Special Issue of IEEE
Advanced Solutions for 6G satellite
Systems Workshop

Reference Architectures for Enabling Integrated Satellite-6G Applications and Services

Debabrata Dalai
Indian Institute of Space Science and Technology, Trivandrum, India
695547
ddalai@ieee.org

Sarath Babu
Iowa State University, Ames, USA
50011
sarath.babu.2014@ieee.org

B.S. Manoj
Indian Institute of Space Science and Technology, Trivandrum, India
695547
bsmanoj@ieee.org

ABSTRACT

Reference Architectures (RAs) play an important role in the integration of 6G terrestrial and satellite networks. In this paper, we present the essence of the reference architectural roadmap as per the Edition-3 document of the Satellite Working Group of IEEE Future Networks Initiative (FNI). We focus on an integrated virtualized 6G-satellite architecture. Further, we present one of the case studies, Space Based Hosting Service (SBHS) approach with simulation results. SBHS approach deploys the content-servers in LEO satellite to achieve the low-latency service requirements. The architecture of SBHS is a special case over Reference Architecture-3. We achieved minimum average end-to-end latency of 7.75ms for the geographical area covering India by the proposed SBHS approach.

Index Terms—6G-satellite integration, reference architecture, satellite network, virtualization, MANO, satellite edge computing, content server.

1. INTRODUCTION

Recent studies in [1] [2] [3] estimate that approximately 37% of the world's population is unconnected to high-speed Internet access. Terrestrial networks cannot guarantee access to the Internet to the users on aircraft or high-speed trains, highways, ships, and remote rural areas due to lack of infrastructure deployment. However, the nodes in Non-Terrestrial Networks (NTNs) such as Low Earth Orbits (LEOs), Medium Earth Orbits (MEOs), Geostationary Equatorial Orbits (GEOs) satellites, Unmanned Aerial Vehicles (UAVs), and High-Altitude Platforms (HAPs) can help in providing Internet to such scenarios.

The integration of 6th Generation (6G) wireless communication systems with NTNs has brought a paradigm shift in employing technologies such as softwarization and virtualization. The elements of NTNs primarily include satellites in LEO, MEO, GEO, and Highly Elliptical Orbits (HEO), flying nodes such as UAVs, and HAPs. In the decade 2020–2030, it is envisioned to deploy LEO and mega-LEO constellations (with the number of satellites on the order of several thousands) to provide global Internet services. However, to achieve the vision of satellite-6G network integration, appropriate Reference Architectures (RAs) need to be designed and developed.

In [4], RA-3 focuses on 6G-satellite integration where the satellite acts as an access network. In this work, we discussed a unique application over RA-3, SBHS [5], which emphasizes the impact of satellite broadband Internet on rural and remote areas around the world with the help of the next generation mega satellite constellations. The SBHS focuses on achieving the goal of connecting the digitally unconnected population. SBHS deals with hosting an entire content-server in the LEO satellites to reduce the end-to-end latency. In this work, the RA-3 is utilized to deliver the SBHS as an application.

The remaining of the paper is organized as follows: Section II introduces the reference satellite architecture for 6G satellite network integration. Section III details possible use cases and case studies using RA-3. Section IV explains the simulation environment used to study the SBHS approach using RA-3. Section V provides performance results related to SBHS. Finally, Section VI concludes the paper.

2. REFERENCE ARCHITECTURES TOWARD 6G-SATELLITE NETWORK INTEGRATION

One of the most significant aspects of 6G-satellite network integration is the reference architecture. In this paper, we consider three RAs: (i) non-virtualized satellite networks (RA-1), (ii) separate virtualized satellite networks (RA-2), and (iii) integrated virtualized 6G-satellite networks (RA-3) [4]. The interfaces defined for RAs are closely related links to those specified in 3GPP TR 38.821 Rel. 16 [6].

For the 5th Generation (5G) communication systems, two RAs were outlined in [7] for 5G-satellite integration. In the first RA (RA-1), named as non-virtualized 5G-satellite networks, the satellite infrastructure is envisioned to use as the backhaul infrastructure for 5G-terrestrial networks. In the second RA (RA-2) [7], named as separately virtualized 5G-satellite networks, satellite network forms a virtualized network infrastructure, however, separated from the terrestrial 5G virtualized network.

The RA for 6G-satellite network integration is an extended version of RA-2, named integrated virtualized 6G-satellite networks (RA-3) [4]. The scheme RA-3 is expected to include only a single Management and Network Orchestration (MANO) for the satellite and terrestrial segments. In RA-3, the control plane design, control operations, network slicing, network functions, network interfaces, network orchestration approaches, and functional aspects of the network follow the same pattern for both the virtualized satellite and terrestrial 6G networks. The virtualized network (i.e., integrated satellite and terrestrial 6G) maintains a single MANO module for its respective management activities. The responsibilities to carry out resource management, routing of packets, channel management, slice management, edge computing decisions, and federation functions rest with the integrated MANO module of the network.

Besides the functions outlined in 3GPP, two additional network functions for RA-2 and RA-3 are defined: Satellite Edge-computing Function (SEF) and Satellite Network Federation Function (SNF). A part of the SEF is already considered in [8] with a multi-tier caching framework for Satellite Edge Computing (SEC) for 5G satellite integration with inter-satellite cache transfer.

3. REFERENCE ARCHITECTURE USE-CASES

A set of 13 use-cases were proposed in [7] for 5G terrestrial networks employing satellite network infrastructure as the backhaul infrastructure. The use-cases include communication between Distributed Unit (DU) and Centralized Unit (CU) through singlehop/multihop links using federated/non-federated LEO network. Further, the use-cases with UAVs and HAPs, employed for backhaul infrastructure, were discussed in [7]. HAPs can be served as flying airborne base stations to connect the unconnected or the under-connected [9]. HAPs can be deployed up to an altitude of 30 km [10] and offer round-trip latency of the order of less than 1.2 ms. In fact, HAPs can be integrated to the backbone network. HAPs act as a tower-in-the-air by relaying data between the BS and eNodeB/eNodeG where either mobile UEs or access points are located in under-served regions [11].

The backhaul service scenarios for NTN are described in [4] where the satellite network infrastructure is used for direct access. The new use-cases for direct access to satellite networks focus on the entire spectrum of NTNs including HAPs, UAVs, and satellites. Two major directions are considered with an eNodeB/gNodeB being (i) on-NTN or (ii) on-ground. Further, three direct access modes for NTN nodes are discussed: (i) gNodeB/eNodeB onboard the NTN node (satellite/HAPs), (ii) relay access where the backhaul traffic is forwarded to another high-level node by the NTN node, and (iii) bent-pipe by NTN node (satellite/HAPs). The entire functions of eNodeB/gNodeB are included in the assumption of eNodeB/gNodeB irrespective of its location in NTN. The use-cases are divided according to LAPs, HAPs, and satellites. Using LAPs and HAPs as gNodeB/eNodeBs, 16 use-cases are described where seven use-cases are defined for satellites acting as gNodeB/eNodeB [4].

The physical layer assumptions for the use-cases discussed in [12] include: (i) the use of LEO satellites constellation, (ii) circular orbit around the Earth with a typical beam footprint of 100–1000 km, (iii) transparent or regenerative LEO satellite payload, (iv) no inter-satellite links, (v) fixed or movable beams (moving or fixed footprint on the ground), (vi) below 6 GHz frequency band, and (vii) direct or indirect access network (indirect access via terrestrial gateway or HAPs).

a. Space-Based Hosting Service

In [5], an approach for SBHS was proposed to deploy content servers in LEO and GEO satellites. The SBHS framework was envisioned to play an important role in accomplishing the goal of connecting the digitally unconnected population. In [5], the SBHS demonstrated an example of hosting a complete content server in a LEO satellite. Iridium-NEXT satellite constellation [13] was used for the simulation studies. The simulation studies showed the feasibility of hosting an entire content server in space to achieve ultra-low latency compared to the traditional satellite-based web services.

Figure 1 illustrates the use of RA-3 in SBHS. SBHS uses the regenerative satellite payload where an entire content server is present. LEO satellites are used to host the content server in SBHS. To reduce the delay, the LEO satellite serves directly to the users. The integrated 6G-satellite control plane is located in LEO satellites. The terrestrial 6G part is not present as SBHS only uses LEO satellites to serve the end users. Further, the networking functions present in the MANO are modified to suit the SBHS.

4. SIMULATION SETUP

We considered Iridium-NEXT satellite constellation for our simulation. A Python-based library, skyfield [14] is used to create the LEO satellite network topology. The network parameters used in the simulation are described in TABLE I. Iridium-NEXT constellation consists of 75 satellites placed in polar orbits of altitude 780 km and an inclination of 86.4^{o}. We assumed the users are present in a 10×10 km^2 area within India. Multiple user densities were considered in the simulation. The uplink and downlink end-to-end data rates between UE and LEO satellites are set to 100 Mbps and 200 Mbps, respectively. The CPU processor capacity in LEO satellites is assumed to be 1 GHz. The size of a request message from user to satellite is taken from a uniform distribution between 1–300 Bytes. The average content size is assumed as 5 KB which is present in the LEO satellite. The simulation experiment is carried out for 100 minutes which is the average orbital period of satellites in the Iridium-NEXT satellite constellation.

5. PERFORMANCE ANALYSIS

We evaluated the performance of the proposed SBHS through average end-to-end delay. Figure 2a illustrates the average end-to-end delay, round trip propagation delay, and queuing delay. We observed the lowest average end-to-end delay of 7.75 ms. In Figure 2a, the significant contributing factors to the end-to-end delay are round trip propagation delay and queuing delay. We considered two queues in our simulation. One queue is used to collect the user requests and the second queue is used to transmit the content to the user. The propagation delay contributions to the end-to-end delays for 2000, 5000, and 10,000 users are 91%, 91.6%, and 88%, respectively. Similarly, queuing delay contributions to the same user densities are, respectively, 26.5%, 30%, and 33.5%. In 5G systems, the delay related Key Performance Indicator (KPI) is 1 ms. However, it is impossible to achieve a 1 ms delay with Iridium-NEXT satellite constellation. This is due to the high propagation delay which depends on the altitude of content server satellites. Therefore, the propagation delay is not reducible. The queuing delay can be reduced by increasing (i) the number of cores and frequency of the processor and (ii) the number of transmission channels. However, reducing queuing delay is not sufficient as the major contributing factor to the end-to-end delay is propagation delay.

Figure 2b illustrates the other minor delays that contributed to the end-to-end delay. The minor delays consist of uplink transmission delay, downlink transmission delay, delay to search the contents in the database, and delay for retrieving contents from the database. The minor delays are in the microseconds range. Therefore, the significance of those delay components is less. The end-to-end delay experienced by different densities of users is similar. This is due to the small content size.

6. Conclusion

In this paper, we considered the reference architectures based on both backhaul and direct access of NTN elements for 6G systems integration with the satellite networks. An integrated virtualized 6G-satellite architecture was discussed based on NTN elements such as LEO, MEO, GEO, HEO satellites, UAVs, and HAPs. Finally, an application services case study of Space Based Hosting Service (SBHS) was presented. We observed a minimum average end-to-end delay of 7.75 ms for the country India using SBHS approach.

Acknowledgements

This work is funded in parts by IIT Palakkad Technology IHub Foundation Doctoral Fellowship IPTIF/HRD/DF/032.

Table 1. SIMULATION PARAMETERS

Parameter	*Value*
User population	2000, 5000, and 10,000
Number of satellites	75
Request message size	1 -- 300 bytes
Processor frequency	1 GHz
End-to-end uplink data rate	100 Mbps
End-to-end downlink data rate	200 Mbps
CPU cycle/bit	10
Queue length	100
Simulation time	100 minutes

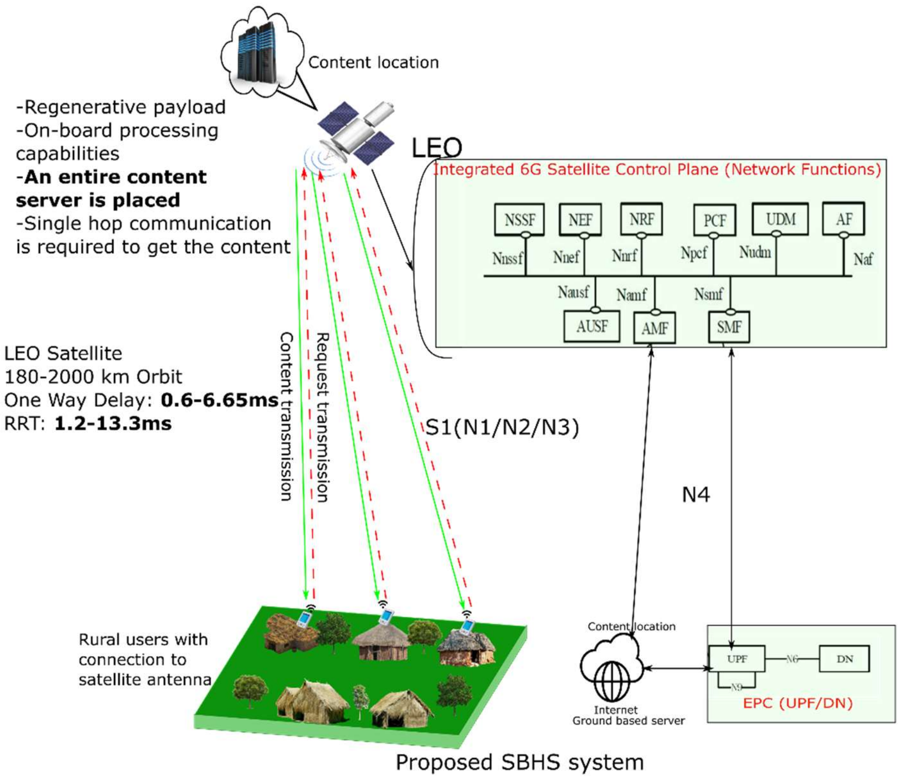

Fig 1: SBHS over Reference Architecture-3

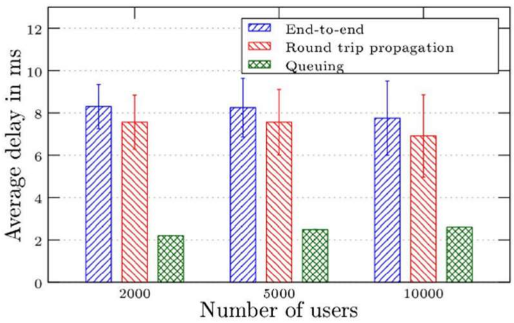

Fig 2a: Different delays for various user densities.

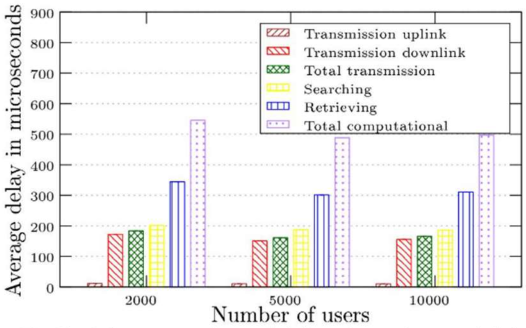

Fig 2b: Minor contributed delays in end-to-end delay for different user densities.

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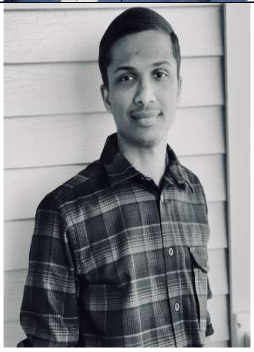
	Debabrata Dalai (Graduate Student Member, IEEE) received the bachelor’s degree in electronics and telecommunication engineering from Biju Patnaik University of Technology (BPUT), Rourkela, India, and the master’s degree in computer science and engineering (Advanced Networks) from the Indian Institute of Information Technology and Management, Gwalior, India. He is currently a Senior Research Fellow with the Department of Avionics, Indian Institute of Space Science and Technology, Thiruvananthapuram, India. He serves as the current chair of IEEE IIST Student Branch. His research interests include advanced wireless networks, satellite-IoT networks, satellite edge computing, and 5G/6G satellite integration.
	Sarath Babu (Member, IEEE) received his Ph.D. degree from Indian Institute of Space Science and Technology, Thiruvananthapuram, India in 2021. He completed his master’s degree in Computer Science and Engineering (Information Security) from National Institute of Technology, Calicut, India, and bachelor’s degree in Information Technology from Mahatma Gandhi University, Kottayam, India. He is currently working as a Research Scientist at the Department of Electrical and Computer Engineering, Iowa State University, USA, and affiliated to the Center for Wireless, Communities, and Innovation (WiCI). His primary focus is on the project ARA-Wireless Living Lab for Smart and Connected Rural Communities, a part of NSF Platforms for Advance Wireless Research program. His research interests include next generation wireless infrastructures, software defined networks, complex networks, systems security, and intelligent transportation systems.
	B. S. Manoj (Senior Member, IEEE) received the Ph.D. degree in computer science and engineering from the Indian Institute of Technology Madras in 2004. He was an Assistant Research Scientist and a Lecturer with the Electrical and Computer Engineering Department, University of California at San Diego. He is currently a Professor with the Department of Avionics, Indian Institute of Space Science and Technology, Thiruvananthapuram, India. His current research interests include complex networks, ad hoc wireless networks, delay tolerant networks, next generation wireless architectures, wireless sensor networks, wireless mesh networks, satellite networks, 6G-satellite integration, and quantum computing.