usually sets a target packet error rate (PER) as a reference, such as 10^{-7} for the forward link.

On the DVB-RCS2 link, DVB-RCS2 can also feature return link FMT, with the help of known symbols, or pilots, included in bursts. Once the gateway receives a burst, it can estimate link quality with those pilots, and adjust the modulation and coding (MODCOD) used in the timeslots allocated to the terminal. The gateway may also adapt the time-frequency distribution, considering the channel conditions.

2.3.5. Terminal admission control. The terminal admission control is a method that can be used to restrict the access to a network. If a network device has been configured to consider admission control, it may force user authentication before granting access to the network.

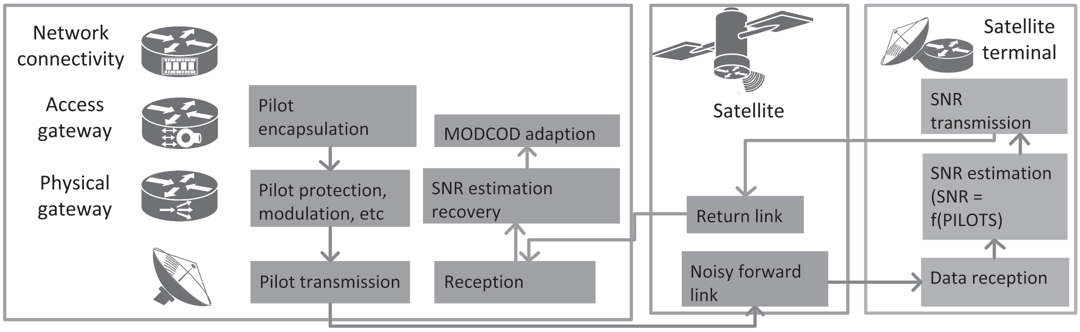

Figure 8. Fade Mitigation Techniques mechanism on forward link. SNR, signal-to-noise ratio.

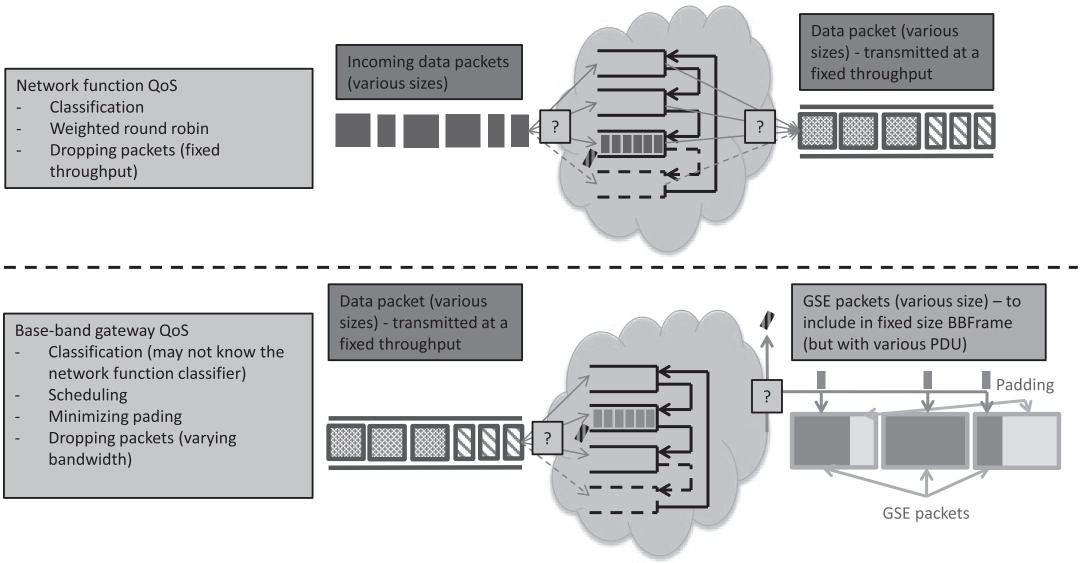

Figure 9. Example of the network function Quality of Service (QoS) and of the baseband gateway QoS. GSE, Generic Stream Encapsulation; PDU, protocol data unit.

An application running on the terminal connects to the network by a logical session. Based on the protocol used, subscriber sessions are classified into types that depend on whether the interconnectivity is dealt with at layer 2 or layer 3.

2.3.6. Control plane QoS. The QoS is the capability of a given network to carry out a given data flow in good conditions (in terms of delay, jitter, loss rate, capacity, etc.). Thus, as shown in Figure 2, the QoS optimization process operates at both the access gateway and the network connectivity block. This process can be divided into two sub-processes: the 'network function QoS' and the 'baseband gateway QoS'.

The combination of the network function QoS and the baseband gateway QoS deals with variously sized incoming packets, such as shown in Figure 3, and a limited resource as shown in Figure 5. Figure 9 is an example on how the network function QoS and the baseband gateway QoS can interact.

The network function QoS classifies the packets in dedicated sub-queues depending on defined parameters (tag, flow, packet size, etc.): The objective is to adapt a scheduling algorithm so that packets are dequeued with considerations of the requirements for each given class of traffic. Network-level QoS is usually responsible for multiplexing the incoming flows before passing them to the access layer. When a sub-queue is full, incoming packets are dropped. The classifier may consider the nature of the transport protocols in its classification, so that the sub-queues containing flows that are reactive to congestion can consider active queue management [19] techniques to reduce the buffering and the

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latency [20]. Because they cannot access to the lower layer characteristics, some implementations of network function QoS consider that the whole available goodput can be exploited by the lower layers: This case is referred as the 'clear sky' case. Because the throughput is sensible to channel quality (because of FMT), the lack of information can lead to overflows. Several QoS architectures have been proposed, such as differentiated services IP QoS [21] or Metropolitan Ethernet QoS [22], or specific to the satellite return channel [23, 24].

As shown in Figure 9, data packets of various sizes enter the baseband gateway with a fixed throughput. The baseband gateway generates variously sized Generic Stream Encapsulation packets that are to be included in BBFRAME. The payload in a BBFRAME depends on the MODCOD. Joint algorithms on the decisions of the scheduling and the available payload have been proposed [25]. The baseband gateway QoS must therefore deal with fixed throughput incoming data and variable available throughput for outgoing packets, while minimizing the amount of padding and the number of dropped packets. The incoming traffic can be classified and re-organized in a variable number of sub-queues, which usually corresponds to a mapping between QoS defined at the network level and access level. The purpose of the scheduler on the baseband gateway is to ensure that it can cope with throughput variations without affecting traffic QoS.

In Figure 2, the baseband gateway QoS is shown to be at both the MAC and the physical layers, because information from the physical layer of the return link may be exploited by this process.

2.4. Management plane processes

The non-exhaustive list of management plane processes that is shown in Figure 2 features the fault management (collecting data from various equipment to handle alarms or to detect and correct troubles), the configuration management (equipment configuration, device discovery, network provisioning), the accounting management (service billing), the performance management (collect error logs), and the security management. More information of these processes can be found in [15, section 8.1.1], from where this list has been extracted.

3. ROADMAP TOWARD THE DEPLOYMENT OF SATELLITE CLOUD RADIO ACCESS NETWORK

In this section, we present the Cloud Radio Access Network (CloudRAN) approach, which represents the actual trend in virtualizing the terrestrial mobile access. We also show how our proposed approach, the SatCloudRAN, is aligned with the virtualization process of the CloudRAN.

3.1. Trends in virtualizing the terrestrial mobile access

If the entire burden of supporting high volumes is pushed to mobile network, this would require operators to upgrade the capacity of their infrastructures by several orders of magnitude. These infrastructures have been traditionally based on a complex set of interconnected proprietary hardware appliances running different types of protocols and requiring specialized vendor-specific configuration tools. Furthermore, the cost for infrastructures in terms of deployment of mobile radio access network (RAN), setup, and operation is high enough to discourage any new hardware investment. It is therefore difficult to scale the network deployments for each situation, considering the cost and complexity constraints. The costs for backhaul from mobile base station to Evolved Packet Core represent a significant part of operator revenue. As operators constantly introduce new sites and increase the number of base stations, the power consumption gets a dramatic rise [26]. Besides this, the introduction of new service would require a new specialized hardware and software to be installed.

To address the aforementioned issues along with capacity, coverage, power consumption, and upgrade, mobile operators are defining new architectures with centralized capabilities and network function virtualization namely Centralized-RAN or CloudRAN.

This cloud-based centralized processing is a promising approach that aims to favor efficient operation, lower power consumption, provide agile traffic management, and improve network reliability. We acknowledge that these objectives may not all be granted, but future work could validate the fulfillness

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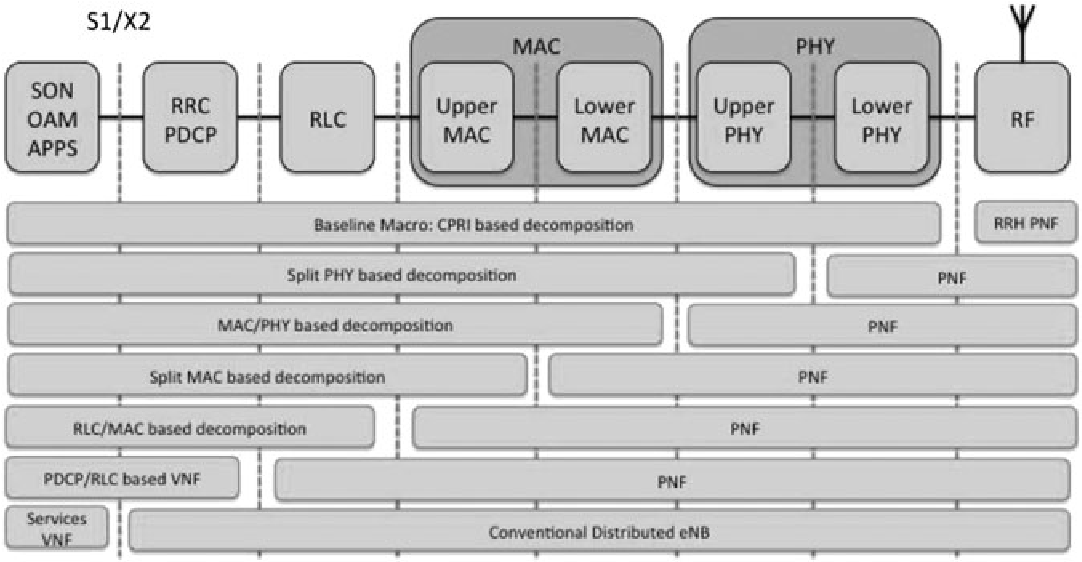

Figure 10. Possible ways to decompose the small cell - source [31]. CPRI, Common Public Radio Interface; MAC, Media Access Control; PNF, physical network function; VNF, virtual network function.

of these objectives. Further, it would enable to stimulate service innovation and reduce time-to-market to deploy new services. CloudRAN was a result of collaboration between Intel and China Mobile [26, 27] and is also of interest for other actors [28, 29]. This latter has conducted numerous trials and is expected to incorporate CloudRAN in its commercially deployed networks in China between 2015 and 2016 [30].

Complementing the CloudRAN approach, several scenarios have been proposed by the Small Cell Forum, where a certain segment of the Small Cell can be decomposed and virtualized as it is presented in Figure 10 [31]. As we move from left to right, the decomposition becomes higher and the remote node that represents the physical entity becomes smaller. The rationale for examining these alternative splits is related to the associated requirements on the transport network for supporting the fronthaul link between the virtual network function (VNF) and physical network function components. As an increasing set of functions are implemented as a virtual network function, the transport requirements in terms of bandwidth and latency become more onerous.

3.2. *The Satellite Cloud Radio Access Network*

The proposed SatCloudRAN concept implements the separated baseband functionalities in a centralized cloud-based processing platform. This separation between the virtualized and the physical components can be achieved at various layers of the satellite architecture model such as the network layer, the MAC layer, the physical layer, or up to the radio frequency front-end of out-door unit.

It seems worth pointing out that our proposed approach to virtualize the satellite network shows a high level of similarities with the approach that is conducted in the current virtualizing of terrestrial RAN networks. This point is however leveraged by the fact that network architectures in terrestrial and satellite systems are quite different.

In Figure 11, we show three different separation variants (A, B, and C). The main difference between those variants concerns the distinction between the functions that would remain located in the satellite hub and those that would be moved to the centralized and/or virtualized infrastructure. Additional alternative decompositions where the split is made within the physical or within the baseband gateway functions could be relevant.

In Figure 12, we present (1) the fronthaul link that is defined as the link between the physical gateway and the access gateway and (2) the network backhaul link that is defined as the link between the access gateway and the network connectivity block.

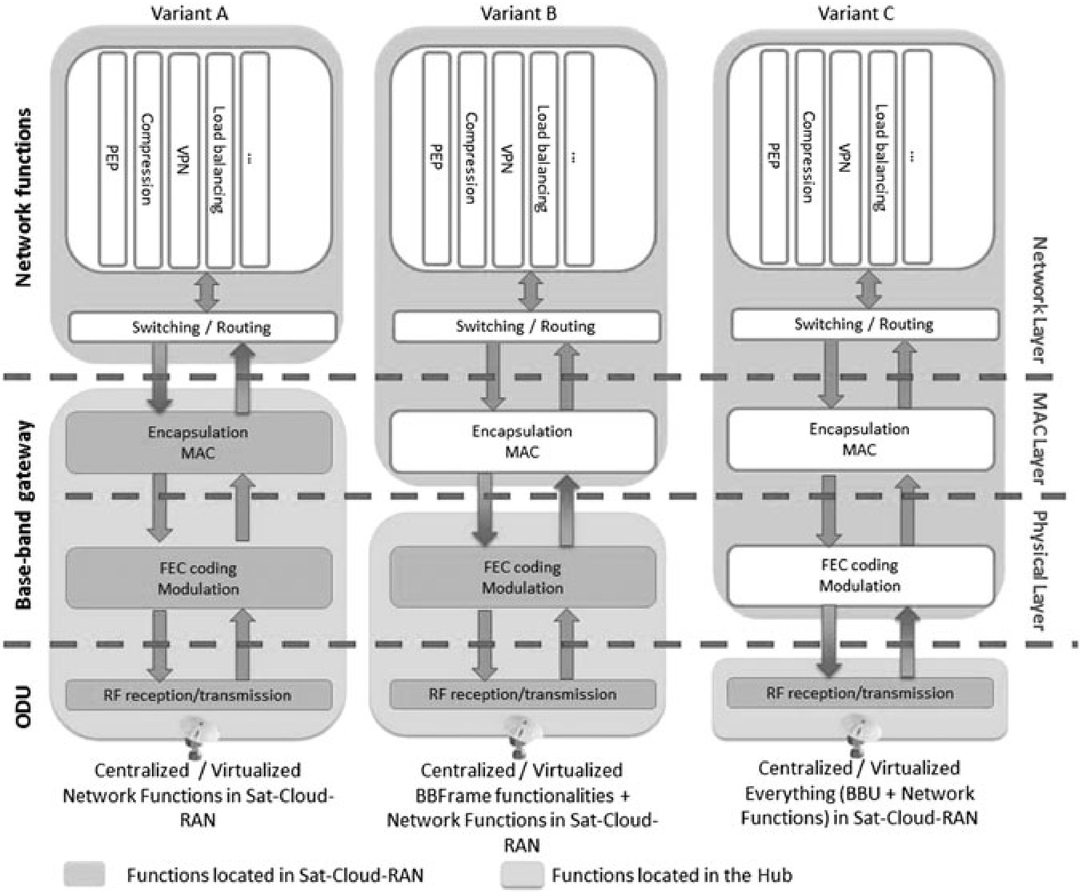

Figure 11. Variants for the functional split. VPN, virtual private network; PEP, performance-enhancing proxy; MAC, Media Access Control; FEC, forward error correction; SatCloudRAN, Satellite Cloud Radio Access Network; RF, radio frequency; ODU, outdoor unit; BBGFrame, baseband frame.

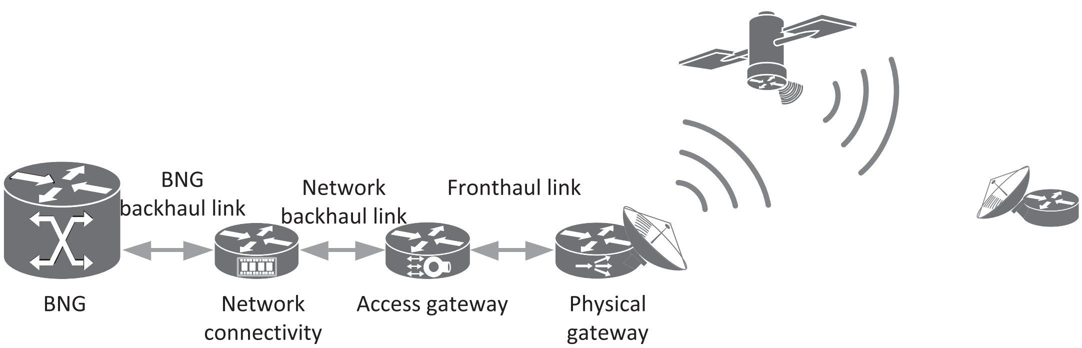

Figure 12. Fronthaul and backhaul. BNG, Broadband Network Gateway.

3.3. *How the Satellite Cloud Radio Access Network can help in opening satellite system to new coming operators*

Satellite network operators are looking for new business models to increase their customer base and extend the reach of their services offering. They are moving toward opening their infrastructure to be shared by multiple tenants, such as SVNOs, and offering pay-per-use models instead of single-owned and used infrastructures. Multi-tenancy in infrastructure sharing model enables multiple tenants to cohabitate while being assured they can manage their own space in an isolated, flexible, and secure fashion.

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The SVNO model has emerged over the last few decades as many efforts have been made to open the satellite system to a new coming operator that can share cost and infrastructure with a host network operator. Different levels of granularity for controlling satellite system are already proposed [32]. The 'managed services' offers a first step toward network control and bandwidth management for the service provider who wants to have a certain control on the underlying resource provided by the satellite operator. The 'SVNO model' allows a virtual network operator to get leased bandwidth with partial hub infrastructure control and management from the hosting satellite operator. SVNO can perform service provisioning, common network operation, and has full control of its own slice of network and end user. The 'hub colocation model' (full SVNO) allows a SVNO to co-locate hub infrastructure in its teleport allowing greater control of the installed network equipment.

The aim of this separation is to enable the creation of an environment with fully virtualized capabilities allowing flexible management, installation, maintenance, and operation of resources and services. This would thus facilitate the integration of a satellite network in hybrid networks as a virtual layer infrastructure that could be managed with the same interfaces. Therefore, the proposed SatCloudRAN, presented in Section 3.2, helps SVNO providers to enter to market faster and at lower cost while gaining advanced control, more flexibility, and programmability of its allocated resources.

3.4. Roadmap toward the definition of the Satellite Cloud Radio Access Network

Passing from a non-virtualized environment to the SatCloudRAN requires a specific roadmap including (1) identifying the functions that can be isolated from the gateway and analyzing their potential centralization (Section 4), (2) discussing the virtualization of the separated functions (Section 5) and (3) assessing the SDN control of the functions (Section 6).

4. FUNCTIONAL SEPARATION OF PROCESSES

In this section, we present the functional separation of processes that take place within the satellite core network and the satellite gateway.

4.1. Fronthaul link characteristics and control plane processes

4.1.1. Variant A. In the case of the variant A, there is a separation between satellite core network functions (PEP, load-balancing VPN, etc.) and the satellite gateway. Data packets to be forwarded are IP packets, and thus, there is no specific issue in carrying them out on the aggregation network and managing the connectivity between the gateways and the BNG.

The control processes that take place in this variant are the admission control and the network QoS. The network-level QoS adds packets to a specific sub-queue at a speed that is related to the network underneath and to the rate of incoming packets. Thus, the fronthauling link has not only a direct impact on the rate at which the packets arrive at the baseband gateway, but also on the relevance of the ordering of the incoming packets that depends on their class.

4.1.2. Variant B. With the variant B, the data packets that are forwarded to the physical gateway are BBFRAME. In the case of no padding, directly carrying out fixed packets would only add the GSE header to the IP data packets. The connectivity between the access gateway and the physical gateway can be ensured by the use of layer 2 network segregation techniques.

However, the question of the feasibility of this variant in terms of appropriate interactions between physical and MAC layers must be addressed. In this context, we present in Figure 13 the interaction between the control processes at these two layers.

For the logon process, the terminal applies a timer to retransmit its logon burst in case no acknowledgement has been received. The number of logon burst retransmission is limited. The norm does not detail the possible values for both the timer and the maximum number of trials, which are both implementation dependent.

For the synchronization process, if the fronthaul link exhibits jitter, the NCR may not be transmitted at a fixed rate. Whatever the jitter in the fronthaul network, according to the normative documents,

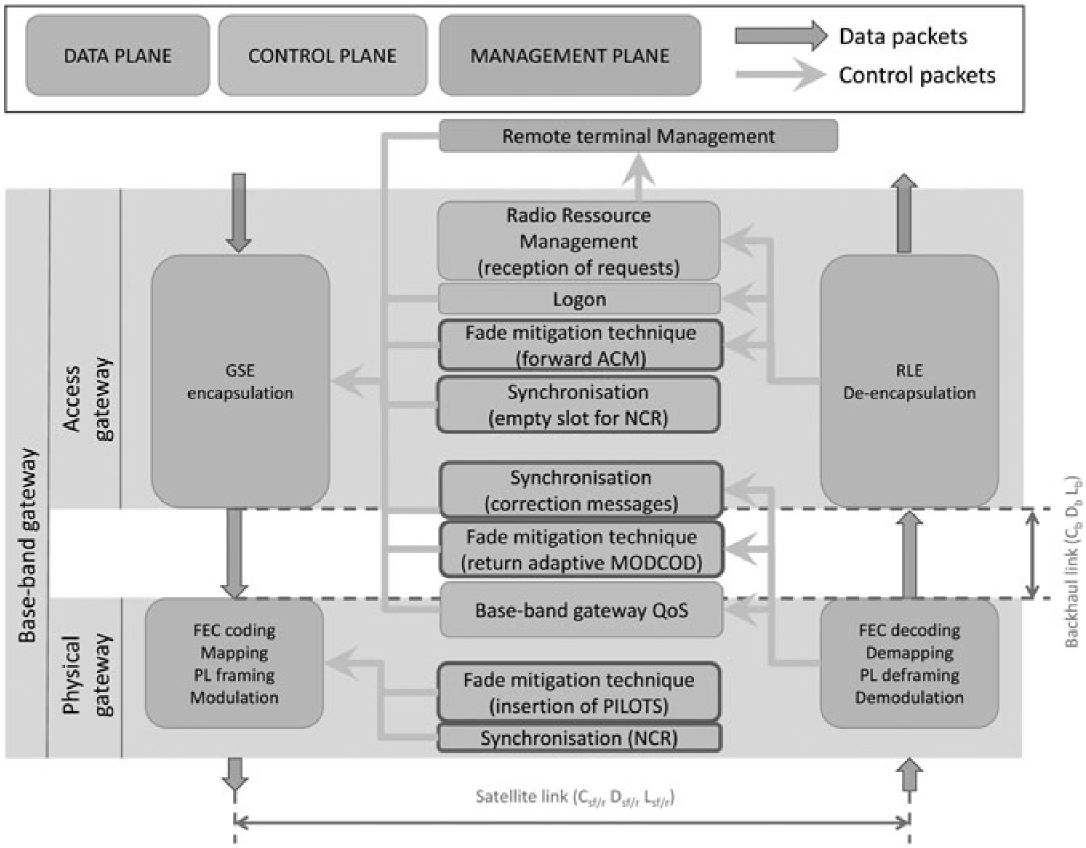

Figure 13. Interaction between the processes in the physical and the access gateways. ACM, Adaptive Coding Modulation; NCR, Network Clock Reference; GSE, Generic Stream Encapsulation; FEC, forward error correction.

the NCR shall be updated at least 10 times per second. On top of the issue related to the jitter in the fronthaul network, the potential losses of the BBFRAME carrying an empty slot for the NCR is a critical issue. If the terminal considers the NCR to be lost, it shall cease the transmission of data until it is synchronized again.

For the FMT process, if the precision of the measurement itself is not impacted by the splitting of variant B, the interactivity of the mechanism could be degraded by a fronthauling link introducing an important delay. This can result in selected MODCOD not matching the target PER, which would lower overall performance. It is worth pointing out that there are ACM margins that may avoid this to happen.

If the fronthaul link between the physical and the access gateways shows a high PER, introduces a non-negligible amount of delay, or introduces jitter, there may be destructive impact on the logon procedure and the synchronization process. It is worth pointing out that it is easier to target a low PER than overcoming latency issues. Moreover, this may also result in a non-adequacy between the reported SNR and the actual channel conditions and thus an inefficient use of the expensive satellite resource.

4.1.3. Variant C. With the variant C, the data packets that are forwarded to the ODU are either physical layer frame (I/Q symbols) or directly the L band. The connectivity between the access gateway and the ODU can be ensured by the use of layer 2 network segregation techniques. In that context, the dedicated fronthaul channel could use the Common Public Radio Interface between the SatCloudRAN and the ODU.

The I/Q symbols may be transmitted over an optical network, which would ease the fulfillness of the requirements in terms of one-way delay, jitter, throughput, and bit error rate, as opposed to variant B. The L band signal could either be digitized or analogically transmitted.

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If the L band is digitized, there is no specific need for a dedicated network. However, the choice of the fronthaul network would have an impact on the resulting feasibility of this solution, because the bandwidth requirements for digitizing the L band is far more important than I/Q transmission. Such as it has been mentioned in Section 4.1.2, the adequacy between, as one example, the chosen MODCOD and the satellite channel conditions may not be granted because losses, delay, and jitter in the fronthaul network could occur.

The idea is transmitting analog L band signal on optical networks is justified by its usage in commercial products, such as Cable TV where this concept is exploited to broadcast analog video signals to subscribers. The key concept is to avoid the complexity of digitizing the L-band, a complex operation, by transmitting directly the analog signal over a fiber. It is considered as more simple to setup, as well as being more reliable and predictable. Because the signal is analog, it needs a dedicated fiber to be transmitted, and cannot be conveyed along digital signals. Hence, the capacity of the fronthaul link is not the dimensioning parameter here: either a dark fiber is available for the fronthaul link, or none is available and a dedicated network has to be built. Dimensioning this solution lies with the maximum reachable distance: because the signal is analog, the integrity of the information it conveys will be degraded by attenuation and non-linearity in the transmission.

However, the constraints inherent to the analog solution seem to overwhelm the sole performance advantages, except considering short distances for the fronthaul link, and again the availability of dark fiber. Given the expected distance of the gateways required to provide diversity or to guarantee that feeder links of the gateways do not interfere, this solution may be expensive. Moreover, the flexibility brought by capacity leasing in the digital case is a valuable asset compared with the fixed capacity of dark fiber leasing.

4.2. Synthesis on the functional split

In the variant A, only the network functions are centralized. Even though no functional issue could be exhibited, this variant does not fully exploit the possibilities offered by the virtualization concept, which requires firstly an isolation of the functions.

The variant B does not only centralize the network function, but also the access gateway. In the future, this may even result in the virtualization of all these functions. As opposed to the variant A, the variant B would then let more room for the virtualization of some processes. Our analysis however showed that even if it can be separated from the physical gateway, the potentially virtualized access gateway would need to be close to the physical gateway, or the specific processes that need some interactions between those gateways should be adapted. The analysis of the feasibility to centralize the whole gateway (network functions, access and physical gateways) showed that the variant C could be envisioned only if the L-band signal is digitized. The requirements for this variant would impose much more bandwidth than the variant B.

In the light of our analysis, an interesting trade-off for the centralization of the gateway, in terms of performance, cost-effectiveness, and feasibility, would be to isolate the network functions and the access gateway from the hub, where the physical gateway shall remain. Also, in this case, we recommend to let the access gateway close to the hub, or to adapt its exchanges with the physical gateway. The processes of the network functions and access gateway are subject to virtualization.

5. VIRTUALIZATION OF THE FUNCTIONS CONSIDERING THE SATELLITE CLOUD RADIO ACCESS NETWORK TOPOLOGY

In this section, we analyze the virtualization of the satellite gateway that allows an operator to run multiple instances of virtual gateway so that each pool of virtual gateways can be used by particular satellite network operator or assigned to different SVNOs in a scalable way. We focus on the variant B, where both the network connectivity and the access gateway are subject to virtualization, such as concluded in Section 4.2.

5.1. Architecture for virtualizing satellite gateway functions

5.1.1. General architecture. In Figure 14, we propose a general architecture of the virtualized environment.

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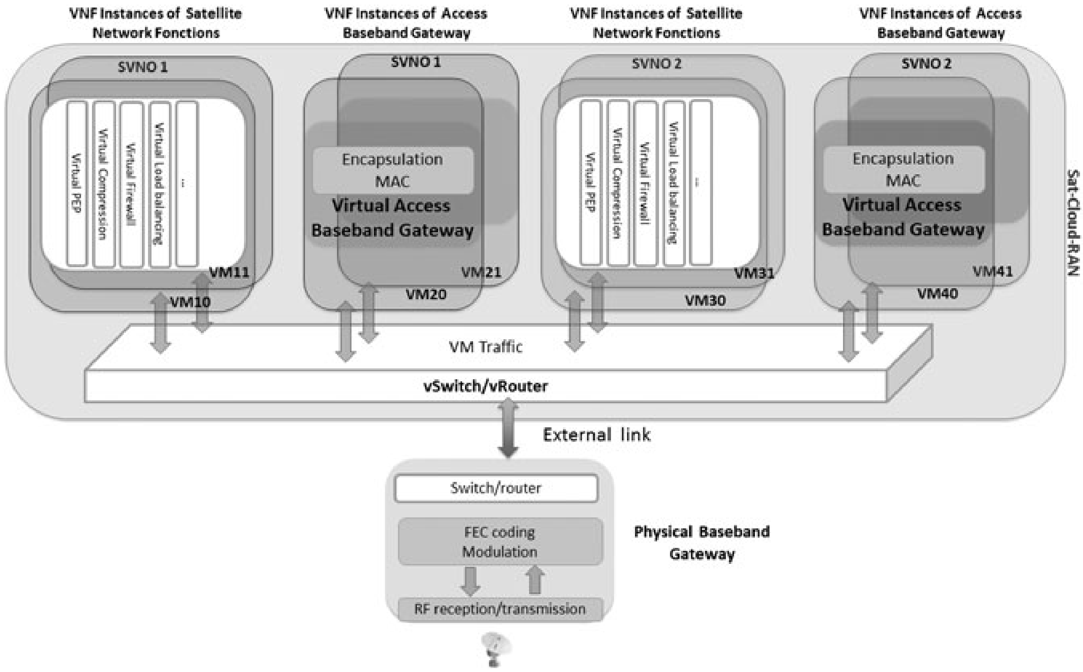

Figure 14. Virtualization of network functions and access baseband gateway. MAC, Media Access Control; SVNO, Satellite Virtual Network Operator.

Table II. Discussion on the support of multiple tenants.

Case	Shared virtual environment	Shared physical gateway	Shared outdoor unit
C1		✓	✓
C2	✓	✓	✓
C3	✓		✓

5.1.2. Virtualization environment for the network connectivity. The functions of the network function block can be virtualized as virtual instances running in software modules described using the VNFs approach. Each VNF is executed on a dedicated or shared virtual machine (VM) so that multiple SNOs or SVNOs can be hosted on single physical infrastructure characterized by particular computational, storage, and networking hardware resources.

Figure 14 illustrates the environment in which the virtual switch is responsible for switching network traffic both internally between the VMs and externally with the physical gateway. The vSwitch runs on the same server platform as the VNFs. The virtual satellite network functions such as virtual PEP, virtual VPN (vVPN), and virtual load balancing are further being connected and chained to provide a dedicated service through different VNFs combinations.

For example, a first group of users of $SVNO_1$ will be provided only vVPN service whereas a second group will be provided vVPN and virtual PEP service function chain.

5.1.3. Virtualization environment for the access gateway. In this scenario, the support of multiple tenants can be done using sharing or not the physical baseband gateway. We detail in Table II some use-cases on how the virtualized environment can be shared among SVNOs.

In the case *C1*, each SVNO has its own virtualized environment, with a dedicated pool of virtual access baseband and dedicated network gateway. The sharing is done at the physical gateway. Sharing of physical gateway means sharing of spectrum or sharing of hub sites to allow each SVNO to bring its own equipment. When the spectrum is shared, the isolation of SVNO can be realized logically at bandwidth group level.

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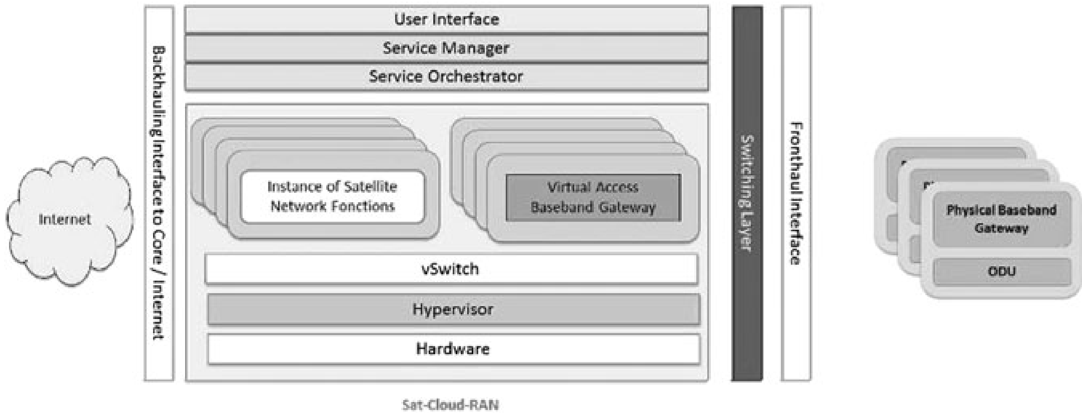

Figure 15. Overview of Satellite Cloud Radio Access Network (SatCloudRAN) key functionalities installed on Network Function Virtualization Infrastructure Point of Presence. ODU, outdoor unit.

In the case *C2*, this case is similar to the previous one, except that the virtualized environment is shared between SVNO. In the case *C3*, when the physical gateway is dedicated, each SVNO bring its own modules for modulation and demodulation of traffic if the same site is used. The ODU can be shared.

5.2. Functional architecture of the Satellite Cloud Radio Access Network

Figure 15 describes a functional architecture of the SatCloudRAN by focusing on some keys of the functionalities related to access baseband gateway, network functionalities, or fronthauling link to connect the instances of virtual access baseband with the physical baseband gateway. This architecture can be implemented as part of a NFV Infrastructure Point of Presence that hosts the deployed functions.

The design of the SatCloudRAN architecture will be supported by a set of following functional elements: (1) the User Interface, which allows the operator to interact in user-friendly manner with SatCloudRAN in order to create instance and manage their functionalities. (2) The Service Manager, which provides supporting services for the user interface. It interacts with the service orchestrator and is responsible for managing the service orchestrator of a particular tenant. (3) The NFV manager that is in charge of the lifecycle of running VNF instance, to create, configure, orchestrate and manage the instances of created functions. The Service Orchestrator (SO) is also in charge of making in decision that needs to maintain the performance guarantee such as workload on the VMs. If any instance of function has to be scaled up or down, the SO will add or remove virtual machines and instantiate a new instance or delete an old instance to deal with the current load. Configuration will be then triggered to chain those new instances. (4) The Virtualized Infrastructure Manager, which provides the interfaces as northbound and southbound control planes used by the Service Manager and SO for abstracting the physical resources and instances running on cloud. (5) The service catalogue that contains a list of the available services offered by the provider.

5.3. Discussion on virtual network functions

Figure 16 shows how the SatCloudRAN can be instantiated on this architecture when there are two SVNOs. The virtualization paradigm makes it easier to propose slices of virtual networks such as shown in this figure. In this view, the access gateways are not centralized. By centralizing them in a pool, it would be even easier to manage the satellite gateway diversity, because there would be only one MAC layer for a given SVNO. However, the relevance of such approach is related to the deployment, the fronthaul link characteristics, and the resulting performance in terms of satellite resource utilization, quality of experience, and so on.

Because there are many interactions between an access gateway and a physical gateway, we provide some focus on them. In Figure 17, we show the interactions of the access gateway VNF with the other elements. The links on the west and south bounds of the SBG VNF block refer to the data packets

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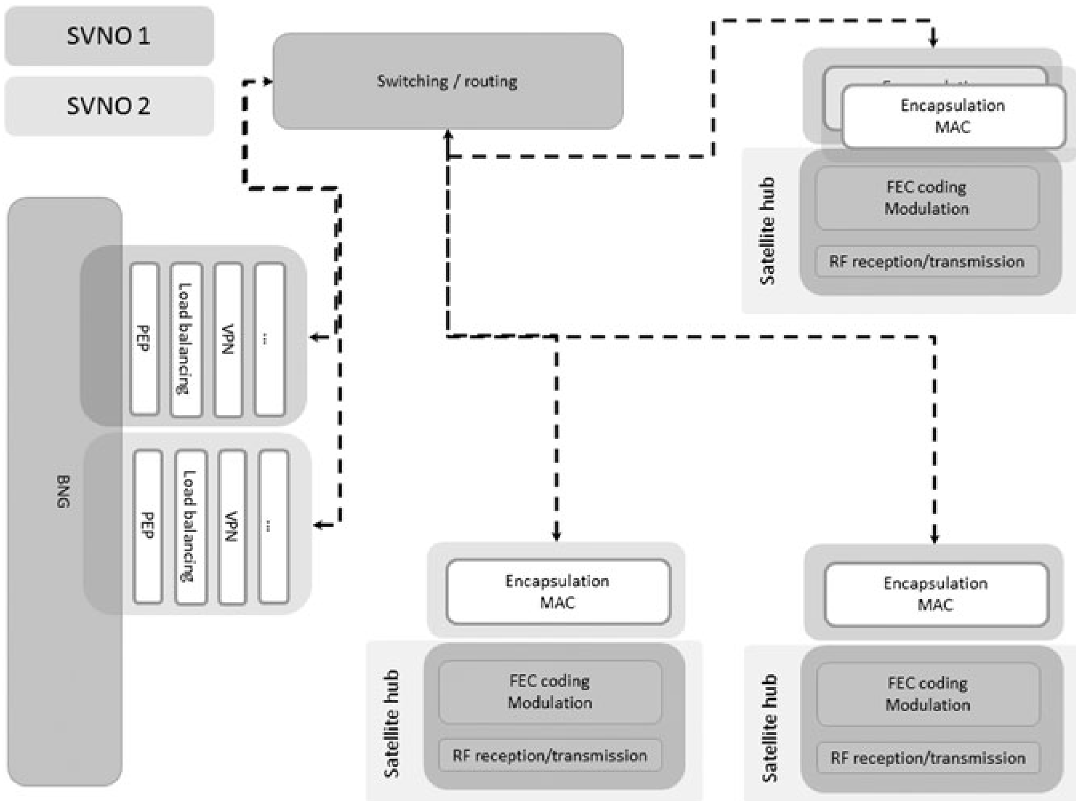

Figure 16. Satellite Cloud Radio Access Network instanciation in a multi-gateway scenario. VPN, virtual private network; PEP, performance-enhancing proxy; MAC, Media Access Control; FEC, forward error correction; RF, radio frequency..

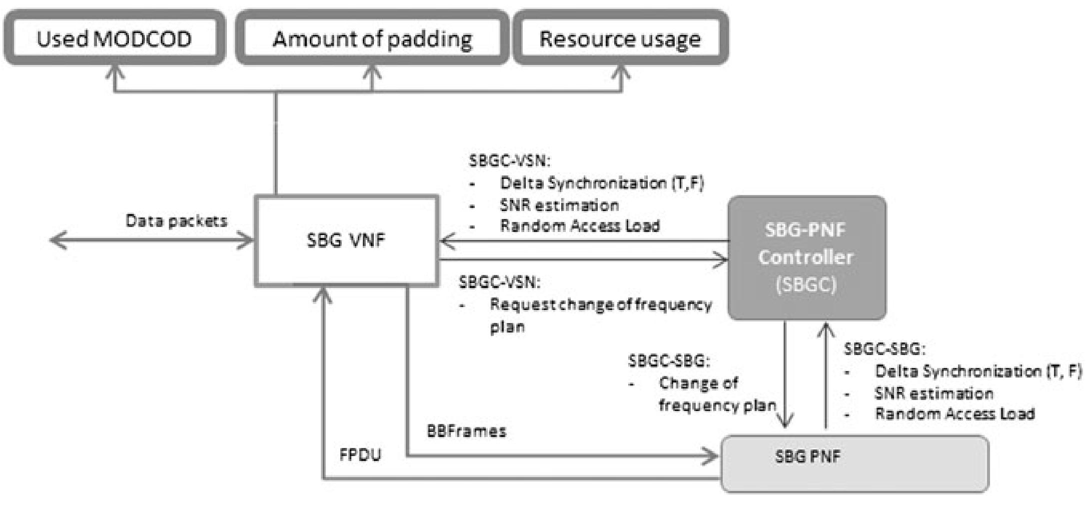

Figure 17. Input and output for the access gateway virtual network function (VNF). SPG, Satellite Baseband Gateway; PNF, physical network function; FPDU, Frame Protocol Data Unit; MODCOD, modulation and coding; SNR, signal-to-noise ratio.

that are actually transmitted in the network (which may carry control plane information, such as the BBFRAMEs), the links on the north bound of the SBG VNF block refer to the log information that could be forwarded to an SDN-controller, and the links on the east bound of the SBG VNF block refer to the control information exchanged between the physical gateway and the access gateway, through a physical gateway controller (the Satellite Baseband Gateway Physical Network Function (SBG-PNF) Controller).

This section will present and detail these interactions; this contribution is essential to further describe this VNF. Then the specific algorithmic elements within the access gateway VNF can hardly be provided because it is specific to the implementation of the normative documents, but the description of these interfaces would let one Satellite Communication (SATCOM) manufacturer to propose an access gateway VNF that can be easily integrated with any existing systems, if the current approach is respected.

The north bound of the access gateway VNF shows the log information that can be forwarded, and taken into account in higher layer algorithms, particularly related to resource management. We propose the used MODCOD, the amount of padding, and the resource usage.

The west bound of the access gateway VNF represents the data that is forwarded from/to the network gateway through the transport network.

The east bound of the access gateway VNF forwards the frequency plan changes, so that the bandwidth for the return and forward links can be adapted. This is one of the responsibilities of the RRM process.

The east bound of the access gateway VNF receives the variations related to the synchronization in both time and frequency (related to the synchronization process), the SNR estimation on the return link (related to the FMT process), and the load measured on the random access slots (related to the RRM process). This information is measured directly on the received signal; thus it is not carried out naturally by the Frame Protocol Data Unit. The existing SBG-PNF interface can be exploited to carry out this information, or another control interface has to be defined. The south bound of the access gateway VNF forwards the BBFRAMEs to the SBG-PNF, along with the MODCOD to apply on the BBFRAMEs. BBFRAMEs contain more information than just data plane packets, because control information and data plane packets are multiplexed in BBFRAMEs. According to the Digital Video Broadcasting public documents, BBFRAMEs also contain layer 2 control information, for example, information related to the way the channel capacity is shared on the return link (related to the RRM), the NCR, or other information related to the network management.

The south bound of the access gateway VNF receives the Frame Protocol Data Unit from terminals. These packets contain more information than just data plane packets. As one example, they contain information related to the logon information from a given terminal (related to the logon), the resource access requests from the terminal (related to the RRM process) or the SNR on the forward link estimated by the terminal (used by the FMT algorithm). This view could be discussed because there are no specific requirements on these aspects in the public documents; however, we think this approach provides a good trade-off between complexity and flexibility. The proposed approach lets the access gateway VNF host most of the decisions related to the control processes, while the SBG-PNF is limited to the management of the actual radio frequency resources, on which the RRM maps its allocation.

6. SDN CONTROL OF A SATELLITE CORE NETWORK

Further to the satellite function virtualization, we discuss in this section the SDN control of a satellite network and we illustrate three key examples of SDN-based controlled functions: (1) bandwidth on demand, (2) dynamic QoS, and (3) satellite gateway diversity.

6.1. *Overview of software-defined networking controllers*

Software-defined networking is envisioned to be a key enabler of the 5G to fulfill the objectives of providing flexibility and network programmability. This concept breaks the vertical network integration by separating the network's control logic from the underlying routers and switches that forward the traffic. Moreover, with a separation of the control and data planes, network switches become simple forwarding devices and the control logic is implemented in a logically centralized controller, simplifying policy enforcement and network reconfiguration and evolution.

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However, it is essential to point out that network programmability is not something new, and SDN is not the only technique that could provide such flexibility and programmability. Indeed, the authors of [33] provided an historic perspective of programmable networks and clearly position the emerging concept of SDN.

Within this concept, the OpenFlow protocol [34] has emerged as an enabler being promoted by the Open Networking Foundation [35], on the industry side, and by the OpenFlow Network Research Center [36] at the academic side. OpenFlow aims at standardizing the exchanges of information between the centralized SDN-controller and the components of the network. Other programmable networking efforts can be noticed and should not be neglected. However, the Open Networking Foundation has been able to largely gather academics, researchers, and industry: this may result in OpenFlow being a de-facto standard.

The authors of [33] also proposed a list of the switches and controllers that are compliant with the OpenFlow standard. The paper[37] assesses the maturity of five state-of-the art SDN-controllers by evaluating their capacity to process small packets based on a global view of the network. They conclude that it is necessary to rethink current SDN controllers to better leverage the energy efficiency and high network traffic capabilities. Depending on the deployment use case, the adequacy of the SDN controllers may be questioned. That being said, specific environments such as data centers, enterprise networks, or home and small business already exhibit a heightened interest for adopting the SDN concept.

6.2. *Software-defined networking-based control architecture*

Figure 18 details the proposed satellite architecture that enables SDN control of the virtualized environment. It is composed of a high level controller in charge of controlling and managing the entire network resources whereas the low-level controller is in charge of controlling and managing a specific network element or domain-specific resources. For example, the Host Network Operator controller can be used as an entire network controller and SVNO controller for each SVNO subnetwork. The Host Network Operator would be in interaction with the Satellite Control Center and the mission segment to evaluate the available capacities of the satellite or to update its configuration.

The SDN controller would be in charge of multiple interdependent blocks. The SDN controller is responsible for accepting a new demand of bandwidth allocation. It allows also verifying if the network can handle the traffic demands of the application without impacting other applications adversely. Toward this end, this module needs to have an accurate view of network resources in use. Secondly, the QoS optimization is responsible for mapping (using cross-layer optimization) the traffic across a different layer of networking taking into consideration the actual link performances and the defined class of services in terms of traffic classification, marking, and flow control. Thirdly, the traffic engineering is responsible for centralized traffic engineering to dynamically reallocate bandwidth among different customers in case of outage or failure. It is also responsible for managing available network capacity according to application priority. Finally, the radio resources management is responsible for managing the radio resource in terms of bandwidth allocation, packet scheduling, fading mitigation technique, and efficient utilization of the satellite resources.

We detail in the rest of this section three SDN-based applications that were first identified in our previous work [11], namely, (1) SDN-based bandwidth on demand (Section 6.3), (2) SDN-based dynamic QoS (Section 6.4), and (3) SDN-based satellite gateway diversity (Section 6.6).

6.3. *Software-defined networking-based bandwidth on demand*

The aim of the SDN-based flexible satellite Bandwidth on Demand (BoD) is to improve the typical satellite broadband access service with the ability to allow service providers to dynamically request and acquire bandwidth in a flexible manner. On-demand bandwidth services are established by the customer requesting change of the allocated bandwidth by interacting with corresponding SDN-based application (i.e., SDN-based bandwidth on-demand). This latter interacts with the Admission Control (AC) function at the SDN controller using the SDN northbound application programming interface. One of the goals of the AC function is to accept or to reject user requests of network bandwidth corresponding to a Class of Service (CoS) according to resources availability and customer SLA.

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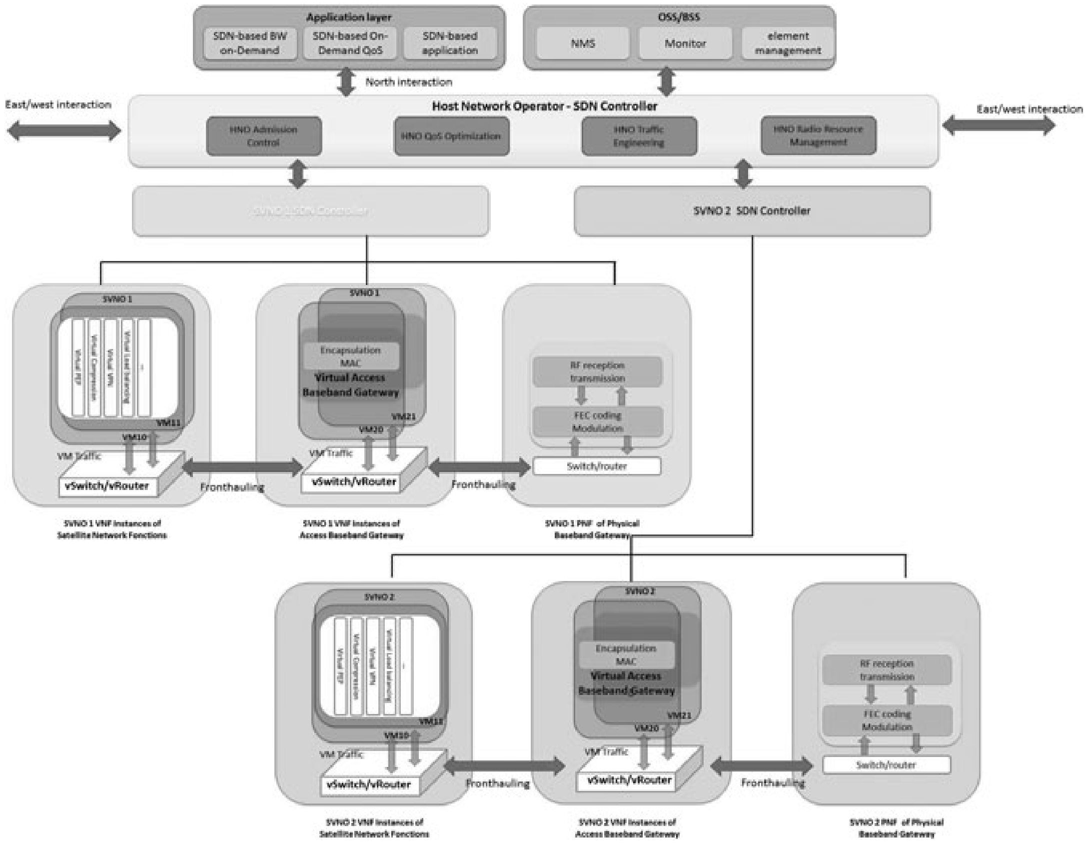

Figure 18. Multiple software-defined networking (SDN)-based control architecture for Satellite Virtual Network Operator (SVNO) support. VPN, virtual private network; PEP, performance-enhancing proxy; MAC, Media Access Control; FEC, forward error correction; RF, radio frequency.

Requested bandwidth parameters can be communicated to the SDN-based application through a portal or based on application and service profiles.

Indeed, the time-division multiplexing forward link, which is managed by the SVNO in our architecture, is shared between customers in regard of their SLA. Bandwidth profiles are specified in SLAs to quantify agreed limits on service frame bandwidth and, as a consequence, they define traffic management operations within networks, such as policing, shaping, and scheduling. All these tasks are managed by a bandwidth management function that may reside in the SDN controller. It allows to structure the bandwidth for groups (group of remotes, SVNO, users) an allocated this bandwidth accordingly. For each bandwidth group, it is possible to specify the bandwidth size, the priority (high or low priorities), the policy applied to the group in case of overflow, or the smoothing function to adopt in case of slice overflow.

For the BoD service, it is essential to dynamically update the bandwidth profile for L2 connectivity and/or the per-hop behavior for L3 connectivity. It should be noted that BoD service shall be configured to be used when needed or for a specified scheduled time. The resources released should become immediately available for other connections and usage.

6.4. Software-defined networking-based dynamic quality of service

The aim of the dynamic QoS is to dynamically adjust the network connectivity characteristics and the amount of bandwidth associated with various CoS. That would result in a better match between the application needs in terms of QoS and take into account the physical characteristics. The SDN-controller would be responsible in setting the dynamic parameters and taking decisions on how to update them to improve the quality of experience at the end user level.

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The SDN controller must be informed about the actual CoS bandwidth capacity available for a user at a given time, the new entering flows, and the conditions of fading for each terminal destination to adapt in near real time the QoS of the network and optimizing the performance of a network by dynamically analyzing, predicting, and regulating the behavior of data transmitted over that network (i.e., traffic engineering).

Such SDN-controller mechanisms will close the loop between the applications, network connectivity, and radio resource management with the goal of providing dynamic QoS and traffic engineering of bandwidth capacity for each CoS sharing the same link, with the aim to optimize end user quality of experience at all times.

For example, at L2 connectivity, if an OpenFlow switch of the SVNO receives a packet that has been never seen before and for which it has no matching flow entries to the controller, the controller can call upon the process of AC and QoS optimization to take into account this new traffic and make a decision on how to handle this flow. To help in the identification and the classification of the new packets, the controller could use the service of deep packet inspection on the traffic to provide a granular control of the data flows to the QoS optimization service in order to dynamically adapt the resources according to the needs.

To address the dynamic QoS challenges, this SDN application could dynamically configure QoS parameters, to ensure a high quality of experience, based on the information of actual and predictive traffic loads and available bandwidth limited by the fading.

6.5. Software-defined networking-based satellite gateway diversity

The aim of this application is to provide a diversity scheme in the forward link by allowing multiple gateways to feed simultaneously the satellite to accommodate a high capacity aggregation using a high number of beams while ensuring gateways' resiliency. The SDN application would thus collect information related to bad channel conditions, to the detection of failure issues or to the efficiency of the resource utilization to potentially change the usage of the available gateways.

This satellite gateway diversity implies (1) inter-gateway handover technique to cope with the cases where gateway feeder links experience outage because of meteorological conditions or failure (the handover typically implies that additional traffic is addressed toward another gateway to handle the capacity reduction of the affected gateway); (2) permanent monitoring of hub and radio resources to detect the outage, failure or any problem; (3) reconfiguration of the network capacity, optimizing traffic engineering, routing table, and forwarding elements of the core satellite network provider to support temporarily capacity changes.

6.6. Applicability of the software-defined networking to Satellite Cloud Radio Access Network

Depending on the deployment context, dedicated controllers may be required. Control processes related to the MAC layer are indeed closely related to the characteristics of the medium used to transmit the data. Some related work proposed specific controllers for satellite communications [38–40]. However, the dynamically controlled parameters could be located at the satellite platform level, at the access gateway, or at the network level. The parameters of the access gateway that could be exposed to a centralized controller are deeply related to SATCOM, whereas those of the network functions may not. This section has extended the use-cases proposed in the literature and has included the SDN controllers in the frame work of the SatCloudRAN.

The deployment of the SDN paradigm within SATCOM equipments induce a split between data and control planes that is not straightforward. From a functional perspective, the logical separation of data, control, and management plane functions has been actually reflected in the reference model for broadband satellite multimedia systems developed in ETSI [41]. However, it is worth pointing out that this view is not reported to be widely implemented in current systems and interoperable. If some algorithms can be considered as quite straightforward, such as the ACM operation (which is only one part of the FMT), RRM and QoS can encompass numerous complex parameters, which are not part of the standard. The interest of further splitting the access gateway in multiple VNFs shall be looked at by the satellite ground segment manufacturer because it is closely related to the specific implementation of the public normative documents.

We believe that the view proposed in this article is a workflow toward decoupling the data and the control planes and including both NFV and SDN paradigms in SATCOM. Indeed, the identification of the possibility to decouple and centralize processes of a satellite gateway shed a light on the potential issues and the need for rethinking the system. The identification of common interfaces between the physical and access gateway would ease the decoupling of the data and control planes to further apply the SDN concepts in the aggregation network.

7. CONCLUSION

The role that satellite communications can play in the forthcoming 5G ecosystem is being revisited. This paper contributes to this vision through researching on the adoption of SDN and NFV technologies into the satellite domain. These concepts are seen as key facilitators to make satellite communications becoming a constituent part well integrated within an anticipated heterogeneous 5G network architecture. With the introduction of SDN and NFV, greater flexibility is expected to be achieved by satellite network operators, in addition to the much-anticipated reduction of both operational and capital expenses in deploying and managing SDN and NFV compatible networking equipment within the satellite networks. This proposed concept, namely, satellite cloud RAN, exploits cloud-based infrastructure and data-center virtualization to deliver cost-efficient, high-level resources availability and flexible resources sharing. This concept sheds light on better interaction and integration of the satellite network with terrestrial functionalities while supporting advance features such as traffic engineering and load balancing.

The decomposition of the satellite and network gateway into multiple functional elements allows for identifying three main splitting approaches where the virtualization benefits are associated with the gain obtained from the centralization of the functions and their multiple instantiations. It is worth pointing out that our approach can be applied to other satellite systems, because similar specific functions such as the FMT, the QoS or the synchronization would have to be dealt with.

The public normative documents do not provide information related to the implementation. We believe that going further in the chaining of the multiple internal satellite access gateway is not necessary to illustrate the interest of introducing the NFV paradigm within the SATCOM industry. Moreover, if some algorithms can be considered as quite straightforward, such as the ACM operation (which is only one part of the FMT), RRM and QoS can encompass numerous complex parameters, which are not part of the standard.

It is the first step of access softwarization, which can be seen as an overall transformation trend in SATCOM for designing, implementing, deploying, managing, and maintaining access entity, exploiting characteristics of software such as flexibility and rapidity of design, development, and deployment.

As a future work, a proof-of-concept prototype will be designed, aiming at evaluating, among others, the practical application of virtualizing a given function and to determine the most promising virtualization capacities envisioned in this paper. The OpenSAND (ex-Platine) [42] will be used as a proof of concept platform to emulate the DVB-S2 and the DVB-RCS2 network including the physical link, the ODU, the physical gateway, and BBFRAME handling.

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REFERENCES

1. Association GI. 5G Vision. *Technical Report 5G PPP*, 2015. https://5g-ppp.eu/wp-content/uploads/2015/02/5G-Vision-Brochure-v1.pdf [accessed on 23 January 2017].
2. NetWorld2020 - SatCom WG. The role of satellites in 5G. *Technical Report*, Networld 2020, 2014. www.networld2020.eu/wp-content/uploads/2014/02/SatCom-in-5G_v5.pdf [accessed on 23 January 2017].

3. Courville N, Bischl H, Lutz E, Svigelj A, Chan PM, Papapetrou E, Asorey-Cacheda R. Hybrid Satellite/Terrestrial Networks: State of the Art and Future Perspectives, *QShine 2007 Workshop: Satellite/Terrestrial Interworking*: IWSTI '07, ACM: New York, NY, USA, 2007; 1:1–1:7. DOI: 10.1145/1577776.1577777.
4. Evans B, Werner M, Lutz E, Bousquet M, Corazza G, Maral G. Integration of satellite and terrestrial systems in future multimedia communications, *IEEE Wireless Commun.* 2005; **12**(5):72–80, DOI 10.1109/MWC.2005.1522108.
5. Ahn DS, Kim HW, Ahn J, Park DC. Integrated/hybrid satellite and terrestrial networks for satellite IMT-Advanced services, *Int. J. Satell. Commun. Networking* 2011; **29**(3):269–282, DOI 10.1002/sat.977.
6. Dai L, Chan V. Capacity dimensioning and routing for hybrid satellite and terrestrial systems, *IEEE J. Sel. Areas Commun.* 2004; **22**(2):287–299, DOI 10.1109/JSAC.2003.819976.
7. Border J, Kojo M, Griner J, Montenegro G, Shelby Z. Performance enhancing proxies intended to mitigate link-related degradations. RFC 3135 (Informational) Jun 2001. http://www.ietf.org/rfc/rfc3135.txt.
8. ETSI. Digital Vidideo Broadcasting (DVB); Second Generation DVB Interactive Satellite System (DVB-RCS2); Part 2: Lower Layers for Satellite standard. *Technical Report V1.1.1*, European Telecommunications Standards Institut, 2011.
9. Boucadair M, Jacquenet C. Software-defined networking: a perspective from within a service provider environment. RFC 7149 (Informational) Mar 2014. http://www.ietf.org/rfc/rfc7149.txt [accessed on 23 January 2017].
10. ETSI. Network Functions Virtualisation (NFV); Virtual network functions architecture. *Technical Report V1.1.1*, European Telecommunications Standards Institute, 2014.
11. Ferrús R, Koumaras H, Sallent O, Agapiou G, Rasheed T, Kourtis MA, Boustie C, Gélard P, Ahmed T. SDN/NFV-enabled satellite communications networks: opportunities, scenarios and challenges, *Phys. Commun.* 2016; **18**(2):95–112. DOI: https://doi.org/10.1016/j.phycom.2015.10.007, http://www.sciencedirect.com/science/article/pii/S1874490715000543 [accessed on 23 January 2017].
12. Mijumbi R, Serrat J, Gorricho J, Bouten N, De Turck F, Boutaba R. Network function virtualization: state-of-the-art and research challenges, *IEEE Commun. Surv. Tutorials* Firstquarter 2016; **18**(1):236–262, DOI 10.1109/COMST.2015.2477041.
13. ETSI. Digital Video Broadcasting (DVB); Second generation framing structure, channel coding and modulation systems for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications (DVB-S2). *Technical Report V1.2.1*, European Telecommunications Standards Institut, 2009.
14. EBU-UER DVB. Digital Video Broadcasting (DVB); Second Generation DVB Interactive Satellite System (DVB-RCS2); Part 1: Overview and System Level specification. *Technical Report V1.1.1*, European Telecommunications Standards Institut, 2012.
15. EBU-UER DVB. Digital Video Broadcasting (DVB); Second Generation DVB Interactive Satellite System (DVB-RCS2); Part 3: Higher Layers Satellite Specification. *Technical Report V1.1.1*, European Telecommunications Standards Institut, 2012.
16. ETSI. Digital video broadcasting (dvb); user guidelines for the second generation system for broadcasting, interactive services, news gathering and other broadband satellite applications (dvb-s2). *Technical Report V1.1.1*, European Telecommunications Standards Institut, 2005.
17. FTSI. Satellite Earth Stations and Systems (SES); Hybrid FSS satellite/terrestrial network architecture for high speed broadband access. *Technical Report V1.1.1*, European Telecommunications Standards Institute, 2015.
18. Andersson L, Madsen T. Provider Provisioned Virtual Private Network (VPN) Terminology 2005; **18**:95–112. RFC 4026, RFC Editor.
19. Baker F, Fairhurst G. Ietf recommendations regarding active queue management, 2015. BCP 197, RFC Editor.
20. Kuhn N, Ros D, Bagayoko AB, Kulatunga C, Fairhurst G, Khademi N. Operating ranges, tunability and performance of CoDel and PIE, *Comput. Commun.* 2016. DOI: https://doi.org/10.1016/j.comcom.2016.07.013.
21. Babiarz J, Chan K, Baker F. Configuration Guidelines for DiffServ Service Classes, 2006. RFC 4594, RFC Editor.
22. Santitoro R. Metro Ethernet Services-A Technical Overview. *Technical Report*, Metro Ethernet Forum, 2003. https://www.mef.net/Assets/White_Papers/Metro-Ethernet-Services.pdf [accessed on 23 January 2017].
23. Alphand O, Berthou P, Gayraud T, Combes S. QoS Architecture over DVB-RCS satellite networks in a NGN framework, *Globecom 2005,* St Louis, United States, December 2005; 5p. https://hal.archives-ouvertes.fr/hal-00356869 [accessed on 23 January 2017].
24. Fairhurst G, Secchi R, Yun A. A flexible qos architecture for dvb-rcs2, *Int. J. Satell. Commun Networking* 2013; **31**(5): 219–232, DOI 10.1002/sat.1026.
25. Dupe J, Chaput E, Baudoin C, Bes C, Deramecourt A, Beylot A. Optimized GSE packet scheduling over DVB-S2, *IEEE Global Communications Conference, GLOBECOM 2014*: Austin, TX, USA, 8–12 December 2014; 2856–2861. DOI: 10.1109/GLOCOM.2014.7037241.
26. C-RAN The Road Towards Green RAN. *White paper,* China Mobile Research Institute, 2013. http://labs.chinamobile.com/cran/wp-content/uploads/2014/06/20140613-C-RAN-WP-3.0.pdf [accessed on 23 January 2017].
27. Chih-Lin I, Huang J, Duan R, Cui C, Jiang J, Li L. Recent Progress on C-RAN Centralization and Cloudification, *Access, IEEE* 2014; **2**:1030–1039, DOI 10.1109/ACCESS.2014.2351411.
28. Fronthaul Challenges and Opportunities. *Presentation at lte world summit*, Orange Labs Network, 2014. http://www.e-blink.com/sites/default/files/documents/LTE_world_summit-Orange.pdf [accessed on 23 January 2017].
29. Checko A, Christiansen H, Yan Y, Scolari L, Kardaras G, Berger M, Dittmann L. Cloud RAN for Mobile Networks - A Technology Overview, *IEEE Commun. Surv. Tutorials* Firstquarter 2015; **17**(1):405–426, DOI 10.1109/COMST.2014.2355255.

30. C-RAN Vendors Ready for Virtualization as Asian Operators Pursue Wide-scale Deployments. *Web press release*, ABIresearch, 2014. https://www.abiresearch.com/press/c-ran-vendors-ready-for-virtualization-as-asian-op/ [accessed on 23 January 2017].
31. Virtualization of Small Cells: Overview. *Technical Report 106.05.1.01*, Small Cell Forum, 2015. http://scf.io/en/documents/106__Virtualization_for_small_cells_Overview.php [accessed on 23 January 2017].
32. HTS Business Models. *Technical Report*, iDirect. http://www.idirect.net/Company/Resource-Center/Collateral-Library/~/media/Files/Infographics/HTS-Business-Models-Infographic.ashx [accessed on 23 January 2017].
33. Astuto BN, Mendonça M, Nguyen XN, Obraczka K, Turletti T. A Survey of Software-Defined Networking: Past, Present, and Future of Programmable Networks, *Communications Surveys and Tutorials, IEEE Communications Society* 2014; **1617–1634**(3), DOI 10.1109/SURV.2014.012214.00180. https://hal.inria.fr/hal-00825087, accepted in IEEE Communications Surveys & Tutorials, [accessed on 23 January 2017].
34. McKeown N, Anderson T, Balakrishnan H, Parulkar G, Peterson L, Rexford J, Shenker S, Turner J. Openflow: Enabling innovation in campus networks, *SIGCOMM Comput. Commun. Rev.* 2008; **38**(2):69–74, DOI 10.1145/1355734.1355746.
35. Open Networking Foundation. https://www.opennetworking.org/about/onf-overview [accessed on 23 January 2017].
36. Open Networking Research Center. http://onrc.stanford.edu/ [accessed on 23 January 2017].
37. Mallon S, Gramoli V, Jourjon G. Are Today's SDN Controllers Ready for Primetime? *CoRR* 2016; **abs/1608.05140**.
38. Kulatunga C, Kuhn N, Fairhurst G, Ros D. Tackling Bufferbloat in capacity-limited networks, *2015 European Conference on Networks and Communications (EuCNC)*: Paris, 2015; 381–385. doi: 10.1109/EuCNC.2015.7194103.
39. Gopal R, Ravishankar C. Software Defined Satellite Networks, *32nd AIAA International Communications Satellite Systems Conference, SPACE Conferences and Exposition*, 2014. DOI: 10.2514/6.2014-4480.
40. Bertaux L, Medjiah S, Berthou P, Abdellatif S, Hakiri A, Gelard P, Planchou F, Bruyère M. Software Defined Networking and Virtualization for Broadband Satellite Networks, *IEEE Commun. Mag.* 2015; **53**(3):54–60. https://hal.archives-ouvertes.fr/hal-01107652 [accessed on 23 January 2017].
41. ETSI. Satellite Earth Stations and Systems (SES); Broadband Satellite Multimedia (BSM); Services and architectures. *Technical Report V1.2.1*, European Telecommunications Standards Institute, 2007.
42. Baudoin C, Arnal F. Overview of platine emulation testbed and its utilization to support dvb-rcs/s2 evolutions, *Advanced Satellite Multimedia Systems Conference (ASMA) And The 11Th Signal Processing for Space Communications Workshop (spsc), 2010 5th*: Cagliari, Italy, 2010; 286–293. DOI: 10.1109/ASMS-SPSC.2010.5586897.

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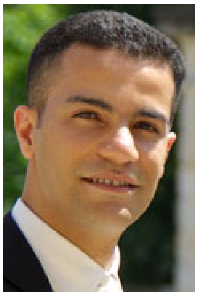

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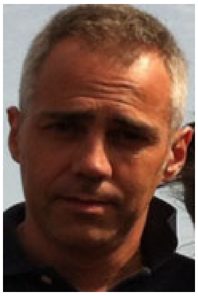

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