# Fixed, mobile, and satellite convergence through integrated network control systems

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Beyond fifth generation (5G) and sixth generation (6G) mobile networks aim to integrate Non-Terrestrial Networks (NTNs), such as satellites, with Terrestrial Networks (TNs) to offer high quality global communication services worldwide. Standards development organizations, such as the International Telecommunication Union (ITU), are advancing the standard specifications required for the TN-NTN integration, also known as Fixed, Mobile, and Satellite Convergence (FMSC). ITU has issued several ITU-T Recommendations for FMSC, including ITU-T Y.3207 (2024), which specifies an Integrated Network Control Architecture (INCA) for FMSC. This article presents a study on the design and development of an experimental system to validate the INCA's feasibility and capabilities. It covers the design and development of network controllers for both TN and NTN segments, and the functions and interfaces required for interconnecting them. The study demonstrates INCA's capability to configure network services with a required Quality of Service (QoS) across both TN and NTN segments. Furthermore, it validates INCA's capability to dynamically monitor and control computing and bandwidth resources in both TN and NTN segments to ensure end-to-end QoS despite fluctuation in network traffic demands.

Keywords – Integrated network control architecture, non-terrestrial network, terrestrial and non-terrestrial network integration, fixed, mobile and satellite convergence

## 1. INTRODUCTION

Beyond fifth generation (5G) and sixth generation (6G) mobile networks aim to integrate Non-Terrestrial Networks (NTNs), such as satellites, with Terrestrial Networks (TNs), including cellular and fixed Internet networks [1]. This integration is expected to provide high quality communication services worldwide and promote digital inclusion in underserved and unserved regions and communities.

Current 5G networks support enhanced Mobile Broadband (eMBB), massive Machine-Type Communication (mMTC), and Ultra-Reliable Low-Latency Communication (URLLC) by seamlessly connecting handheld and IoT devices over a shared, virtualized infrastructure [2]. However, these services are mainly accessible only from urban areas, leaving remote regions underserved due to economic and geographical constraints. The excessive cost and low revenue generation potentially discourage operators from deploying terrestrial network base stations in rural areas, while deserts, seas, and mountains present additional infrastructure challenges.

For seamless global connectivity in 6G systems, integrating NTN, including satellites and High Altitude Platform Stations (HAPS), with the Internet and terrestrial mobile networks is essential [3]. This convergence ensures reliable communication, particularly during natural disasters like earthquakes, tsunamis, and wildfires, which can disrupt terrestrial infrastructure [4,5].

The study of fixed, mobile, and satellite convergence (FMSC) has been advancing rapidly, with standards development organizations such as the International Telecommunication Union (ITU) and the 3rd Generation Partnership Project (3GPP) working on essential frameworks and mechanisms. ITU defines FMSC as the capability to deliver services and applications to users regardless of their location or network type [6]. Note that ITU uses the term of *IMT-2020 networks and beyond* to collectively refer to 5G and beyond 5G (i.e., 6G) networks.

This paper reviews ITU-T Recommendations on FMSC, with a particular focus on Recommendation ITU-T Y.3207 [7] that specifies the key aspects of the Integrated Network Control Architecture (INCA). To evaluate the feasibility and capabilities of INCA, we have designed and developed an experimental system implementing its key functional elements and interfaces, including controllers for fixed, mobile, and satellite network segments. Specifically, the experimental system meets the core functional requirements for monitoring and controlling both TN and NTN segments, as well as autoscaling their computing and communication resources to ensure high quality network services.

This article presents an operational validation of the INCA implementation through experimental results, providing practical insights into a more detailed design of functional elements and interfaces. The experiment system is composed of a Data Network (DN), a 5G Core (5GC), a 5G Radio Access Network (RAN), and NTN segments. Although this NTN integration research targets 6G networks, 5G network architectural functional components are used for experimentation because 6G architecture components have not yet been specified. The DN is built on OpenStack and the Open Source MANO (OSM) platform, while the 5GC and RAN leverage the open source Free5GC and UERANSIM software, respectively. NTN includes a satellite network simulator for executing control plane functions and a bandwidth and latency emulator for forwarding application data packets in the data plane, both developed in our lab.

A preliminary version of this study was presented at the ITU Kaleidoscope Academic Conference 2024 [14]. Relative to our prior publication, this paper incorporates additional analyses of recently approved ITU-T Recommendations, elaborates on the architectural design of individual segment network controllers, and introduces novel scenarios that demonstrate real-time NTN path adjustments. These adjustments are enabled through traffic trend analysis and predictive modeling of resource demands using machine learning techniques.

This paper is organized as follows. Section 2 reviews standardization, research, and development efforts. Section 3 outlines INCA functions and control messages, while Section 4 describes the experimental system. Section 5 presents validation results and Section 6 concludes this paper with future directions.

## 2. RELATED WORK

Non-terrestrial networks, encompassing satellites, HAPS, and drones, enable extensive connectivity with their global reach and multilink transmission capabilities. High Throughput Satellites (HTS) are being deployed to enhance small cell coverage, extending urban 5G capacity to underserved rural and remote regions. The growing deployment of Low Earth Orbit (LEO) satellites supports high bandwidth, low latency communications essential for applications in eMBB, mMTC, and URLLC.

Rapid advancements in research, development, and standardization are driving the integration of TN and NTN. To provide a broader perspective, we also summarize key ITU and 3GPP standards relevant to this convergence.

Table 1 summarizes the ITU-T Recommendations on FMSC recently developed by ITU-T Study Group 13. Recommendation ITU-T Y.3200, approved in 2022, defines FMSC requirements, classifying them into the categories of service and network capability. It also presents use case scenarios with IMT-2020 (i.e., 5G networks) and beyond. Recommendation ITU-T Y.3201 establishes a comprehensive framework for integrating terrestrial and satellite networks, identifying key enabling technologies such as mobility and session management, service continuity, network slicing, Multi-access Edge Computing (MEC), Artificial Intelligence (AI) and Machine Learning (ML), Distributed Ledger Technology (DLT), and quantum information technology.

**Table 1** – FMSC-related ITU-T Recommendations

| Rec. No. | Title | Year of approval |
|---|---|---|
| ITU-T Y.3200 | Fixed, mobile and satellite convergence – Requirements for IMT-2020 networks and beyond | 2022 |
| ITU-T Y.3201 | Fixed, mobile and satellite convergence – Framework for IMT-2020 networks and beyond | 2023 |
| ITU-T Y.3202 | Fixed, mobile and satellite convergence – Mobility management for IMT-2020 networks and beyond | 2023 |
| ITU-T Y.3203 | Fixed, mobile and satellite convergence – Connection management for IMT-2020 networks and beyond | 2023 |
| ITU-T Y.3204 | Fixed, mobile and satellite convergence – Service continuity for IMT-2020 networks and beyond | 2023 |
| ITU-T Y.3205 | Fixed, mobile and satellite convergence – Requirements of integrated user-centric service units | 2023 |
| ITU-T Y.3206 | Fixed, mobile and satellite convergence – Capability exposure for IMT-2020 networks and beyond | 2023 |
| ITU-T Y.3207 | Fixed, mobile and satellite convergence – Integrated network control architecture framework for IMT-2020 networks and beyond | 2024 |
| ITU-T Y.3208 | Fixed, mobile and satellite convergence – Session management with satellite backhaul for IMT-2020 networks and beyond | 2024 |
| ITU-T Y.3209 | Fixed, mobile and satellite convergence – Traffic scheduling for IMT-2020 networks and beyond | 2024 |
| ITU-T Y.3210 | Fixed, mobile and satellite convergence – Distributed ledger technology for IMT-2020 networks and beyond | 2024 |

Recommendation ITU-T Y.3202 describes the framework and requirements for FMSC mobility management, including architecture and service procedures. Recommendation ITU-T Y.3203 focuses on connection management, specifying requirements, scenarios, and functional architecture. Similarly, Recommendation ITU-T Y.3204 addresses service continuity, outlining mechanisms to maintain seamless operation for mobile users.

 

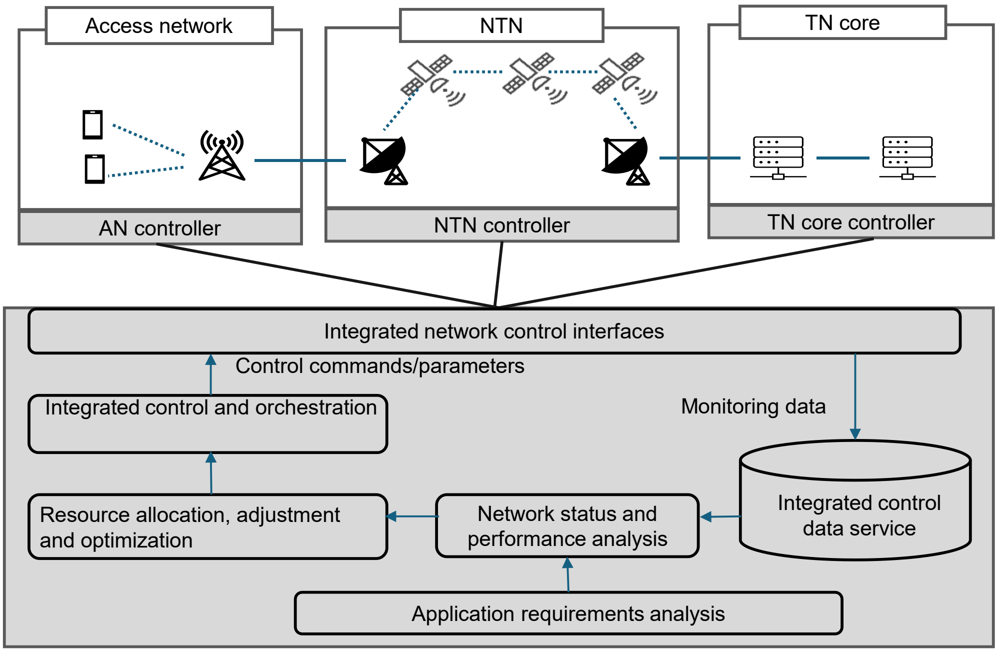


**Figure 1** – TN-NTN integrated network control architecture (ITU-T Y.3207)

Recommendation ITU-T Y.3205 introduces the Integrated User-centric Service Unit (IUSU), allowing users to define network and service capability profiles. Recommendation ITU-T Y.3206 defines capability exposure mechanisms, enabling network functions to share capabilities with external entities, such as users or other operators.

Recommendation ITU-T Y.3207 describes the integrated network control system, detailing procedures for TN and NTN service orchestration, performance monitoring, and resource control. Further insights into its functional components and control message flow are provided in the next section.

Recommendation ITU-T Y.3208 specifies session management procedures and security aspects for FMSC when satellite networks are used as backhaul networks.

Recommendation ITU-T Y.3209 covers traffic scheduling frameworks, while Recommendation ITU-T Y.3210 focuses on DLT applications in FMSC, including requirements and information flows.

3GPP has explored TN-NTN integration issues since Release 15, addressing the deployment scenarios, service requirements, propagation models, and satellite and HAPS system parameters. Release 16 introduced architectural considerations for satellite access integration in TR 23.737 [8] and management and orchestration aspects in TR 28.808 [9]. TR 23.737 examined radio access and core network challenges, proposing procedural solutions, while TR 28.808 outlined service and network management issues, presenting a reference architecture.

From Release 17 onward, 3GPP has been developing normative specifications for NTN integration into 5G, including New Radio (NR) and Narrowband Internet of Things (NB-IoT) support. Future releases aim to enhance direct smartphone-to-satellite connectivity, improve Public Land Mobile Network (PLMN) selection through User Equipment (UE) location verification (TR 24.821 [11] enhancement), and support non-continuous coverage with sparse constellations and satellite backhauling. Additional details on 3GPP NTN developments can be found in [12].

The key differences between ITU-T and 3GPP standardization in the context of TN-NTN integration are as follows: ITU-T has focused on defining generic requirements, clarifying use cases and scenarios, and specifying functional architectures and procedures. In contrast, 3GPP has focused primarily on radio aspects, such as specifying link technologies for NR and NB-IoT devices.

## 3. TN-NTN INTEGRATED NETWORK CONTROL ARCHITECTURE (INCA)

This section presents an overview of the INCA functional components and control messages.

### 3.1 Integrated network control architecture

Fig. 1 shows the functional architecture of the integrated network control system, which consists of five key functional components: (a) integrated control data service, (b) application requirements analysis, (c) network status and performance analysis, (d) resource allocation, adjustment and optimization, and (e) integrated control and orchestration. The system communicates with network controllers of individual network segments, including access networks, NTN, terrestrial mobile core networks, and fixed data networks, via integrated network control interfaces. These interfaces enable the collection of monitoring data from individual network controllers and dispatching control parameters in the reverse direction.

 

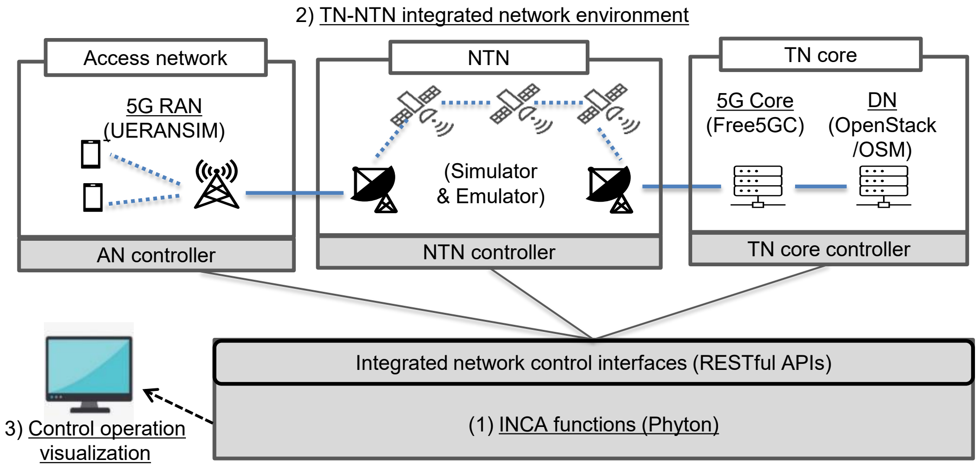


**Figure 2** – Experimental system layout

## 3.2 Architectural functional components

The key functional components of the architecture are described below.

**(a) Integrated control data service function:** This function gathers and manages monitoring data from individual network segments, storing it in a centralized database. The data is continuously updated to maintain consistency and can be provided at varying levels of granularity to the network status and performance analysis function.

**(b) Application requirements analysis function:** This function interprets user and service provider requirements, often expressed as high-level policies or intents. These intents are translated into system configuration or QoS parameters, serving as input for network service status evaluation.

**(c) Network status and performance analysis function:** This function assesses network resource usage, performance metrics, and service quality. It determines whether resources are underutilized, overloaded, or optimally allocated while predicting future demands based on usage trends.

**(d) Resource allocation, adjustment, and optimization function:** Based on network performance analysis, this function formulates optimal resource allocation strategies.

Different network segments vary in the degree of scarcity of different types of resources. For example, terrestrial DNs deployed in virtualized cloud platforms have abundant computational resources (e.g., CPUs, GPUs, memory, and storage), as well as ample communication bandwidth. In contrast, NTN satellites operate with more constrained resources. To optimize performance, these limited resources must be allocated and controlled with finer granularity. Therefore, the proposed system focuses on near real-time control of the TN-NTN integrated network segments, ensuring efficient resource allocation based on dynamic demand fluctuations.

**(e) Integrated control and orchestration function:** This function generates network control decisions by compiling configuration parameters for each segment involved in an E2E service. These parameters are then transmitted to individual network system controllers via integrated control interfaces.

## 3.3 Individual network segment control systems

The integrated network control system operates with the assumption that each network segment's control system operates with functional components similar to those of the integrated network control architecture but within a localized scope. The individual network segment's control system has internal and external interfaces. Internal interfaces collect monitoring data from network elements at different time scales and levels of granularity. External interfaces connect to the integrated network control system for sending monitoring data and receiving control decisions containing control parameter values.

## 3.4 Control signaling message flow

Recommendation ITU-T Y.3207 [7] defines the signaling message sequences required to perform INCA's two main operations: (a) creating network services across TN and NTN segments and (b) monitoring performance and resource utilization and dynamically adjusting resources.

For network service creation, signaling messages are used to support the exchange of service requirements, available resource lists, network design templates, resource reservations, and network service configurations. Similarly, data subscription and collection methods and messages are used to monitor performance and resource utilization status, while resource control request and response messages are used for dynamic resource control.

# 4. EXPERIMENTAL SYSTEM DEVELOPMENT

Fig. 2 presents the architecture of the experimental system, which comprises three main components: (1) INCA functions and integrated network control interfaces, (2) TN-NTN integrated network environment, and (3) control operation visualization tools.

## 4.1 INCA functions and interfaces

The INCA functions and the associated integrated network control interfaces have been implemented in Python. To facilitate interoperability, RESTful APIs have been developed, enabling these interfaces to exchange messages with the network segment controllers. Messages employ the JSON format to represent network monitoring data and control parameters in a standardized and machine-readable manner.

INCA uses machine learning techniques to analyze monitoring data and predict resource demands. The results are used to dynamically adjust allocated bandwidth through the TN and NTN controllers. The system supports various machine learning models, including Support Vector Machine (SVM), linear regression, and Multi-Layer Perceptron (MLP). These models take input data consisting of the expected number of users per service type, traffic rates, allocated and utilized resources (e.g., number of virtual machines, CPU cores, memory, and bandwidth), and end-to-end performance metrics (e.g., throughput and latency). The models predict future traffic rates and corresponding resource requirements, enabling fine-grained adjustments of resource allocations.

## 4.2 TN-NTN integrated network environment

The TN-NTN integrated network environment includes 5G RAN functions, 5GC functions, an NTN simulator/emulator, and a DN. The open-source UERANSIM (https://github.com/aligungr/UERANSIM) and Free5GC (https://free5gc.org) software are used to configure the 5G RAN and core, respectively. UERANSIM was chosen for its flexibility in creating multiple RAN segments and virtual UEs, which can be deployed as software processes within a simulation environment or installed on separate physical devices (e.g., PCs). It also enables the attachment of traffic generators to virtual UEs, allowing us to perform experiments with real data traffic.

Similarly, Free5GC was selected because it facilitates easy deployment and configuration of 5G core network functions in containers and virtual machines, enabling the efficient monitoring and dynamic adjustment of computing and bandwidth resources. The 5GC network functions encompass several functions such as the Access and mobility Management Function (AMF), Session Management Function (SMF), Policy Control Function (PCF), Network Exposure Function (NEF), and Network Repository Function (NRF) in the control plane and the User Plane Function (UPF) in the data plane. Further details on 5GC functions are available in [13].

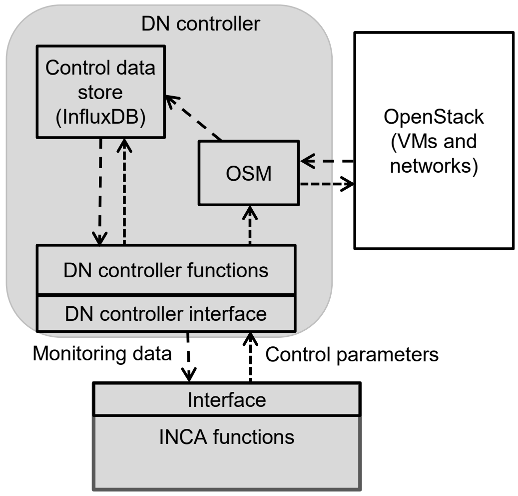


**Figure 3** – Data network controller

The NTN segment comprises a satellite network simulator for control plane operations and an NTN path emulator with configurable parameters for bandwidth, latency, jitter, and packet loss in the data plane. In the network topology shown in Fig. 2, UPFs is also collocated with the 5G RAN, allowing the NTN segment to be inserted between the UPFs deployed in the 5GC (i.e., the TN core segment) and the UPFs collocated with the RAN. This configuration thereby enables the extension of high quality terrestrial RAN coverage to remote regions through the backhauling support of the NTN segment.

The DN is deployed on the OpenStack platform and managed via OSM software (https://osm.etsi.org). These platforms provide user-friendly interfaces for configuring virtual networks, monitoring, and controlling resources allocated to network functions and application servers. A video application server configured with MPEG-DASH hosted in virtual machines in the DN to stream video files of varying quality. UEs, represented by laptops running UERANSIM, fetch and play videos from the DN through 5GC, NTN, and 5G RAN.

In designing the experimental setup, scalability has been treated as a primary consideration. Large-scale networks are emulated through the generation of numerous virtual UEs in UERANSIM. The required number of control and data plane

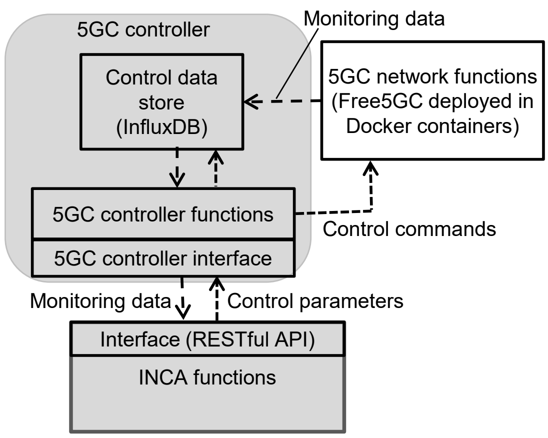


**Figure 4** – 5G core network controller

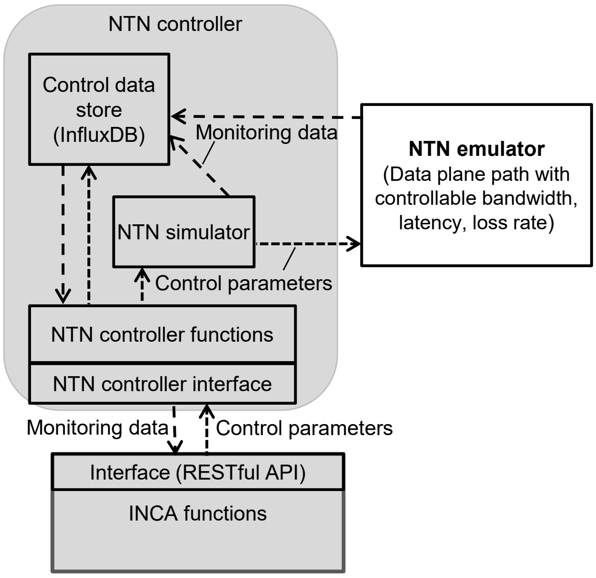


**Figure 5** – NTN controller

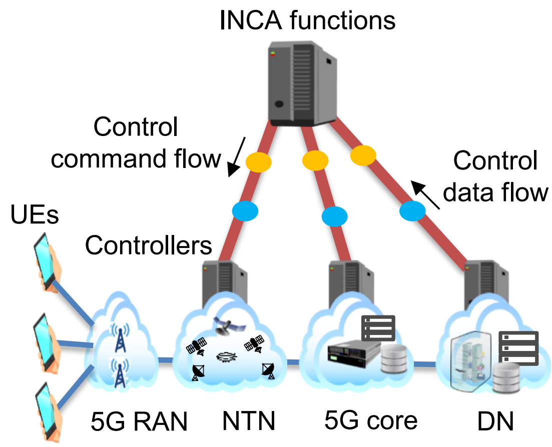


**Figure 6** – Illustration of end-to-end network topology and control message flows

functions in the 5GC and DN can be dynamically deployed in containers or virtual machines on resource virtualization platforms, thereby enabling dynamic scaling of resources for large-scale deployments.

Each segment has a dedicated controller for collecting resource utilization and performance metrics and for executing resource control commands. In the current implementation, the RAN controller is a simple module that provides functional interfaces to create UEs and configure their parameters to attach them to the gNodeB. It is not yet capable of monitoring or controlling the performance and resources of the RAN segment. Therefore, excluding the RAN controller, the DN, 5GC, and NTN controllers, each capable of monitoring and controlling resources in their respective segments, are described below.

**a) DN controller**

The DN controller, shown in Fig. 3, is deployed in a Docker container. Using OSM, it manages virtual resources (CPU, memory, bandwidth) of the DN configured in OpenStack. It stores performance monitoring data, including throughput and latency, in the control data stored implement in Influx DB software. It periodically sends monitoring data to the INCA functions. It receives resource control commands from INCA functions, converts them into OSM instructions, and executes them in the OpenStack platform.

**b) 5GC controller**

As shown in Fig. 4, the 5G core network has a 5GC controller to collect monitoring data from 5GC network functions and execute resource control commands on them via platform-specific tools such as Docker Compose. The 5G controller stores monitoring data in Influx DB. Monitoring data formatted in JSON is periodically transmitted to INCA functions via the integrated network control interfaces implemented in RESTful APIs. In response, resource control commands are received as HTTP requests, which are executed using Docker Compose tools.

**c) NTN controller**

Fig. 5 illustrates the NTN controller components and their interactions. HTTP requests from INCA functions specify resource parameters, including service type, UE count and location, traffic rates, feeder link gateways, and latency and jitter requirements.

Fig. 5 illustrates the NTN controller components and their interactions. HTTP requests from INCA functions specify resource parameters, including service type, user equipment (UE) count and location, traffic rates, feeder link gateways, and latency and jitter requirements. These inputs are translated into control parameters for the NTN simulator, which configures paths through predefined GEO satellites and LEO constellations. Simulation outputs are stored in Influx DB, and data plane path configuration parameters are transferred to the NTN emulator to establish emulation paths via virtual satellite nodes. Simple emulation paths can be configured using Linux *tc* commands.

## 4.3 Control operation visualization tools

Four types of visualization tools are developed for the demonstration of a) E2E network topology and message flows, b) 5GC, NTN, and DN resource monitoring graphs, c) NTN paths, and d) application QoS parameters.

**a) End-to-end network topology and message flows**

Fig. 6 illustrates the E2E topology and control message flows on a browser-based visualization monitor. The linear topology comprises UEs, 5G RAN, NTN, 5G core, and DN. Colored dots indicate the flow of monitoring data from controllers to INCA functions, while differently colored dots in the opposite direction represent control commands and parameters.

**b) 5GC, NTN, and DN resource monitoring graphs**

Real-time monitoring graphs showing resource utilization for 5GC, NTN, and DN are displayed using Grafana, an open-source analytics and monitoring platform software. The 5GC graphs visualize the CPU, memory, and bandwidth allocation and utilization of 5GC control and data place functions. NTN graphs visualize the NTN path bandwidth utilization and latency, as well as the number of satellite hops. DN graphs depict the CPU, memory, and bandwidth utilization of the application server deployed in the data network.

**c) NTN paths**

NTN paths are rendered in Ansys System Tool Kit (STK) using simulator output data. The tool depicts ground station locations, intra-orbital and inter-orbital satellite links, and five possible communication directions in each satellite: two intra-orbital, two inter-orbital, and one ground station link. The NTN controller configures forward and reverse paths separately, which may pass through the same or different sets of satellites.

**d) Application QoS graphs**

The application QoS graphs displayed alongside the video played on UEs depict the throughput, latency, and jitter of the end-to-end path from the UE to the video streaming server located in the DN.

## 5. VALIDATION OF SYSTEM CAPABILITIES

The experimental system verifies two key operational capabilities of INCA as described in Recommendation ITU-T Y.3207: (a) the establishment of network services across TN and NTN segments based on specified QoS requirements, and (b) the dynamic monitoring and control of resources to maintain QoS under varying network conditions, including fluctuations of user numbers and traffic demands. To demonstrate these capabilities, the following system components are configured with the parameters shown in Table 2.

**Table 2 –** Parameter settings

| Network segments | Parameters |
|---|---|
| DN (App server) | CPU: 1 Core, MEM: 8 GB, BW: 1 Gbps |
| 5GC (UPF) | CPU: 1 Core, MEM: 1 GB, BW: 1 Gbps |
| NTN | LEO constellation parameters<br>Altitude: 1000 km<br>ISL (BW: 1 Gbps, Latency: 10 ms)<br>BW and latency requirements<br>HD service – BW: 5 Mbps, Latency: 30 ms<br>SD service – BW: 2 Mbps, Latency: 45 ms<br>LD service – BW: 1 Mbps, Latency: 60 ms |

**Data network:** The application server in the DN is set up with 1 CPU core, 8 GB of memory, and 1 Gbps of Bandwidth (BW) to stream video services of three different qualities using MPEG-DASH: High Definition (HD), Standard Definition (SD), and Low Definition (LD), with data rates of 3 Mbps, 1 Mbps, and 500 kbps, respectively. The DN controller monitors and manages DN resources of CPU, memory, and bandwidth allocated to the virtual machine hosting the application server.

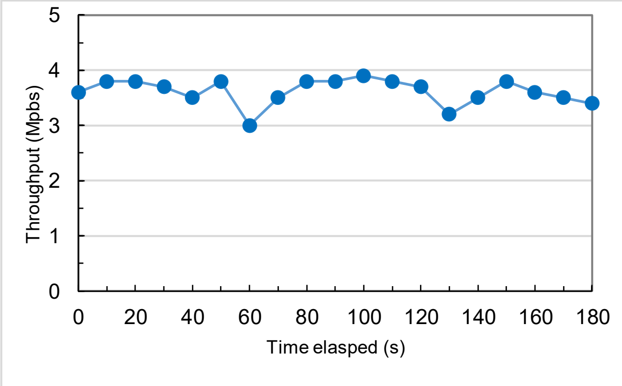


**Figure 7** – HD video application data throughput

**5G core:** UPFs and control plane network functions deployed in containers are initialized in standalone 5GC deployment mode. The 5GC controller, also deployed in a container, is activated to monitor and control resource allocation, focusing on UPFs, which are initially assigned with 1 CPU core, 1 GB of memory, and 1 Gbps of bandwidth.

**5G RAN:** The gNodeB module is configured in UERANSIM through the AN controller and a UPF collocated in the 5G RAN side is also initialized. The resources allocated to this UPF are the same as the UPFs in the 5G core.

**UEs:** Three UEs are connected to the gNodeB module, with the relevant subscription details stored in the Unified Data Management (UDM) function of the 5GC. Their browsers are configured to receive streaming videos, while the QoS probe tool is initialized to monitor throughput, latency, and jitter. Grafana is initialized for real-time visualization of the monitoring graphs.

**NTN simulator and emulator:** Simulation scripts are prepared to establish NTN communication paths through a LEO satellite constellation deployed at an altitude of 1000 km. The satellite orbits are configured such that the Inter-Satellite Link (ISL) latency is 10 ms. The parameters in the simulation scripts are dynamically set using resource requirement parameters received in control commands sent from the INCA's control and orchestration functions. To configure NTN paths capable of transmitting HD, SD, and LD video application data, the bandwidth and latency requirements of three NTN paths are set as shown in Table 2.

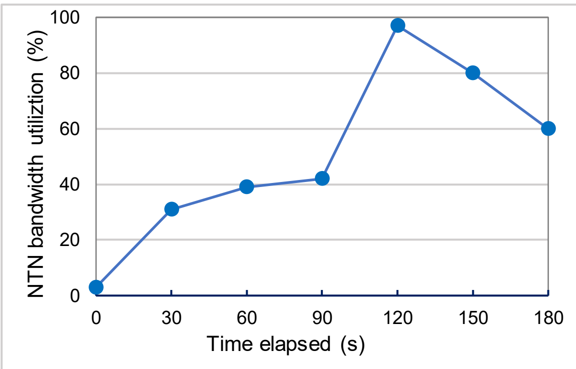


**Figure 8** – NTN bandwidth utilization

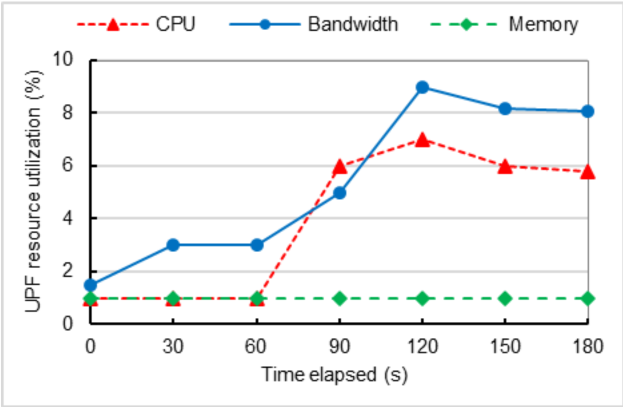


**Figure 9** – UPF resource utilization

The bandwidth requirements are set slightly higher than the video stream data rates to accommodate their instantaneous fluctuations. NTN emulator paths are configured with the output parameters obtained from the NTN simulator, and the paths are visualized by the STK tool.

**INCA functions and interfaces:** INCA modules are executed to initialize the integrated control interfaces to communicate with TN and NTN controllers via RESTful APIs.

**Control operation visualization monitor:** Grafana tools are initialized to display real-time monitoring graphs drawn with control data fetched from INCA's integrated control data service function. To balance monitoring overhead with the need for fine-grained resource control, performance measurements were collected every 10 seconds from UEs to assess application QoS (e.g., throughput and latency) and every 30 seconds from the TN and NTN controllers to monitor resource utilization.

### 5.1 Validation 1: Network service creation

This validation confirmed that INCA successfully instantiated three network services tailored to HD, SD, and LD video qualities. Upon initiation of service requests, the INCA functions orchestrated interactions between the 5GC, NTN, and DN controllers. Once associated with their respective network services, the UEs began receiving video streaming. QoS metrics, including throughput, round-trip time, and jitter, were displayed alongside the video playback screens. For example, the HD video application throughput is shown in Fig. 7.

The control operation visualization graphs depicted the bandwidth utilization of NTN, as shown in Fig. 8 and 5GC UPF's resource utilization of CPU, memory, and bandwidth, as shown in Fig. 9. The NTN topology animation also confirmed the establishment of three NTN paths.

### 5.2 Validation 2: Network monitoring and control

This validation demonstrated the INCA's capability to continuously monitor and dynamically adjust resources in NTN, 5GC, and DN to maintain the required level of QoS. A single network service was created with a 25 Mbps bandwidth allocation in the NTN segment (no limitation of bandwidth in other segments), highlighting the mechanism of NTN bandwidth adjustments due to an NTN's limited capacity compared to TN. Three UEs were connected to the same network service and made them download streamed HD video and display their respective QoS metrics in real time.

To assess INCA's adaptive capabilities, network congestion was introduced using *iperf,* injecting background traffic into the UPF located in the 5G core, routing it through the NTN, and terminating at the UPF located in the 5G RAN. Since INCA does not manage RAN resources, congestion was applied only to 5GC and NTN segments. After having created congestion in the NTN path, monitoring graphs showed a surge in NTN bandwidth utilization approaching 100% at around 120 s (Fig. 8), along with a slight increase in 5GC UPF bandwidth and CPU utilization (Fig. 9). The bandwidth limitation in NTN caused MPEG-DASH to reduce video quality from HD to LD.

Using machine learning models such as SVM, INCA analyzed monitoring data to predict resource demands and sent a resource adjustment request to the NTN controller to dynamically allocate additional NTN bandwidth. The NTN simulator recomputed NTN paths, and the emulator adjusted the capacity accordingly. Once additional NTN bandwidth became available, video quality automatically reverted to HD. After stopping background traffic, INCA detected a drop in utilization below 40% and subsequently reduced the allocated bandwidth to optimize resource efficiency, stabilizing NTN usage at around 60% without impacting service quality.

These results demonstrate INCA's ability to maintain network services with specified QoS levels, even under dynamic network conditions. Additionally, they exhibit INCA's ability to enhance resource utilization by dynamically scaling resources up or down based on real-time demands, ensuring optimal performance and efficiency.

## 6. CONCLUSION AND FUTURE WORK

This article described the implementation of INCA's functional components and interfaces, as specified in the Recommendation ITU-T Y.3207, alongside the development of individual controllers for DN, 5GC, and NTN segments. The experimental results demonstrated INCA's capability to establish network services spanning TN and NTN segments, while ensuring the required QoS levels. Furthermore, INCA dynamically monitored and adjusted computing and bandwidth resources to ensure end-to-end QoS despite traffic fluctuations. Through the implementation and evaluation of the experimental system reported in this article, we have validated the core functional requirements of monitoring and controlling various TN and NTN segments and autoscaling of their computing and communication resources to ensure high quality network services.

Additional work is needed to implement other functional requirements such as roaming, mobility management and authentication mechanisms, which are essential for supporting seamless mobility of subscribers across fixed, mobile, and satellite networks. Additionally, Recommendation ITU-T Y.3207 does not contain the detailed specifications of functional elements, interfaces and parameters exchanged between the control and data planes, which require further standardization efforts for practical deployment. In future work, we will contribute these refined functional elements and interface designs to ongoing standardization efforts to further enhance interoperability and efficiency. Additionally, we will improve the INCA experimental system by developing advanced user interfaces and automation tools to streamline the system operation and management, making it more accessible for real-world deployments. A detailed performance comparison of different AI/machine learning models, based on standard architecture frameworks such as those described in [15], has also been left for future work.

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