# Digital Twin Approach for 3D Visualization and Optimization of 5G Non-Terrestrial Network

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## ABSTRACT

Non-terrestrial network (NTN) is an important technique to provide extreme coverage towards 5G and beyond. High altitude-platform-station (HAPS) and satellites, as key enablers in NTN, is attracting a lot of attention in both research and industry. To achieve better resource utilization and performance, a unified 5G digital twin (DT) design for NTN is necessary for orchestration, testing and assurance providing an emulated, software replica of the 5G physical network that allows for continuous prototyping, testing, assuring and self-optimization of the actual network. Currently, there are many simulation solutions for NTN but the DT solutions are designed as a control loop to collect relevant data of the actual system and then happen again in the simulator before sharing back with the original source objects. In this paper, we proposed a complete solution for NTN which is studied to tackle the backhaul network in a disaster situation. interference coordination method based on the distribution of traffic load as well as the deployment of HAPS and terrestrial networks. By testing a use case scenario for the flood in Munich 2021, we showcase the 3D visualization and dynamic management of the NTN 5G DT framework and demonstrate the validity and efficacy of the Software-in-the-Loop (SIL) and Hardware-in-the-Loop (HIL) simulations for the NTN orchestrator network.

Keywords—Digital Twin, NTN, HAPS, 5G, Virtualization

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**Kaniz Mahdi** is the Group Chief Architect and SVP of Technology Architecture and Innovation (TAI) at Deutsche Telekom. In this role, she shapes the company's global technology architecture, anticipating industry trends and translating business challenges into clear technology strategies. Kaniz represents Deutsche Telekom at the FCC's Technological Advisory Council and multinational industry boards, fostering technology collaboration worldwide. Previously, she was the VP of Distributed Edge at VMware, where she established a new technology focus area. Kaniz co-founded the Open Grid Alliance, driving advancements in distributed intelligence for emerging technologies. With extensive experience at Ericsson, Huawei, Ciena, and Nortel, Kaniz holds over 45 patents and has been influential in the development of Voice over LTE and disruptive 5G technologies like SDN/NFV and O-RAN.

**Jaroslav Holiš** is currently working as a Senior Manager in Group Technology at Deutsche Telekom. He completed his Ph.D. in Radio Network Engineering. He joined Deutsche Telekom shortly after graduating and worked on LTE, LTE-A and pre-5G network development. His specialization is in Radio Access Network, especially in antenna techniques, interference coordination, proof of concepts and field trials. He is currently working on 5G networks evolution towards 6G "3D" networks and also driving DT internal HAPS research program with a focus on flight trials, capacity modelling and coexistence studies. He also currently serves as the HAPS Alliance Telecommunications Working Group Chair.

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## INTRODUCTION

Digital twin network (DTN) is an emerging network that leverages digital twin (DT) technology defined by Grieves et al. (Grieves, 2014) to create virtual replicas of physical objects. These digital twins enable a co-evolution between the physical and virtual spaces through advanced DT modeling, communication, computing, and data processing technologies. Although there is little work in digital twin networks, the concept, model and solution are not well explored in the environment of 5G with Non-Terrestrial Networks (Giordani & Zorzi, 2020). The introduction of 5G technology presents distinctive difficulties in ensuring dependable wireless communication services. In order to tackle these challenges, an encouraging solution has emerged known as High Altitude Platforms (HAPs) (Tozer & Grace, 2001; Karapantazis & Pavlidou, 2005). HAPs are airborne plat- forms strategically positioned at high altitudes within the Earth’s atmosphere, serving as effective intermediaries to enhance connectivity for a wide range of applications. Within the context of the aforementioned network, communi- cation can involve multiple network layers, including transmissions from User Equipment (UE) to ground-based stations, from the ground to airborne base stations (BS) such as Unmanned Aerial Vehicles (UAVs), drones, and HAPs, from one airborne platform to another with similar or different altitudes, and even to satellites.

Incorporating Digital Twins (DT) within NTN introduces several complex considerations. Particularly in the context of NTN, numerous challenging aspects must be taken into account. One significant challenge involves radio frequency propagation within the three-dimensional (3D) environment, as the net- work covers a substantial geographic area. This necessitates a comprehensive understanding of how radio waves propagate in such an environment, consider- ing factors such as obstacles, reflections, and signal attenuation.

Furthermore, the integration of DT in NTN requires accommodating the utilization of different frequencies and technologies across the network. This introduces the need for seamless interoperability and efficient communication between diverse network components operating at varying frequencies. Managing the spectrum allocation and ensuring harmonious coexistence of these different frequencies are crucial aspects of implementing DTN effectively. Additionally, the flows of data and information from User Equipment (UE) to the core network traverse multiple network entities, adding to the complexity of DT implementation in NTN. These flows encompass various network layers, involving interactions with base stations, routers, gateways, and other intermediate elements. Ensuring smooth data transfer, optimizing routing protocols, and addressing potential bottlenecks or congestion points become essential con- siderations in this context. Consequently, successfully applying DT within the NTN necessitates ad- dressing these challenging aspects. Comprehensive studies and innovative solutions are required to overcome the complexities associated with radio frequency propagation, integration of different technologies and frequencies, and managing the intricate data flows throughout the network. By tackling these challenges, our proposed solution aims at the first DT solution for NTN. Summarily, the contributions of our work are listed as follows:

- An architectural design of a NTN Orchestration Frame- work that leverages virtualization and digital twin capa- bilities to improve network management and operation: The development of a robust and efficient NTN Orches- tration Framework is crucial for effectively managing and operating the complex Digital Twin Network (DTN).
- A practical implementation of the proposed frame- work: To realize the benefits of the NTN Orchestra- tion Framework, a practical implementation is required. This involves the deployment of virtualization technolo- gies, such as Network Function Virtualization (NFV), Software-Defined Networking (SDN), and robotics to create a flexible and programmable network infrastructure.

- A practical use case scenario for the framework: One practical use case scenario for the NTN Orchestration Framework is in the domain of smart cities. In this scenario, the framework can enable efficient management of various interconnected systems, such as transportation, energy, and public services.

The rest of our study is organized as follows. In the first section, we discuss selected prior works that relate to our study. In the second section, we present the overall architecture and design of the proposed NTN orchestration framework. In this section we describe the different components, their functionalities, and how they interact with each other to achieve the desired network orchestration goals. The next section discusses the practical implementation aspects of the proposed framework. It describes the software and hardware components used, the integration of virtualization technologies, and the development of digital twin models for the network elements. We then present the simulation and testing result using a practical use case of floods in Munich in 2021. Finally, we conclude our work in the last section.

## RELATED WORK

### Digital twin concept

In the state of the art, the concept of the Digital Twin (DT) was elaborated by the authors in (Grieves, 2014). Grieves expanded the definition by outlin- ing three key components that constitute a Digital Twin including a physical product, a virtual representation of that product, and the bidirectional data connections that facilitate the exchange of data between the physical and virtual representations. This flow of data occurs in a control-loop manner, forming a twinning relationship between the physical and virtual states. The data flows from the physical product to its virtual representation, while information and processes flow from the virtual representation back to the physical product. The virtual representation comprises various sub-spaces that enable specific virtual operations such as modeling, testing, optimization, and more.

Since its introduction in 2003, DT concept has gained significant attention and is now recognized as a key strategic technology trend (Top 10 strategic technology trends, n.d.). This increased interest can be attributed to advancements in various related technologies and initiatives, including the Internet of Things (IoT), big data, multi-physical simulation, Industry 4.0, real-time sensors and sensor networks, data management, data processing, and telecommunication (J. Cheng, Chen, Tao, & Lin, 2018; Y. Cheng et al., 2018; Chhetri, Faezi, & Faruque, 2017; Damiani et al., 2018). Both academia and industry have been actively researching, developing, and attempting to implement Digital Twins or the underlying principles they repre- sent. However, the DT concept is not well explored in the NTN area such as architecture, data flow, and key objects.

### The Digital Twin in telecommunications

As one of a few works in DT with telecommunication, (Seilov et al., 2021) presented the first DT model for telecommunication where a control loop is designed with a simplified life cycle of the telecommunication network. They then model to monitor and optimize the traffic in the network. Furthermore, the industry has also recognized the potential of DT technology in telecom networks. Aveva (cited as (Aveva, n.d.; Jevera, n.d.)) have demonstrated that DT technology enables the tracking and operation of telecom networks, facilitating the simultaneous collection of data from diverse sources. Telecom companies, in addition to managing their networks, often integrate connected devices and additional spectrum bands to enhance their services. In this context, digital twins play a vital role in real-time monitoring and improvement of these complex systems.

To implement the DT, the methodologies used in the current works are varying and depending on each specific task in the architecture. As one of the key elements of DT, monitoring network and collecting network data use various methods, such as Packet Sniffing, crawler, Simple Network Management Protocol (SNMP), Flow-based Monitoring, etc (Seilov et al., 2021). Centralized controller (etc, SDN), or distributed architectures are used to control and col- lect data. Once the network data is saved into a database, various data analysis methods can be applied to filter and extract valuable insights. These methods can include statistical analysis, machine learning algorithms, data mining techniques, or customized analysis algorithms specific to the network's requirements. The goal is to uncover patterns, anomalies, and meaningful information from the collected data. The extracted data can then be visualized in the form of graphs, charts, or reports to facilitate understanding and decision-making (Varnum, 2019; Bao, Guo, Li, & Zhang, 2019). Various methods and techniques can be used to visualize data in a digital twin context such as graphs and charts, 3D Models and simulations (Huang, Ji, & Xu, 2022; Matlink , n.d.). To visualize data in real time, real-time data stream methods are considered (Angelov, 2012; Soumaya, Amine, Soufiane, Abderrahmane, & Mohamed, 2017). Machine learn- ing and AI methods will be invoked to process and learn data such as clustering, anomaly detection, and pattern recognition methods (Lu et al., 2020). Last but not least, the optimization component seems vital.

## NTN DIGITAL TWIN FRAMEWORK DESIGN

The proposed framework allows for the monitoring of NTN communication networks. For each network Node, the framework builds a digital twin model and orchestrates its functions and data based on the processing, analytics and validation of internal and external collected information. It involves a control module that collects network and non network data, creates corresponding digital twins, runs simulation and visualization while optimizing the overall network. The communication between this module and the networking nodes is done through the Application Programming Interface (API) module. The control module may orchestrate both internal and external network functions. Internal functions correspond to orchestration modules located at each network node and manage in turn internal components; application module (that includes the current running applications on the embedded node), resources management module, sensing module, energy management module, and communication module.

The resource management module monitors the resources consumed by each flying base station (that includes RAM, CPU, storage resources) and incorporates algorithms and decision-making tools to optimize the allocation of resources based on operational requirements. It considers factors such as mission objectives (from the application module), weather conditions, and regulatory constraints to determine the most efficient use of resources throughout the flight. The sensing module includes software and algorithms for automating the sensing process on each node. A range of sensors are available to capture data about the flying network node’s environment and specific parameters. These sensors can include cameras, lidar (light detection and ranging), radar, infrared sensors, and other specialized sensors. Each sensor provides specific information, such as visual data, distance measurements, heat signatures, or atmospheric conditions. The energy module continuously monitors the energy consumption and performance of different systems within the flying network node, such as engines, avionics, lighting, environmental control systems, and auxiliary power units (APUs). It collects data on energy usage, fuel flow, power generation, and distribution.

Based on the collected data, the orchestration module employs sophisticated algorithms and control strategies to optimize energy usage. It balances power demands, adjusts energy distribution, and prioritizes energy allocation to minimize waste and maximize efficiency. The module may also consider external factors such as altitude, weather conditions, and mission requirements to optimize energy consumption. As illustrated in Figure 1, the control module consists of four major components: (1) Network Monitoring, (2) Network Configurator, (3) Emulator, and (4) Visualiser.

### Network Monitoring

This module involves collecting data related to network topology, traffic, and environmental factors. Network Topology Data includes information about the network infrastructure, such as user devices, base stations, and link data. Traffic data encompasses both control and service data. Control data relates to signaling and management information, while service data refers to the actual user traffic flowing through the network. Environmental Data includes information such as weather conditions, maps, and platform mobility. Collecting data from these various sources can provide valuable insights for managing and optimizing network performance. Network Topology data helps in understanding the physical layout of the network and the connections between different components. Analyzing traffic data can provide insights into network congestion, quality of service, and resource utilization.
Furthermore, incorporating environmental data into network monitoring allows for assessing how external factors can impact network performance. For example, weather conditions may affect signal propagation, and platform mobility data can help optimize network coverage for moving vehicles.

Then, the collected data will be sent to a data analytic sub-module for processing, verification, validation, and report generation to extract meaningful information from them. Using AI algorithms for data processing can help in identifying patterns, anomalies, and trends that might be difficult to detect using traditional methods. The Data Analytics sub-module processes the collected data then verifies and validates the results to ensure accuracy and reliability. This step involves assessing the performance and effectiveness of the collected data. This helps in identifying network issues, predicting future network behavior, and suggesting optimization strategies. The final step involves generating reports based on the processed data. These reports can provide valuable insights for network operators and administrators, enabling them to make informed decisions regarding network management, optimization, and troubleshooting.

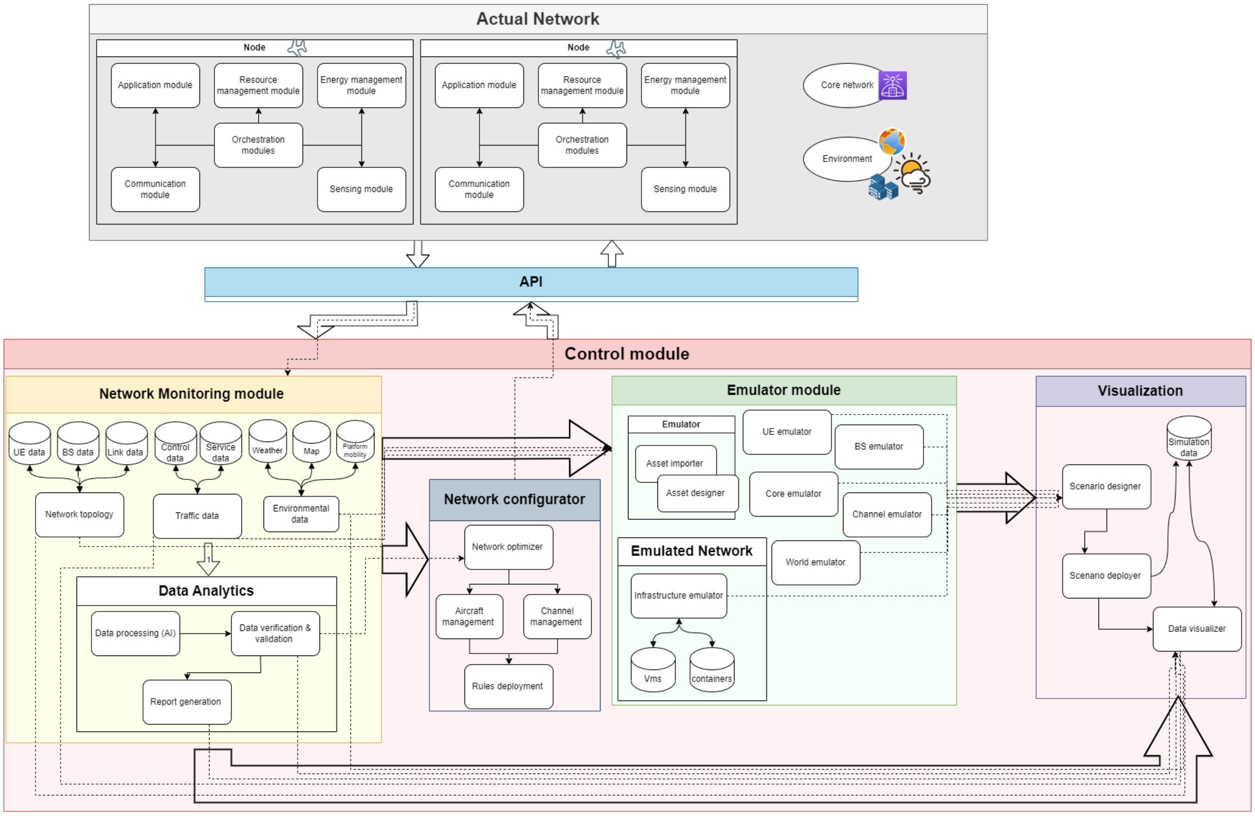


**Figure 1. Block diagram of NTN Digital Twin solution**

**Network Configurator**

The Network Configurator module takes the output from the Data Analytics module, applies network optimization techniques for both aircraft and channel management, and then deploys the updated rules to ensure the network operates based on the optimized configuration. In more detail, after receiving the results from the Data Analytics Module, which includes the insights, recommendations, and optimization suggestions generated by analyzing the collected data, the Network Configurator applies network optimization techniques to improve both aircraft management and channel management. This involves implementing changes to the network configuration, parameters, and settings based on the recommendations derived from the data analytics. Optimizing network resources and connectivity for aircraft operations may involve adjusting routing paths, bandwidth allocation, prioritization of traffic, or other measures to ensure efficient communication and data transfer between aircraft and ground stations.  Channel management refers to the efficient allocation and utilization of communication channels in the network. The Network Configurator module may optimize channel assignments, frequency allocation, interference mitigation techniques, or other strategies to improve overall network performance and minimize signal degradation.

After applying the network optimization techniques, the Network Configurator deploys the updated network configuration rules. These rules define how the network infrastructure, devices, and components should operate based on the optimized settings. The rules ensure that the network operates according to the desired performance objectives, service level agreements, and regulatory requirements. By deploying the updated rules, the Network Configurator effectively implements the recommended changes derived from the data analytics module. This helps to enhance the overall network efficiency, reliability, and quality of service. The rules will be applied on the flying network node through the API module that connects the control module to the rest of the network.

**Emulator**

The Emulator module plays a crucial role in simulating and emulating various network components and their behavior based on the data received from the Network Monitoring module. It creates a simulated environment or context in which the network operates. It can include factors such as geographical layouts, terrain, weather conditions, and user mobility patterns. This enables the emulation of real-world scenarios and their impact on network performance. In addition, the emulator simulates user devices or equipment that interact with the network. It replicates the behavior of UEs in terms of data transmission, signaling, and mobility patterns as well as the behavior of base stations in the network. It replicates the communication protocols, signal propagation characteristics, and resource management of BS. The routing, switching, and processing capabilities of the core network elements are also simulated. Further, the emulator replicates the behavior of the network channels through which data is transmitted. It simulates the characteristics of different types of channels, such as wireless, wired, or satellite, including propagation delays, signal quality, and interference.

The simulated environment is initialized with the necessary assets required for emulation using the asset importer component. This component is responsible for importing predefined network assets, such as network topologies, base station configurations, core network settings, and user profiles. We can also design and configure custom network assets using the asset designer interface within the emulator module. This interface allows flexibility in creating specific network scenarios for emulation (create or modify network topologies, define base station characteristics, set up core network parameters, and customize user equipment properties). The emulated network includes an infrastructure emulator based on virtual machines (VMs) and containers. This component provides a virtualized representation of the network infrastructure, allowing the emulation of various network elements and their interactions. VMs and containers enable the creation of isolated environments for different network components, facilitating scalability and flexibility in the emulation process.

**Visualizer**

The Visualizer module allows visualizing data and generating scenarios based on inputs from both the Emulator module and the Network Monitoring module. It leverages the data received from the Emulator module, which includes the simulated behavior of network components such as UEs, BSs, core network, network channels, and the world, to generate and design network scenarios. It allows users to configure specific network conditions, test different parameters, and observe the effects on the network behavior and the simulated interactions and performance of the network through visual representations. Also, it interfaces with the Emulator module to implement the specified configurations and initiate the emulation based on the defined scenarios.

In addition, the Visualizer module obtains data from the Network Monitoring module. This data includes network topology, traffic data, and environmental data collected in real-time from the live network. It visualizes this data, presenting it in a graphical format to provide insights into the current state of the network. Validated and Verified Data are also visualized showcasing the identified patterns, anomalies, and insights derived from the data analytics process. This visualization aids in understanding the performance issues, optimizing strategies, and making data-driven decisions. The Visualizer module also incorporates the generated reports from the Data Analytics module. It presents the key findings, recommendations, and performance metrics in a visual format, allowing users to easily comprehend and interpret the report contents. This report is considered as a preliminary evaluation report that will be sent to the regulator.

## NTN DIGITAL TWIN FRAMEWORK IMPLEMENTATION

To demonstrate the feasibility of NTN orchestrator solution with the 3GPP-compliant implementation of 5G technology, we used Hyper-X-space (HxS) platform as the emulated module to showcase the integration of the NTN orchestrator within a Digital Twin and OpenAirInterface (OAI), which provides the ability to study/test network protocols, signaling technologies and access to the radio channel. OAI is used to emulate the networking nodes, the network channels as well as the core network.

HxS is used to design and run the emulated components (as the emulated module) and the simulated scenario (within the visualiser module). It is a platform for the development, testing, certification and rapid deployment of advanced multi agent systems. It has been developed by Humanitas to provide a promising environment for

Software-In-the-Loop (SIL) and even Hardware-In-the-Loop (HIL) multi-robot 3D simulation in order to accelerate and make more robust the realization and experimentation of autonomous multi-agent technologies. By incorporating multi-physics simulation, HIL and SIL simulation paradigms, data analytics, and machine learning capabilities, HxS create digital twins that can demonstrate the impact of NTN algorithm, usage scenarios, environmental conditions, and other endless variables significantly decreasing the need for physical prototypes, hardware and field tests, reducing development time and budget, and improving quality of the project outcome. Generally speaking, depending on which stages of the product cycle HxS models, the digital twin can be used for the improvement of development and performance.

- Development Product Twin: Leveraging photorealistic 3D modeling, multi-physics, HIL and SIL paradigms, and container technology to speed up software development and incremental tests along with the in-office development process.
- Performance: Visualizing products and codes in use by real users and remotely monitoring the operation with digital twin and real-time dashboards for reporting, analyzing, and preventive maintenance.

Built on top of HxS, the proposed NTN Digital Twin could be the first NTN simulation platform to bring together the following values like no other existing solutions; Virtualization framework to ensure seamless real-world deployments, Distributed architecture to enable massively multi-agents simulations, Integrated network emulation to ensure lifelike communication performance, Photorealistic graphics rendering to train AI vision applications and, High-fidelity physics, sensors and actuators to design reliable control systems.

OAI is an open-source software-based implementation of the 3GPP 5G standards (Written in C). It is used in the provided NTN orchestrator prototype to build and customize LTE and 5G base stations (OAI eNB, and gNB), a user equipment (OAI UE) and a core network (OAI EPC, OAI 5GC). The OAI software provides the following features:

- 5G gNB: 15kHz and 30kHz SCS for FR1 and 120kHz SCS for FR2.
- UE: 15kHz and 30kHz SCS for FR1 and 120 kHz SCS for FR2
- 5G Bandwidths: 10, 20, 40, 80, 100MHz ( max 273 Physical Resource Blocks PRBs)
- LTE: Bandwidth: 5, 10, and 20 MHz (max of 100 PRBs)
- OAISim module that allows for virtualization of network nodes within physical machines and distributed deployment on wired Ethernet networks.

**Radio Frequency Integration**

To showcase the HIL and SIL Terrestrial and non-terrestrial network systems simulation, we designed and integrated a Radio Frequency (RF) module into the Digital Twin. The resulting visualization provides a representation of the RF environment, allowing for detailed analysis and optimization of network performance. The integration is done through the development of some plugins and libraries to support the RF integration to the HxS platform, this includes:

- Developing a graphics rendering plugin within HxS to showcase the path of RF waves through different scenarios with regions of varying propagation velocity, absorption characteristics, and reflecting surfaces. This plugin enables RF Ray tracing within the digital twin.
- Designing and implementing a module within HxS that enables a 3D visualization of the RF signal strength in a specific location based on a dynamic calculation of path loss information from the digital twin. This module enables a 3D heatmap visualization.
- Developing a module for the routing, assignment and placement of flying 5G base stations to showcase the network deployments on the air using UAVs, Drones, HAPs and satellites. The LOS and NLOS RF visualization in ground and flying units are verified and visualized based on the real map of Munich.
- Developing a management module for the RF to study and visualize the direction of a wireless signal toward a specific receiving device. This module enables beam forming features within the digital twin. This involves simulating the behavior of the wireless signal in the real environment, taking into account factors such as antenna direction, reflection, refraction, and interference. The resulting visualization provides a powerful tool for network operators to optimize network performance and ensure reliable connectivity.

**NTN Orchestrator Integration**

For real time validation of the terrestrial and non-terrestrial network systems, we designed an integration module for NTN orchestration algorithms into the Digital Twin network simulator. This module resides in both data analytics and network configurator modules in the NTN framework and it is done through the development of some plugins and libraries for the HxS platform, this includes the development of API to connect NTN algorithms to HxS. This interface implements API calls to get measurements and configuration from network agents simulated into the HxS, but also to set network routing and Base Stations (BS) configurations. It includes:

- Interface for Software-In-the-Loop and Hardware-In-the Loop simulation
- API for languages and framework used by the robotics community (C++, Python, ROS)
- API for languages and framework used by the AI community (C++, Python, OpenAI Gym)
- API for languages and framework used by the telecom community (Matlab, OAI)like Get Position (BS and UE), Channel information (RSRP, RSRQ, SNR, PRB nbr, number of parallel streams enabled by multiple antennas at Tx and Rx), Carrier information (BS), Data Requirements (UE: type of services and running apps), resource consumption (CPU, RAM, Energy), trajectory, Set /configure, Link Config (routing), Placement of the networking nodes, Assignment of the UE to BS nodes.

**OAI RAN Integration**

For a 3D visualization and monitoring of the OAI agents, we integrated the OAI RAN into the Digital Twin. This integration resides into the API module in the NTN framework and it is done through the development of some plugins and libraries for the HxS platform, this includes the development of API to connect OAI RAN software stack running on virtualized or physical base stations (BS) to HxS. OAI RAN is integrated into the terrestrial (e.g., ground base station) and non-terrestrial network (e.g., HAPs, UAVs and Drone) including gNB functions.

OAI 5G Core is also deployed at ground base stations to serve the UEs. All of the OAI RAN and OAI 5G Core elements are containerized to be integrated into our HxS platform. This interface implements API calls to get measurements and configuration from agents in the networks. It also includes Get Calls to get topological coordinates and geographic coordinates of networking nodes (position of both BS and UE), trajectory of the flying BSs, log data related to all the connections and events happening in the base station, CPU resource consumption per network node, available network connections and resource consumption by network node (RAM, CPU, Energy)

**NTN Dashboard**

To manage, visualize and test NTN orchestration algorithms within the 3D SIL and HIL Humanitas HxS simulator, we designed and implemented an interactive Dashboard on top of the 3D MAP. This dashboard resides into the Visualized module in the NTN framework and it includes a graphical user interface (GUI) and an integrated interface for monitoring and exporting data. It visualizes 3D MAP of the selected area as well as the trajectory of flying BSs and the placement of TN and NTN BSs. The connectivity between the different NTN layers is also provided through 3D RF beams and HeatMap. The dashboard shows also RF ray-tracing of the selected 3D area 2D and 3D Stat along with analytics through charts within HxS (real-time statistical data about the performance of the RSRQ, RSRP and SNR signals during the time, the status of the network for each type of service, network health and the number of terrestrial, non-terrestrial customers during the time, the performance of the real time routing and UE-BS assign- ment algorithms implemented within the NTN orchestrator). Details about each selected base station within the 3D MAP (id, position, status (on,off), antenna images) is also provided along with real and predicted weather information within the selected region. The dashboard includes also:

- A data manipulation module able to collect, extract and parse data from the different APIs to the suitable visualization model within the HxS simulator.
- A module for rendering 2D and 3D RF data in terms of beam forming, heat map and ray tracing.
- A module to present data in a visual form within the HxS Simulator. It includes dynamic charts: Bar Charts, Simple line Charts, Compound line charts, Gauge charts.

**ENABLING DIGITAL TWIN IN NTN USING VIRTUALIZATION AND AND NETWORK AUTOMATION: A PRACTICAL USE-CASE**

To validate the SIL and HIL simulation of the NTN orchestrator network, we showcase a 3D visualization of the dynamic management for 5G network and data connectivity over a basic NTN architecture within a digital twin.

Based on a specific scenario of floods in Munich in 2021, we showcase within a Digital Twin how a software orchestrator running into stratospheric aircrafts backhauled either via ground-air feeder link and via GEO satellite link can be fully integrated into a commercial mobile network. The Digital Twin framework retrieves and visualizes a 3D map of the affected geographic region, specifically Munich. This map provides a visual representation of the landscape, allowing users to understand the topography and the extent of the flood-affected areas. In addition, the framework gathers and presents the GPS coordinates of each terrestrial base station in Munich. It also showcases the characteristics of each base station, such as coverage area, antenna height, transmit power, or any other relevant information. This helps in understanding the distribution and coverage of the terrestrial network infrastructure.

Also, the framework displays the number of base stations within each geographic area, allowing users to assess the density and distribution of network resources in different parts of Munich. Further, leveraging the analytics module, the framework calculates and displays charts related to network availability rates. These charts provide insights into the performance of the terrestrial network (TN) and the non-terrestrial network (NTN) during different weather conditions and flood situations. Users can analyze the data and identify trends or anomalies in the network availability. The Weather data is incorporated in real-time to visualize the current weather con- ditions in Munich. This information is crucial in understanding the impact of the flood on network infrastructure and the need for alternative backhaul links through stratospheric aircraft. Figure 2 illustrates a first scenario where we have a normal weather condition along with a Normal state terrestrial net- work fully operational.

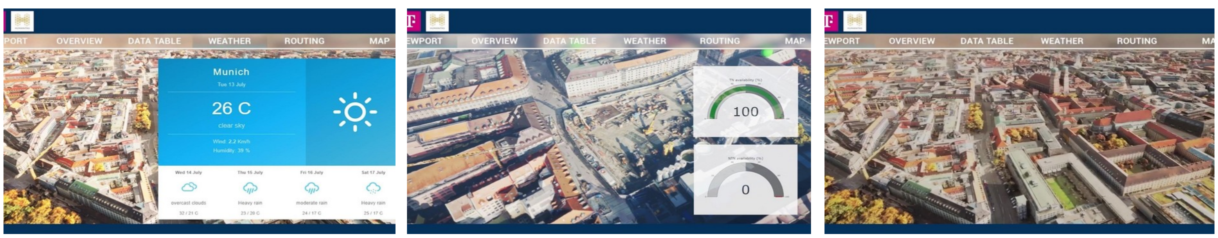


**Figure 2. 3D MAP and Dashboard for the NTN Digital Twin framework**

The main Dashboard contains different windows:

- "VIEWPORT" Window to visualize the real-time statis- tical data about the performance of the RSRQ, RSRP and SNR signals during the time through Compound line charts within the 3D MAP. It also provides details about each selected base station within the 3D MAP (id, position, status (on,off), antenna images), and shows the connectivity between the different NTN layers through 3D RF beams and HeatMap.
- "OVERVIEW" Window for the 3D visualization of RF ray-tracing of the selected 3D area, the visualization of Bar Charts for the status of the network for each type of service, Gauge charts for the terrestrial and non-terrestrial network health, line chart for the number of terrestrial and non-terrestrial customers during the time.
- "DATA TABLE" Window to visualize a table of all statistical information.
- "WEATHER" Window to visualize the real and predicted weather information within the selected region. It uses data retrieved from the "Copernicus" platform.
- "ROUTING" Window to visualize line charts within the 3D MAP to show the performance of the real time routing and UE-BS assignment algorithms implemented within the NTN orchestrator.
- "MAP" Window that enables the visualization of 3D MAP of the selected area as well as the trajectory of flying BSs. Placement of terrestrial and non-terrestrial BSs is also visualized to represent the health of the network in different environment conditions.

We also illustrate, through figure 3, the scenario where we predict heavy thunderstorms that are expected to cause flooding and power disruptions in lowland villages, possibly causing outages in parts of the terrestrial network. Based on severity of predicted weather, the NTN orchestration framework sends HAPS to the stratosphere to allow RAN to be expanded with NTN components during severe weather events. This enables self-triggered and delay-wised network node placement as well as multi-dimensional clustering and optimal assignment of Flying BS (based on capacity, time-to-go and deployment delay).

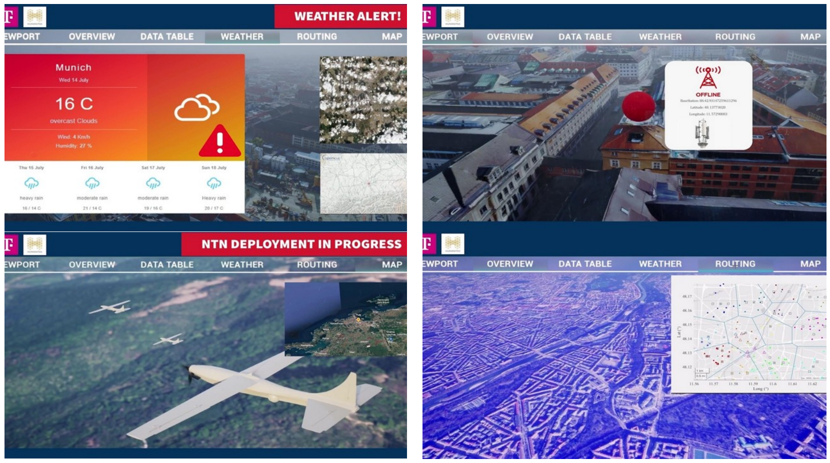


**Figure 3. TN is being recovered**

Figure 4 illustrates the scenario when the TN is being recovered. In this scenario, flying BS continues to serve the area until the terrestrial network provides contiguous coverage. Once the TN is fully recovered, user traffic will be fully transferred to the TN.

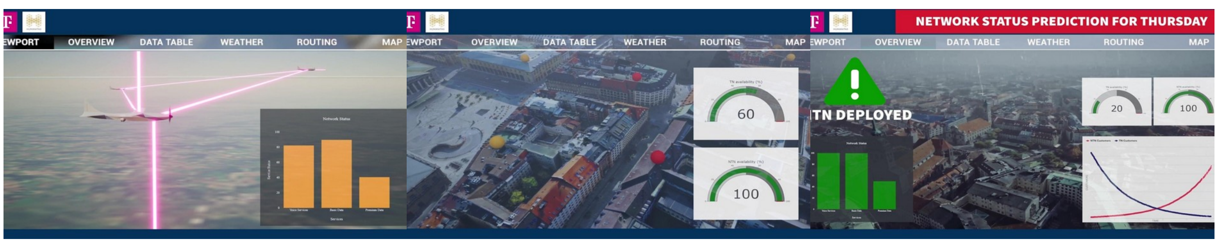


**Figure 4. Self-triggered and delay-wised network node place- ment, clustering and assignment following a partial outage of TN caused by a bad weather condition**

The NTN orchestrator framework will re-dispatched flying BS to the next area of interest (or back to base) based on continuous AI prediction in the data analytics and network configurator modules.

Figure 5 illustrates the emulation and simulation capabilities of the NTN digital twin framework. The emulator and visualiser modules can provide High fidelity models and photo-realistic graphical rendering features for the different assets (Satellite, HAP, drone, user, etc.). They can also provide connectivity simulation and network emulation for RF ray tracing and 3D heatmap.

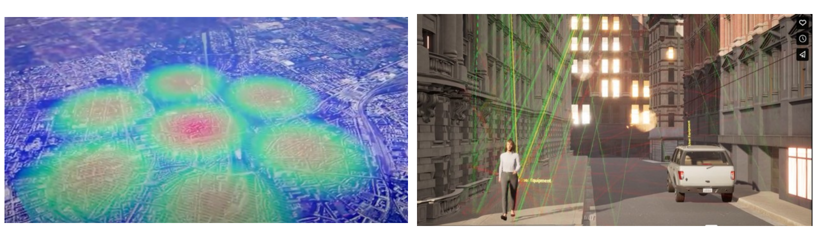


**Figure 5. Visualization capabilities of the NTN Digital Twin orchestration framework**

Through the use of the NTN 5G DT framework, we showcase the validity and efficacy of the SIL and HIL simulations. The framework accurately models the network elements, including stratospheric aircrafts, ground-air feeder links, and GEO satellite links, and simulates their interactions in real- time. It provides an immersive and interactive representation of the network's dynamic management, enabling assessing the system's functionality and performance as well as the evaluation of network management strategies, resource allocation algorithms, and decision-making processes.

## CONCLUSION

We proposed in this paper a framework that leverages virtualization and digital twin capabilities to improve TN and NTN management and operation. We provided insights into the design, implementation, and testing aspects of the framework, offering a foundation for further research and development in this area. The NTN Digital Twin framework comprises several modules and functionalities from the data collection, analysis, optimization, emulation, visualization and report generation. A comprehensive dashboard is also provided for visualizing and analyzing various aspects of the network. Then we illustrated how the proposed NTN orchestrator can effectively manage network resources and ensure continuous connectivity in emergency situations like floods. Our demonstration focuses on a specific scenario of floods in Munich in 2021 and highlights the integration of a software orchestrator running on stratospheric aircrafts into a commercial mobile network through backhaul links such as ground-air feeder link and GEO satellite link. By utilizing the capabilities of the digital twin, the demonstration provides a realistic and interactive visualization of the entire network architecture, enabling stakeholders to understand and assess the functionality and performance of the system. The proposed NTN orchestrator framework can evolve leading to more robust, efficient, and resilient management of 5G network and data connectivity during emergency situations or in challenging environments through the integration of emerging technologies such as edge computing, network slicing, and advanced radio access techniques (e.g., beamforming, massive MIMO). Validation and testing in real-world scenarios could be also another challenge for assessing the framework's effectiveness, reliability, and scalability.

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