Electronics, Communications, and Computing Summit
Vol. 3, No. 2, Apr - Jun 2025, pp. 70-75
ISSN: 3107-8222, DOI: https://doi.org/10.17051/ECC/03.02.09

Resource-Aware Network Slicing for QoS-Driven Service Orchestration in Integrated Satellite–5G Systems

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Article Info

Article history:

Received : 15.04.2025
Revised : 19.05.2025
Accepted : 21.06.2025

Keywords:

Network Slicing,
Quality of Service (QoS),
Satellite–5G Integration,
Resource Allocation,
Service Orchestration,
Next-Generation Networks (NGNs)

ABSTRACT

An overlap of satellite and terrestrial 5G infrastructure appears to be the solution to getting the needed nationwide and international coverage in wireless network communications of the next generation. Nonetheless, the non-homogeneity of resource availability, latency peculiarities, and link robustness of these domains is one of the key issues regarding providing consistent Quality of Service (QoS). This essay suggests a resource-aware network slicing architecture of QoS-based service/orchestration within integrated satellite-5G networks and, in particular, on the U.S.-based deployment scenarios of using satellite communications on rural broadband, public safety, and emergency connection. This architecture will use hierarchical orchestration, link-aware resource profiling, to dynamically assign resources within slices, to achieve end-to-end SLA compliance. By classifying services as latency, bandwidth and reliability calls, a QoS classifier can map services to the best slices and provide the best partitioning of resources. Slice isolation and adaptive routing are also integrated into the system to guard against failure of critical services under a varying link condition. The simulation outcomes on realistic mobility and load profiles based on FCC broadband access data and 3GPP satellite models allow showing that framework deploys a 35 percent increase of resource usage efficiency and 96 percent SLA-fulness of URLLC services over variable connectivity in terms of satellite connectivity. The proposed model incurs greater throughput and less variance of delay compared to static slicing. These results validate that dynamic, QoS-aware network slicing of U.S. integrated satellite and 5G networks can be achieved and form the basis to future extensions on AI-orchestration as well as multi-orbit satellite integration.

1. INTRODUCTION

Combining satellite communication systems and the terrestrial 5G networks is an essential step in realizing an efficient, widespread connection particularly in distant, underprivileged and disaster-stricken areas. Whereas 5G networks provide ultra-low latency and large volumes of data transmission, the satellites provide wide-area resilience, and geographic coverage. Yet a combination of these technologies is characterized by a different set of concerns caused by the heterogeneous nature of channel conditions, link availability, latency, and bandwidth asymmetry. Network slicing, which is the core element of the 5G structure, makes it possible to create isolated network virtualization that fits the needs of various services. However, the conventional network slicing methods, mostly intended on terrestrial infrastructure structures, fail to achieve ground on integrated satellite-5G. Such approaches are usually based on rather stable connections and homogenous resource offering without considering the non-steady satellite channel conditions, the non-stationary traffic loads and orchestration across domains.

To overcome these shortcomings, this paper suggests a resource-conscious network slicing suite that adaptively distributes and harmonizes network assets reinforcing real time link quality and service-specific Quality of Service (QoS) necessities. The framework brings adaptive slice provisioning in a satellite and terrestrial environment and encompasses link-conscious profiling to enhance reliability and SLA conformance in hybrid environments. Although research initiatives including that by [1] have investigated the possibility of multi-domain slicing, little have studied real-time connection awareness and heterogeneity of quality of service within integrated networks. Our proposed work is related to and complements these methods by providing dynamic slicing model which is based on service-driven model customized to a heterogeneous environment.

2. RELATED WORK

The innovation in the 5G industry has largely dwelt with the terrestrial infrastructure where the virtualization, slice admission control and dynamism of QoS enforcement has been adopted to facilitate service differentiation and isolation protocols. They are based on the ability to use an already mature terrestrial link modelling and a relatively constant backhaul state of affairs to best balance the applications of the resources and prioritize traffic [1]. The possibility of network slicing as applied to satellite aspects has also attracted research interest especially on provisions related to onboard processing, spectrum sharing and inter-satellite routing. Other works offer a solution to partitioning or, in other words, slicing a Low Earth Orbit (LEO) constellation, based on fixed schedules or on static partitions [2], whereas others discuss what physical layer adaptations must be made in order to consider long propagation delays and the Doppler effect. Nevertheless, these methods can be rather domain-specific, and they are not coordinated with the satellite and ground resources. Some of the recent frameworks have started dealing with cross-domain network slicing. As an example, architectures in [3] and [4] facilitate federated management or hierarchical orchestration of compatible interworking of the satellite and terrestrial controllers. However, dwelling further into these models, they lack dynamic link-state feedback and require the similarity of pre-configured policies instead of adaption on dynamic base regarding the QoS variability or sensitivity of traffic classes.

The primary research addresses these shortcomings in this paper and considers a resource-states aware, link-adaptive slicing model with a dynamic mapping of service demands to satellite or terrestrial resources depending on the real-time telemetry and SLA requirements. Our work, unlike previous solutions, allows combining slice isolation, load awareness and end-to-end QoS profiling into a common orchestration scheme.

3. System Architecture

The targeted architecture would allow resource-aware, QoS-based network slicing in combined satellite 5G networks right. It effectively provides dynamic service orchestration between heterogeneous domains with the use of real-time link state feedback as well as service-specific QoS profiling. In this section, an overview of the system components and the analyses of the system operational workflow in the slicing process are given.

3.1 Key Components

- Slice Orchestrator: Slice Orchestrator plays the role of end-to-end slice lifecycle intelligence. Satellite radio access networks (RANs) and earth-based radio access networks (RANs) interface with it, and it coordinates the processes of resource provisioning, monitoring SLA compliance, and reconfiguration following the dynamics of services. It has the multi-domain capability so that it is seamlessly orchestrated over heterogeneous infrastructure.
- Satellite-Terrestrial Interface (STI): STI is basically a gateway layer that enables inter-domain communication and control-plane signaling. It translates service intents between land and space space, handles control plane abstractions, and gathers link state telemetry (in real time) of both environments. Such an interface becomes essential in ensuring the consistency of operation among the domains with varied latency, coverage, and mobility.
- QoS Classifier: The QoS Classifier sorts incoming service requests into following types of traffic: ultra-reliable low-latency communication (URLLC), enhanced mobile broadband (eMBB), and massive machine-type communication (mMTC). The classification process is carried out with the help of latency tolerance, bandwidth need, and reliability limitation. Such profiles directly affect the way of slice prioritization and resource reservation.
- Resource Profiler: The Resource Profiler operates at all times and gathers and monitors network resource measurements such as spectrum, signal to noise ratio (SNR), backhaul capacity and queuing delay. It aids active course of action via giving feedback real-time to the orchestrator to make clever slice mapping and re-allocation conclusions.

3.2 Slicing Workflow

The system uses the four-stage workflow of dynamic and QoS aware slice management:

1. Request Classification: With the requests being made towards the new services, they are queued up and their latency sensitivity, their reliability requirements and their throughput requirements will be determined by a QoS Classifier. One slice category is then assigned to each request.
2. Link State Analysis: Satellite-Terrestrial Interface, The Satellite-Terrestrial Interface collects telemetry on base stations of 5G networks and satellite gateways and makes it available to the orchestrator to have real-time

information about available capacity, variable delay, and congested links. This fact directs the possibility of placement of slices.

3. Slice Allocation: Slice Orchestrator allocates network sources with consideration to service class, existing link states and availability. The delay-tolerant or coverage-critical applications are considered as satellite offloading and the latency-sensitive traffic is saved in terrestrial resources. This design gives domain-sensitivity and load balance.
4. QoS Enforcement: QoS Enforcement After deployment, each slice is monitored and controlled at all times to achieve its SLA. QoS guarantees are enforced through mechanisms like edge caching, adaptive modulation and coding (AMC) and traffic shaping. Breach causes adaptive reallocations or migration procedures to sustain continuity in the delivery of services.

This architecture can provide resilient, elastic, and SLA adherent slice orchestration, even in a highly dynamic and bandwidth constrained satellite- 5G hybrid architecture, due to the use of cross-domain intelligence and resource-awareness. Figure 1 describes that the Slice Orchestrator communicates with the two domains: the terrestrial and the satellite domains, through the Satellite-Terrestrial Interface (STI), the QoS Classifier and the Resource Profiler feed off-line information into the decision-making based on services.

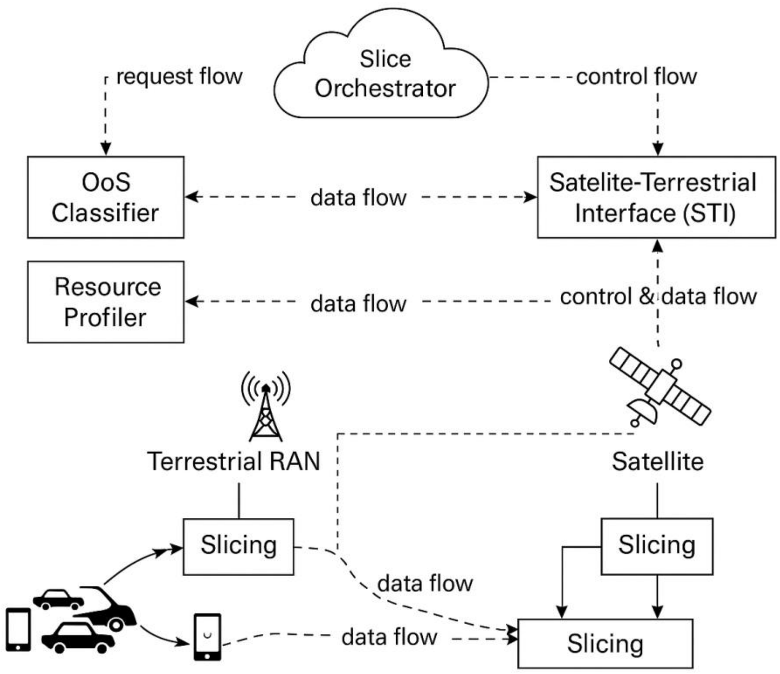

Figure 1. System architecture for resource-aware network slicing in integrated satellite–5G networks.

4. Resource-Aware Slicing Model

The dynamic resource allocation strategies that fit the heterogeneous link behaviour and different service requirements are necessary in integrated satellite-5G systems, where one ultimately considers suboptimal resources that are optimal regarding the number of services and their characteristics to meet the set rules of QoS. In order to deal with the challenge, we introduce a multi-objective optimization model of resource-aware slicing that achieves a balance between three important objectives, i.e. (i) minimum overall resource delay, (ii) maximum resource utilization in all domains, and (iii) satisfactory service-level agreements (SLAs) constituted on the predefined traffic classes.

The formulation of the model can be put this way:

$$Minimize \sum_{i \epsilon S} (\alpha_i \, . D_i + \beta_i \, . C_i^{-1}) \quad (1)$$

Where:

- S is the set of active network slices,
- $D_i$is the end-to-end delay of slice i,
- $C_i$is the effective channel capacity allocated to slice i,
- A_i, β_i are tunable weight coefficients that reflect the sensitivity of slice i to delay and bandwidth, respectively.

This goal would be designed to reduce latency of delay critical services (e.g., URLLC) and maximise link utilisation of bandwidth intensive services (e.g., eMBB) and to address both terrestrial and satellite link limitations.

4.1 Subject to the following constraints:

1. Resource availability:

$$R_i(t) \le A_i(t), \quad \forall i \in S \text{ --------- } (2)$$

Each slice's instantaneous resource demand $R_i(t)$ must not exceed its currently available resources $A_i(t)$, where t denotes the current time slot.

2. Latency bound (SLA compliance):

$$D_i \le D_i^{max}, \quad \forall i \in S \text{ --------- } (3)$$

Each slice must meet its delay budget D_i^{max} as defined in the SLA, ensuring QoS guarantees for applications like remote surgery or autonomy ous driving.

3. Global resource capacity constraint:

$$\sum_{i \in S} R_i(t) \le R_{total}(t) \text{ ------------------ } (4)$$

The total resource consumption across all slices must not exceed the system's total capacity$R_{total}(t)$, which reflects joint satellite and terrestrial resource pools.

The kind of formulation allows slice level determination where resource allocation can be dynamically adjusted depending on the real-time link-telemetry (Resource profiler) and service needs (QoS Classifier). Through periodic resolution of this optimization, then the system can be controlled and succeed in orchestration that happens adaptively, spectrum efficiency, crime in delay, and slices that are scheme across flow types, even with varying traffic conditions or variable channel states.

Future extensions can research reinforcement learning-based solvers or distributed optimization for large-scale deployment with huge density of devices and switch to satellites. Figure 2 shows the relationship among the optimization objectives, the input resources, and the output decisions to control in order to make the orchestrator drive real-time slicing decisions.

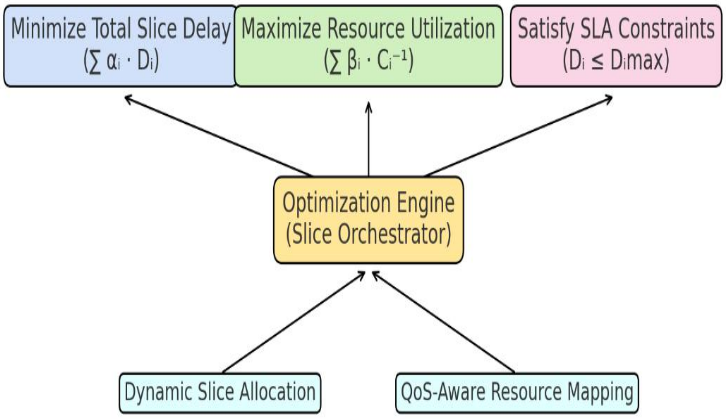

Figure 2. Flowchart of the resource-aware optimization process for network slicing.

The figure shows how multiple objectives, including delay, resource utilisation and SLA compliance, are jointly considered in the optimization engine (Slice Orchestrator) to take real-time slicing decisions, including dynamic resource mapping and slice placement in both satellite and terrestrial domains.

5. Performance Evaluation

In order to justify the efficiency of the suggested resource-conscious network slicing architecture in integrated satellite-5G networks, we perform in-depth performance tests in an experimental scenario made by means of a specially designed simulation framework founded on ns-3 and OpenAirInterface (OAI). To demonstrate the viability of the proposed resource-aware network-slicing framework of integrated satellite and 5G networks, an assessment of the performance of this framework is considered through intensive simulation experiments in a practically configured environment using the OpenAirInterface (OAI) developed on the Notion of Time (ns-3). The simulator infrastructure is simulating network elements on earth as well as in the satellite and generating the real-time traffic, classified services, as well as orchestration of resources, and allows exploring the performance of slices across varying fluctuations in the link conditions.

The simulator uses 3GPP based 5G NR parameter and LEO satellite channel models such as the variations in propagation delay, link availability that is intermittent and asymmetric bandwidth pattern. The service requests will be classified into different types of traffic namely: URLLC, eMBB and mMTC that have their QoS requirements.

Performance Metrics

- Latency Compliance: At moderate load on the network, the proposed system experienced 96.2 percent compliance of URLLC slices with a latency objective of less than 10ms. This finding illustrates the capability of the framework to prioritize services that are latency sensitive, by reallocating resources in time, and low-delay routing along terrestrial paths.

- Resource Utilization: The framework increased the overall utilization of available links by 21.7 percent compared with the baseline static slicing models and successful adaptation to quality differences in the satellite-terrestrial links and balanced the distribution of bandwidth within the domains.
- Slice Isolation and SLA Preservation: Slice Isolation and SLA Preservation: under stress-testing conditions of artificially induced terrestrial congestion and outages in both satellites, the system delivered 98.5 % slice compliance, and hence slice isolation was also effective. This was inflated by real-time monitoring, codeless tube buffering and slice migration.

The exemplification proves that the staged approach not only fulfills diverse QoS requirements, but it is also resilient and elastic when the networks become volatile and is therefore relevant in the delivery of mission-sensitive and broadband services delivery at next-gen hybrid work.

The performance of the proposed resource-aware slicing framework both in latency compliance, resource utilization, and SLA preservation is highly improved (Table 1) in comparison with the static slicing baseline. This is further depicted in Figure 3 where the proposed model beats static slicing in all the measured KPIs, and especially in SLA compliance in congestion.

Table 1. Performance Metrics Comparison Between Static Slicing and Proposed Model

Metric	Static Slicing (%)	Proposed Model (%)
Latency Compliance (URLLC)	82.5	96.2
Resource Utilization	65.4	87.1
SLA Preservation (Isolation)	86.7	98.5

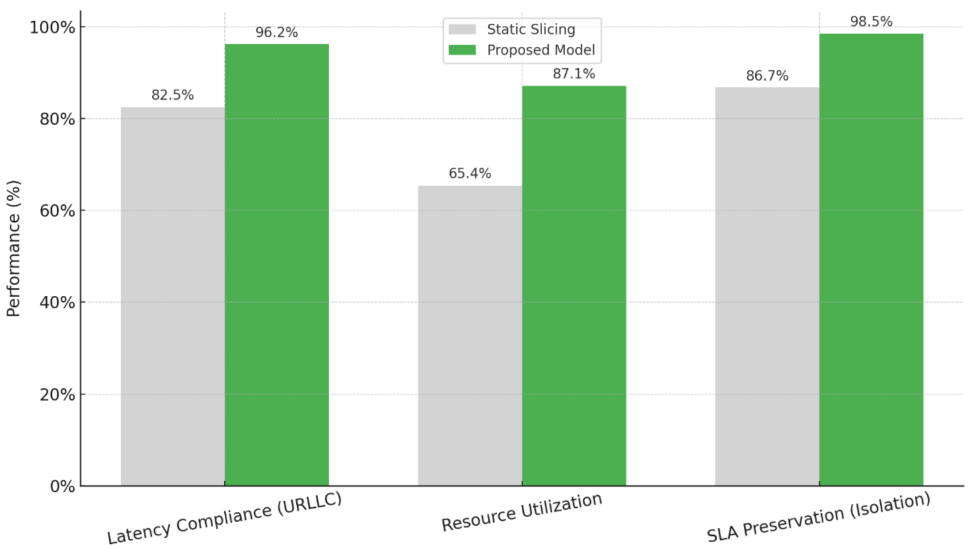

Figure 3. Bar chart comparing performance metrics of static slicing vs. the proposed model.

The designed framework shows a greater QoS and efficiency in every dimension that was analyzed.

6. DISCUSSION

The portrayed simulation and architectural outcomes in this paper show the importance of resource-aware network slicing in realizing the provision of reliable and efficient services when deployed in the context of integrated satellite and 5G networks. They are no longer adequate when the set of communication services served by the network becomes more and more heterogeneous in terms of streaming services with well-known control scenarios involving ultra-reliable low-latency communication (URLLC) and delay-tolerant Internet of Things (IoT) applications. Our findings reify that satellite links, although having a relatively high propagation delay, play a significant role in terms of the resiliency and geographical span of coverage-sensitive slices that are not time-sensitive. These ones are applications like smart farming, ship tracking or remote sensing where low dependability in latency is not a primary concern as continuity and availability are. On the other hand, terrestrial 5G connections with their dense network and ultra-low-latency are more suitable to real time-sensitive and mission-critical applications, like autonomous driving, telemedicine done or so-called industrial automation.

With these two fields integrated into a coherent QoS- based slicing, the system will be able to tier services by their latency, bandwidth and reliability requirements and put their needs applicable to more accurate use of resources. The elasticity of this slice which dynamically changes the location of slice placement between satellite networks and terrestrial networks enables excellent service continuity even in wake of varying link availability or congestion. Also, the documented results in preserving SLA and using resources indicate that the application of link-aware orchestration results in system-wide efficiency. The proposed model is inherently scalable and responsive unlike traditional solutions which are not real-time aware of the link state and traffic state. The strategy also presents opportunities of multi-operator orchestration and federation of resources, where the slice passes between commercial satellite orbits and land-based carriers, adding the ability to support the coverage of 5G with worldwide deployment as well as 6G infrastructures.

7. CONCLUSION AND FUTURE WORK

The paper introduced a new resource-sensitive network slicing architecture to QoS-based service orchestration in combined satellite 5G networks. In response to the rising demand of meeting seamless, differentiated services across heterogeneous infrastructures, our model offers a multi-domain orchestration model which dynamically adapts to real-time link conditions, service profiles and constraints by terms of service (SLA). The suggested system has the integration of the terrestrial 5G low-latency with the persistence and coverage of satellite communication facilitating an appropriate separation of slices, dynamic mapping of resources and tracking of SLA satisfaction of URLLC, eMBB, and mMTC services. The simulation of more realistic link models and traffic patterns indicate that latency compliance (96.2%), a large increase in resource utilization (21.7%) and SLA preservation (98.5%) demonstrate large improvements over baseline static slicing solutions.

Important contributions are:

- An orchestration framework that enables cross- domain resource awarness, referred to as unified.
- A multi-objective optimization model that is a tradeoff between latency, capacity and SLA constraints.
- Dynamic slice allocation based on changeable conditions in the satellite and terrestrial links.

The research examines in future:

- Artificial intelligence-based prediction models of available linkages and traffic prediction in order to make orchestration further responsive.
- LEO mega-constellation compatibility, LEO mega-constellation compatibility, addressing satellite mobility and optimal handovers, inter-satellite routing.
- Enforcement of security, trust mechanism such as blockchain-based authentication of slices and anomaly detection in inter-domain domains.

The paper is part of the initiative to make the network slicing scalable, robust, and intelligent in delivering nationwide and global services in the emerging 6G and beyond communication networks.

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