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On the Virtualization and Dynamic Orchestration of Satellite Communication Services

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Abstract – **Key features of satellite communications such as wide-scale coverage, broadcast/multicast support and high availability, together with significant amounts of new satellite capacity coming online, anticipate new opportunities for satellite communications services as an integral part within upcoming 5G systems. To materialize these opportunities, satellite communications services have to be provisioned and operated in a more flexible, agile and cost-effective manner than done today. In this context, this paper describes a solution for the virtualization and dynamic orchestration of satellite communication services that builds on the introduction of Software Defined Networking (SDN) and Network Function Virtualization (NFV) technologies within the satellite ground segment systems. Along with the description of the main system architecture traits, the flowchart of a general procedure for the dynamic instantiation of virtualized satellite networks on top of a SDN/NFV-enabled satellite ground segment system is provided. The paper also presents experimental results for the dynamic customization of satellite network services through the implementation of a set of virtualized satellite network functions that can be orchestrated over general purpose open virtual platforms.**

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

I. INTRODUCTION

The role that satellite communications can play in the forthcoming 5G ecosystem is being revisited. Technological advances in the satellite domain such as the use of High Throughput Satellites (HTS) in Geostationary Earth Orbit (GEO) [1] is changing the way that capacity is being brought to the market, reducing the price per bit and making it more attractive for other services such as satellite broadband communications. Likewise, a range of disruptive initiatives envisioning the use of non-GEO constellations with a large number of low-cost micro-satellites [2] might come to fruition in the forthcoming years, anticipating a further reduction in the cost of transmitting a bit over a satellite link while enhancing some of the Quality of Service (QoS) metrics such as latency.

In this context, the introduction of Software Defined Networking (SDN) and Network Function Virtualization (NFV) technologies within the satellite ground segment networks is anticipated to be a necessary step in their evolution [3][4]. SDN and NFV technologies can bring greater flexibility to Satellite Network Operators (SNOs), reducing both operational and capital expenses in deploying and managing SDN/NFV-compatible networking equipment as well as facilitating the integration and operation of combined satellite and terrestrial networks [5]-[7]. At the end of the day, SDN/NFV technologies are expected to better prepare SNOs for tomorrow's *softwarised* communications networks [8].

This paper describes an innovative architecture for SDN/NFV-enabled satellite ground segment systems and shows how the proposed architecture is used for the dynamic orchestration of satellite communication services. The proposed architecture improves flexibility and reconfigurability in the delivery of satellite network services by supporting virtualization (i.e. softwarisation) of key satellite network functions together with network abstraction and resource control programmability. Moreover, the proposed architecture supports multi-tenancy to facilitate Virtual Network Operator (VNO) models and federation capabilities for the multi-domain orchestration of network functions and SDN-based control and management across terrestrial and satellite domains.

The rest of this paper is organized as follows. Section II outlines the main architectural traits of the proposed satellite ground segment system architecture. On this basis, section III firstly describes the operation of the proposed architecture through a message chart that shows the dynamic instantiation of satellite communication services and then presents some experimental results that show the feasibility of the dynamic customization feature through the implementation of a set of virtualized satellite network functions that are orchestrated on-demand and executed on general purpose open virtual platforms. Finally, conclusions are drawn in Section IV.

II. ARCHITECTURE OF SDN/NFV-ENABLED SATELLITE NETWORKS

The two central components of a satellite ground segment system for the delivery of broadband satellite communications are the satellite gateway (GW) and the satellite terminal (ST). A satellite GW typically comprises: (1) the Out-Door Unit (ODU), composed of the antenna and radio head units; (2) the Satellite Baseband Gateway (SBG), embedding the physical and link layer functions of the satellite interface; and (3) a set of Satellite Network Functions (SNFs) for the interworking with external networks as well as for the provision of Performance Enhancing Proxy (PEP) functions for satellite transmission (e.g. TCP optimization, content caching) along with other generic functions such as Virtual Private Network (VPN) and firewalling. The virtualization of the satellite GW is studied in [9], identifying different variants with regard to

which functions can be implemented as Virtualized Network Functions (VNF) and which remain as specialized hardware appliances (i.e. Physical Network Functions, PNFs). Without being conditioned to any particular variant, in the following we denote SNF-VNF to the implementation of the SNFs as VNFs, SBG-VNF to the implementation of part of the SBG functions as a VNF and SBG-PNF to the non-virtualized part of the SBG functions. On this basis, a high-level view of the proposed architecture for SDN/NFV-enabled satellite ground segment systems is given in Fig. 1, illustrating the main functional building blocks and the reference points among them.

A. Physical network infrastructure with virtualization support

This building block consists of the virtualization-capable physical network elements, including:

-NFV Infrastructure-Point(s) of Presence (NFVI-PoP(s)) for the deployment of SNF-VNF(s) and SBG-VNF(s). The main resources in these NFVI-PoPs are general purpose network, computing (CPU) and storage. There could be several distributed NFVI-PoPs, including a lightweight NFVI-PoP at the ST side. Resources in each NFVI-PoP are managed by a Virtualization Infrastructure Manager (VIM).

-Satellite Baseband Gateway (SBG) Physical Network Function (SBG-PNF) components, which host the non-virtualized part of the SBG and are directly connected to the ODUs for satellite signal transmission/reception.

-Transport network between the several NFVI-PoPs (backhaul), between the NFVI-PoP and the locations that host the SBG-PNFs (fronthaul), and cross-domain interconnection links. Each transport network segment is assumed to be managed by a WAN Infrastructure Manager (WIM).

-Satellite Terminals (STs), which provide the satellite connectivity and interworking between the satellite connection and a customer premises network (e.g. LAN network) on the terminal side.
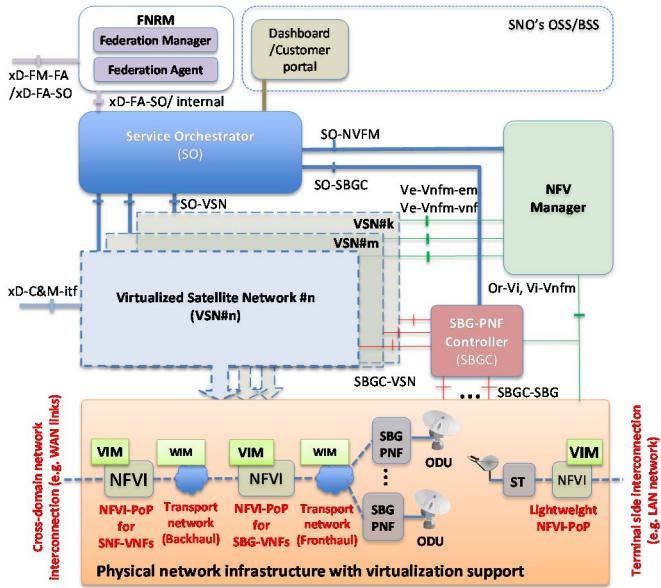

Fig. 1. Architecture for SDN/NFV-enabled satellite ground segment systems

B. Virtualized satellite network

A Virtualized Satellite Network (VSN) is conceived here as a satellite network in which most of their functions are supplied as software components running in one or several NFVI-PoPs. Several isolated VSNs could be deployed over the same physical network infrastructure, as illustrated in Fig. 1. The non-virtualized functions of a VSN are provided through one or several SBG-PNFs, which could be dedicated to a given VSN or shared among several VSNs. The operation of each VSN could be delegated to the customer/tenant, acting as a satellite VNO. Each VSN may be customized to the customer/tenant's needs, including a variety of different network services running as VNFs (e.g. PEP, VPN, etc.). In particular, as illustrated in Fig. 2, the following entities could form part of a given VSN: (1) one or several SNF-VNFs and SBG-VNFs that jointly provide the data plane functions of the VSN; (2) control applications and SDN controllers (all running as VNF instances) for the realization of some VSN control functions (e.g., QoS control, radio resource management [RRM], gateway diversity [GWD], Fading Mitigation Techniques [FMT], etc.); and (3) Network Management (NM) and Element Management (EM) functions, also running as VNFs, which provide a package of VSN management functions (e.g. Fault, Configuration, Accounting, Performance and Security [FCAPS] management). Another key feature of the architecture is the support for cross/multi-domain control and management capabilities through the exposition of the xD-C&M-itf interface, as depicted in Fig. 2. Such interface will enable unified management when the VSN is interworked with terrestrial networks for e.g. end-to-end Traffic Engineering (TE). In this regard, a potential approach being investigated in [3] is the abstraction of the whole VSN as a SDN switch and the use of the OpenFlow protocol in the xD-C&M-itf interface to manage the connectivity services offered by the VSN.
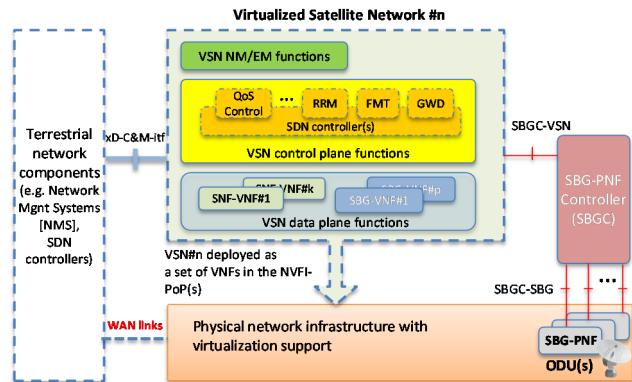

Fig. 2. Illustration of a Virtualized Satellite Network (VSN)

C. Management components

The composition and lifecycle management of the VSNs is realized through a set of functional entities within the SNO domain. In particular, VSNs can be instantiated, terminated, monitored, and modified through the following management components:

- Service Orchestrator (SO), which decides on the composition and capabilities of the VSN. The SO provides the necessary Network Service (NS) deployment templates to the NFV

Manager to deploy and chain the VNFs that compose a given VSN. In parallel, the SO allocates and configures the required resources in the SBG-PNFs that will be used by the VSN. The SO closely interacts with (or ideally is integrated in) SNO's Operations Support Systems / Business Support Systems (OSS/BSS), which may include other components such as dashboards/customer portals that the customers of the SNO can use to order the provisioning of VSNs and related Service Level Agreement (SLA) management.

- NFV Manager. This is the entity responsible for the management of the VNFs that form part of the VSN, taking care of the instantiation, the dimensioning and the termination of the VNFs. The NFV manager receives appropriate commands from the SO, which include the NS descriptors.

- SBG-PNF-Controller (SBGC). The SBGC manages the pool of SGB-PNFs. Through the SBGC, the SO can request the allocation of SGB-PNFs resources (e.g. forward/return channels) for a given VSN. To that end, the SBGC is in charge of slicing the resources of the SBG-PNF so that a logically isolated portion of those resources are allocated to a particular VSN. In addition, the SBGC could provide the interfaces for the control and management of the allocated resources to be exposed to the rest of the VSN components.

-Federation Network Resource Manager (FNRM). This component provides cross/multi-domain service orchestration capabilities. It consists of two separate components: a Federation Manager (FM) and a Federation Agent (FA). The FM supports the logic to federate different domains and orchestrating Multi-Domain Network Services (MD-NSs), while the FA handles the heterogeneity of service orchestrators used in each of the federated domains, interfacing them with the FM. Several federation models are envisioned (hierarchical centralized, distributed in chain, distributed full-mesh, and hierarchical hybrid). An illustrative example is given in Fig.3 for a scenario that involves a SDN/NFV-enabled satellite

ground segment infrastructure, owned and operated by a SNO, and a terrestrial network infrastructure, such as a mobile or fixed communication network, owned and operated by a Terrestrial Network Operator (TNO). The support of federation capabilities may even lead to new business cases for third party companies that could play the role of a Federation Broker [10] and offer added value services through resources allocated across multiple domains, as illustrated in Fig. 3.
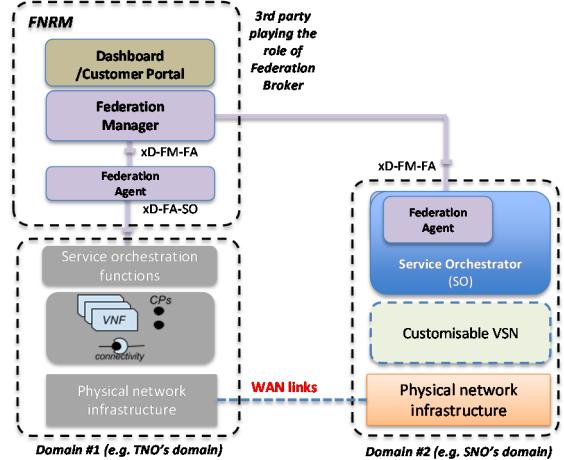

Fig. 3. Illustration of a possible architecture for the multi-domain federation

III. DYNAMIC SERVICE ORCHESTRATION PROCEDURE AND EXPERIMENTAL ASSESSMENT

A. Procedure for the instantiation of a VSN

Fig. 4 depicts a general procedure for the dynamic instantiation of a VSN in the case of a SNO that uses the proposed architecture to allow its customers to set-up satellite service instances through an online customer portal with self-service features. Details of the different steps are given in the following:.
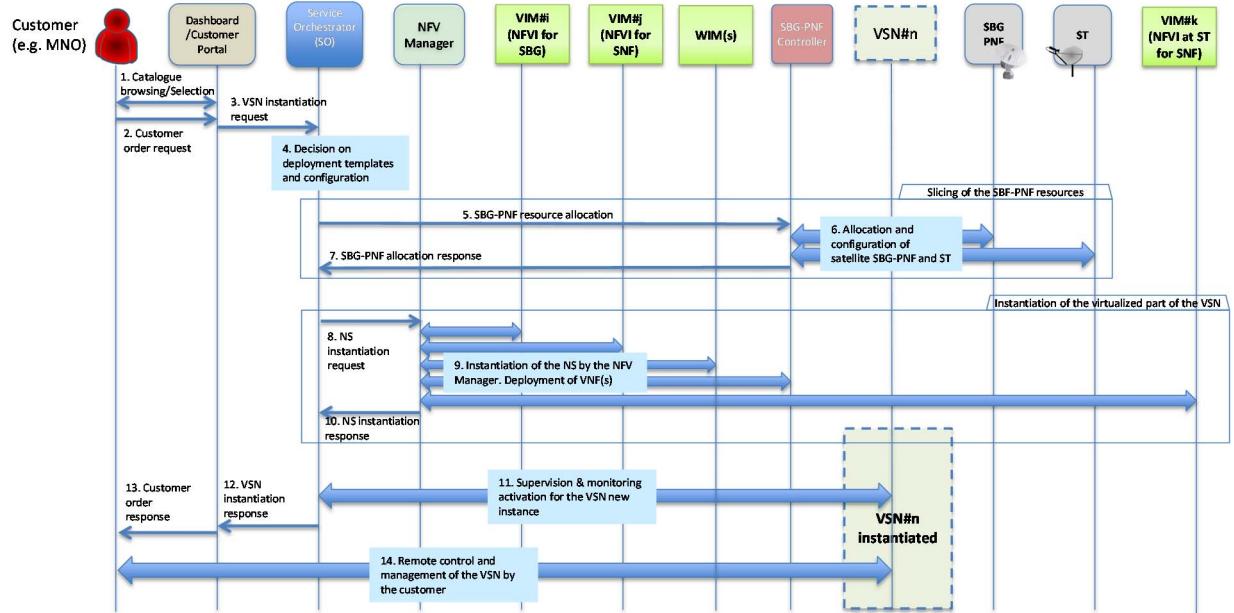

Fig. 4. General procedure for the instantiation of a VSN

Step 1. The Customer (e.g. a Mobile Network Operator [MNO] that wants to use the VSN for mobile backhauling services) uses the online self-service portal to select and configure the characteristics of the VSN, allowing for the customization of the VSN within the limits set by the SNO. This requires the management of a VSN catalogue and customer-oriented descriptions of the VSN features. Descriptors of VSN should also consider SLA parameters (e.g., VSN downtime). This process might also involve access to external catalogues of network functions provided by 3rd parties that could also be delivered as part of the VSN offering by the SNO

Step 2. After the selection and customization of the VSN, the customer orders the desired VSN.

Step 3. The customer portal delivers the request for the VSN instantiation to the SO.

Step 4. Based on a VSN Description (VSND) received from the customer portal, the SO determines the detailed composition of the VSN and how the VSN is deployed in both the virtualized and the non-virtualized infrastructure of the SNO. For those components of the VSN that can be deployed as VNFs, the SO decides on the necessary NS and VNF deployment templates (e.g. network service descriptor [NSD] of the VSN and VNF service descriptors [VNFDs] of the VNF that compose the VSN) to the delivered to the NFV Manager. For those components of the VSN that are supported over specialized hardware appliances (i.e. SBG-PNF), the SO decides on the configuration of these appliances.

Step 5. The SO sends a request to the SBG-PNF Controller to allocate resources in the SBG-PNF for the VSN.

Step 6. The SBG-PNF Controller takes care of the allocation and configuration of SGB-PNFs resources for a given VSN (e.g. forward/return channels). This process can also encompass the configuration of the operational parameters of the STs. On this basis, the SBG-PNF-Controller creates a logical view of the allocated resources so that the control and management of these resources can be integrated with the virtualized components of the VSN.

Step 7. The SBG-PNF Controller acknowledges completion of the allocation and configuration of the SBG-PNF resources.

Step 8. The SO sends a request to NFV Manager to instantiate the NS that provides the virtualized part of the VSN.

Step 9. The NFV Manager instantiates the NS based on the NSD received from the SO. For that purpose, the NFV Manager interacts with the VIMs of the NFVI-PoPs within the SNO infrastructure (e.g., NFVI-PoPs for the deployment of SNF-VNFs and NFVI-PoPs for the deployment of SBG-VNFs) and, potentially including the one in the lightweight NFVI-PoP on the terminal side. The NFV Manager also takes care of laying out the connectivity among the NVFI-PoP(s) and SBG-PNF(s) through the corresponding WIMs. Overall, this step of the general procedure is to be compliant with the NS instantiation procedure specified within the ETSI NFV Management and Operation (MANO) framework [11].

Step 10. The NFV Manager acknowledges completion of the NS instantiation to SO.

Step 11. The SO completes the operational activation of the new VSN. This process might involve a set of NM/EM systems within the SO to activate/turn-on the VSN's components from a management perspective and bring them into operational state. Monitoring processes are also started at this point for the SO to supervise the operational status of the VSN.

Step 12. The SO acknowledges completion of the VSN instantiation to the customer portal.

Step 13. The customer portal informs the customer that the VSN is operational. Detailed information on the settings of the instantiated settings can be made available to the customer at this point, including the addresses and ports for the integration of the VSN with the customer's control and management systems.

Step 14. The control and management connections between the instantiated VSN and the customer equipment are established. From this point onwards, the customer can have access to relevant control and management capabilities for VSN administration (e.g. user/STs provisioning and access control), VSN monitoring (e.g. real time network status/performance, status of the STs), VSN configuration (e.g. QoS configuration, resource allocation and operation modes configuration), VSN troubleshooting/diagnostics (e.g. alarm management) and VSN traffic management (e.g. real-time control of the satellite traffic flows from external network controllers).

B. Testing of SNF-VNFs prototypes for VSN customisation

Three prototype SNF-VNFs have been implemented so that they can be dynamically instantiated and chained on-demand as part of a VSN offering: (1) SNF-VNF#1 - Virtual Private Network (VPN), which provides a secure connectivity service based on IPsec; (2) SNF-VNF#2 - Hybrid Access, which supports data transfers over multiples links used in parallel through the combination of TCP acceleration for long latency links and multi-path routing; and (3) SNF-VNF#3 - WAN optimization, which supports a combination of compression and caching techniques, providing better performance than a typical satellite PEP.

A tested platform has been set up to demonstrate the feasibility to offer dynamically customizable satellite communications services. Among others, the testbed allows us to showcase the dynamic instantiation and conduct a performance assessment of the implemented SNF-VNFs that are used to enhance a baseline satellite communications service offering. The central hardware component of the testbed is an Open Virtual Platform (OVP) prototype capable of executing multiple SNF-VNFs simultaneously. The OVP is essentially an general purpose x86 platform (Intel server 2 x E5-2630v2 2.6GHz x 6 cores, 32 GB memory, 2 SSD 160GB RAID), where one or more SNF-VNFs can be executed. The use of generic hardware reduces the SNF-VNF integration cost to a minimum so the service provider makes its hardware choice purely on the number and resource needed by the SNF-VNFs required to run its own service. Two OVP are interconnected through an emulated satellite connection, thus playing the role of one NFVI-PoPs located within the SNO's infrastructure and the lightweight NFVI-PoP within the customer premises (see

Fig. 1). The orchestration and service function chaining within the OVP is commanded from a management station, which partially implements the functionalities of the SO and NFV Manager components.

Fig. 5 shows some test results with regard to the use of SNF-VNF#3 for the improvement of the delivered satellite communications service. The aim of the test is to verify if the WAN Optimization service delivered by the SNF-VNF#3 can achieve acceptable performance over the emulated satellite link. On a typical satellite gateway, an operator could need to process more than 100 Mbps of traffic with several thousands of concurrent connections with a single device. Therefore, the test scenario consists of simulating users opening up to 10000 TCP connections to a server and download files of various sizes. The generated traffic goes through the two SNF-VNF#3 instances interconnected by the emulated satellite link. The server on the network side delivers a different file to each individual TCP connection on the client side. 90% percent of the files contain pure random data which cannot be compressed by the SNF-VNF#3. The remaining 10% files contain redundant data which can be compressed. The server is configured to limit the output bandwidth to 120Mbps. The test lasts 30 seconds. The input and output bandwidths of the SNF-VNF#3 instance located on the customer side are measured, together with how CPUs are occupied. In terms of memory, SNF-VNF#3 can use up to 28GB of RAM where 13GB are dedicated for the embedded dictionary to achieve the compression/caching. As to computation power, SNF-VNF#3 can use up to 24 VCPUs, each one executing threads that process a pool of concurrent TCP connections.
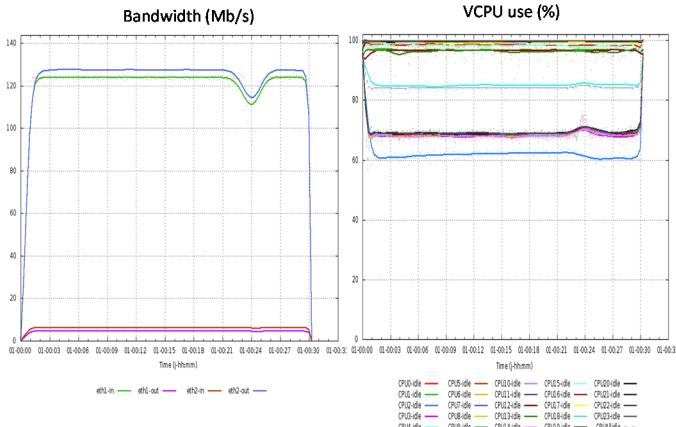

Fig. 5. Performance assessment of the SNF-VNF#3: (a) delivered throughput and (b) consumption of computing resources (CPU usage)

As shown in the left-hand graph in Fig. 5, the target throughput of 120 Mbps can be sustained during the test duration. The output traffic (legend 'eth2-out') is slightly greater than the input traffic (legend 'eth1-in') since 10% of the traffic enters in a compressed form from the satellite link. The SNF-VNF#3 then delivers uncompressed data toward the customer at a constant throughput. Remarkably, the right-hand graph in 5 shows that most VCPUs are idle more than 70% of the time so that the OVP resources are far from being fully loaded. This proves the feasibility of delivering the WAN optimization service in the form of a dynamically instantiable

SNF-VNF, leaving still much processing power available for other SNF-VNFs to be orchestrated in the same platform.

IV. CONCLUSIONS

The adoption of SDN and NFV technologies into the satellite domain is seen as a key facilitator to enhance the delivery of satellite communications services and achieve a better integration of the satellite component within the 5G ecosystem.

This paper has described the architecture of a SDN/NFV-enabled satellite ground segment system that supports on-demand dynamic orchestration of satellite communications services. Together with the main architectural traits, a general procedure for the dynamic instantiation of a VSN through an online customer portal with self-service features has been elaborated. Moreover, the paper has also presented some experimental results that showcase the delivery of customizable satellite communications services on general purpose OVPs through the instantiation of a set of satellite network functions implemented as VNFs to provide VPN, Hybrid Access and WAN Optimization services over satellite links. Some initial performance results have been provided for the virtualized WAN optimization service, showing how the implemented SNF-VNF can achieve the expected performance. Further work is ongoing in [3] to extend the testbed platform to demonstrate and assess the operation of other components of the proposed solution.

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