Advancing the Future of Integrated 5G-Satellite Networks: A Practical Framework for Performance Evaluation, Dataset Generation, and AI-Driven Approaches

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Keywords: Joint Simulation, Network Simulator, LEO Satellite Communications, Satellite-Terrestrial Integrated Networks, Ray Tracing, Back-Hauling.

Abstract: This paper introduces a framework for Satellite, Terrestrial Integrated Network (STIN), a modular and joint simulation tool for simulating and evaluating integrated terrestrial and non-terrestrial communication systems. The framework comprises various modules designed to model real-world environments, compute and analyze constellation features, and perform channel modeling. Through the seamless integration of these components, the STIN framework enables users to assess the performance of satellite constellations under diverse conditions and select optimal configurations for enhanced coverage and communication efficiency. The paper discusses the methodology and workflow of the framework and a preliminary implementation, suggesting avenues for obtaining communication datasets to support AI-driven approaches.

1 INTRODUCTION

Combining 5G and satellite networks is important for future global communication systems. In situations where regular networks don't work well or are hard to use, this combination becomes crucial. Some examples are during disasters, in remote places, or in areas like the ocean or air where normal networks can't reach. User groups like rescue teams, mobile users, and critical infrastructure operators need reliable communication systems in these situations.

In response to these challenges, Satellite-Terrestrial Integrated Networks (STINs) presents a promising solution by merging the high capacity and low latency of terrestrial 5G with the wide coverage and resilience of satellite networks, particularly those utilizing Low Earth Orbit (LEO) mega-constellations. In hybrid architectures, satellites provide remote coverage and act as a backup plan to ensure continuous telecommunication services for critical applications.

However, the integration of terrestrial and non-terrestrial networks (NTN) poses significant technical challenges, such as high propagation delays in satellite links, on-and-off connection due to satellite mobility, the need for seamless handover management between terrestrial and satellite systems, and interference mitigation in shared frequency bands. Additionally, protocol adaptation across different layers, from the physical layer to the core network, is necessary to maintain reliable end-to-end performance within the hybrid network.

Indeed, the complexity of the multidimensional aspects that must be considered in the real-world experimentation of STINs encourages the development of simulation approaches and environments to design and analyze STIN performance and quality. Accurate simulation environments allow researchers to assess whether the designed non-terrestrial network meets specific application requirements across multiple layers, including the physical, network, and application layers. However, existing simulation tools often do not fully address the challenges posed by STINs or lack comprehensive end-to-end analysis capabilities. Some are also not well-suited to interact with various existing simulation platforms.

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Alibabaie, N., Calabrò, A., Cassarà, P., Gotta, A. and Marchetti, E.
Advancing the Future of Integrated 5G-Satellite Networks: A Practical Framework for Performance Evaluation, Dataset Generation, and AI-Driven Approaches.
DOI: 10.5220/0013564400003970
In *Proceedings of the 15th International Conference on Simulation and Modeling Methodologies, Technologies and Applications (SIMULTECH 2025)*, pages 312-319
ISBN: 978-989-758-759-7; ISSN: 2184-2841

Recent real-world projects, including SpaceX Starlink's [1] experiments for 5G backhaul, AST SpaceMobile's [2] direct-to-device satellite service trials, and OneWeb's [3] collaborations with mobile operators for hybrid 5G satellite connectivity, emphasize the growing demand for simulation-based performance evaluation tools. Furthermore, the 3GPP Release 17 guidelines for NTN integration provide a standardized baseline that this proposed simulation framework can utilize to ensure relevance for future system designs.

This paper aims to fill this gap by presenting a simulation-driven evaluation framework for integrated 5G-satellite networks, incorporating cross-layer modeling and multi-tool integration. By focusing on key performance indicators (KPIs) such as end-to-end latency, throughput, handover success rates, and efficiency in mobility management, the proposed framework seeks to provide both new insights into the feasibility and optimization of future STIN deployments and useful datasets.

Therefore, our fist objective is to simulate a STIN network, focusing on the methodology and a preliminary implementation of integrating tools that, while not fully capable on their own, can be combined to effectively simulate and analyze real-world scenarios. Although the tools used in our initial implementation are commercial, the methodology remains valid when replacing each tool with an open-source alternative that offers similar capabilities. This flexibility allows readers to adapt our approach to their needs and resources.

The second objective of our methodology is to provide datasets generated through our simulation framework. These datasets can help researchers overcome obstacles encountered in real-world environments, enabling the analysis and prediction of various features through Artificial Intelligence (AI) and Machine Learning (ML)-driven approaches. Recognizing the current lack of comprehensive and high-quality datasets in the field, our objective is to contribute to the development of a framework that not only facilitates the generation of valuable data for future STIN research but also promotes the sharing of these datasets among researchers. In the long term, this may reduce reliance on proprietary tools, ultimately fostering advancements in the field through data-driven insights and collaborative research efforts.

The remainder of this paper is organized as follows. In Section II, a brief review of the related work on simulation tools applied in STIN research is presented. In Section III, we delve into the methodology of our proposed STIN simulation framework, detailing its design, components, and capabilities that make it well-suited for simulating STINs. In Section IV, we provide a validation example of execution to showcase the performance of our proposed framework in a real-world scenario. In Section V, we conclude the paper by summarizing our key findings and contributions and shedding light on the potential future work.

[1] https://satellitemap.space/
[2] https://ast-science.com/
[3] https://oneweb.net/

2 RELATED WORK

Nowadays, several advanced simulation tools have been developed and utilized to evaluate the performance of STINs. These simulators are broadly categorized based on several key factors. For instance, some tools are specifically designed to support mega-constellations, which consist of large groups of satellites in low Earth orbit working collaboratively to enhance connectivity and coverage.

Additionally, these simulation tools vary in their availability. Some are offered as commercial software, often providing extensive support and specialized features for professional use, while others are available for free, promoting accessibility for researchers and developers. Furthermore, each simulator comes with distinct applications and functionalities, allowing users to adapt their analyses to specific scenarios, whether for network optimization, performance testing under varied conditions, or assessing the impact of environmental factors on satellite connectivity.

Without being exhaustive, this section provides an overview of the tools commonly used to analyze satellite constellations and terrestrial communication systems. More detail on existing solutions, their evaluation, and comparison can be found in (Jiang et al., 2023), (Yastrebova et al., 2021).

NS-2, NS-3: NS-2, an older discrete event simulator, can simulate various network protocols across wired and wireless networks, including satellite networks. However, it lacks a graphical user interface, presenting challenges in usage. NS-3 addresses this limitation with its user-friendly Python interfaces and data analysis tools (Puttonen et al., 2021), (Sormunen et al.,). As an improvement over NS-2, NS-3 offers better modularity, extensibility, and more realistic and accurate models for various network components.

Matlab: it offers comprehensive toolboxes, including 5G and Satellite Communications Toolboxes, making it well-suited for physical layer and link-level simulations in STINs. Its alignment with 3GPP Release 17 and ready-to-use NTN channel models ensures that researchers can easily study waveform adaptation, propagation effects, and initial performance evaluation. The visualization capabilities and integration with Simulink [4] further enhance multi-layer modeling across physical, MAC, and network layers. However, Matlab is a commercial tool and could be expensive when a combination of multiple specialized toolboxes is required. Scalability could be an issue in the case of large-scale network-level simulations (e.g., thousands of satellites and devices). Additionally, its built-in support for higher-layer protocols (e.g., transport and application) could require customization or external integration. Finally, its real-time performance and hardware-in-the-loop capabilities are less mature compared to dedicated network simulators; therefore, for end-to-end, large-scale STIN performance evaluation, a hybrid simulation approach combining Mathlab with other event simulators is recommended (Mannoni et al., 2022).

System Tool Kit (STK): STK is a powerful simulation tool that facilitates the construction and analysis of satellite constellations, exploration of air and spacecraft missions, and modeling of hybrid network performance. It is particularly useful for simulating physical layer performance metrics based on satellite propagation models, path loss models, and antenna and transceiver models. However, STK targets mainly the system-level mission analysis rather than detailed communication protocol simulation. Integration with external tools like Matlab or ns-3 can be required for simulating end-to-end communication stacks or data link, transport, and application layers (Li et al., 2021).

Hypatia: Hypatia is a framework designed for simulating and visualizing Low Earth Orbit (LEO) constellations. It combines NS-3 and the Cesium 3D mapping library, enabling the simulation of satellite trajectories, link utilization changes, and available bandwidth changes over time (Kassing et al., 2020). A notable limitation of Hypatia is its lack of flexibility in constructing various scenarios and its constrained visualization capabilities.

Space Networking Kit (SNK): SNK is a networking platform tailored for LEO mega-constellations. It allows users to easily construct complex scenarios through configuration files and a single bash command, facilitating the evaluation and visualization of communication processes (Wang et al., 2024). While recent enhancements improve SNK's capabilities, they may increase complexity for inexperienced users and demand additional computational resources, potentially affecting simulation efficiency for users with limited hardware.

Satellite Network Simulator 3 (SNS3): SNS3 is a modular and flexible satellite model built upon the open-source Network Simulator 3 (NS-3). It incorporates DVB-S2 and DVB-RCS2 specifications for forward and return links, respectively, making it a scalable and adaptable open-source simulator for networking research and development (Puttonen et al., 2015).

OS3 OMNET++: OS3 is an open-source satellite simulator built on OMNET++, offering modularity, extensibility, and adaptability for simulating diverse satellite constellations and applications (Valentine and Parisis, 2021). Despite the clear documentation and tutorials available for OMNET++, the lack of specific resources for OS3 might pose challenges for users seeking guidance on on its unique features and capabilities. This limited support may prevent users from fully utilizing OS3's potential for various simulation scenarios.

QualNet: QualNet is commonly used for modeling, simulating, and analyzing the performance of communication networks, particularly in scenarios where communication endpoints are constantly changing their position relative to each other or fixed infrastructure (Jennings et al., 2010).

Gpredict: Gpredict is a Linux-based program that provides real-time satellite tracking and orbit prediction. It utilizes the SGP4/SDP4 propagation algorithms and NORAD TLE to achieve this functionality (Jennings et al., 2010). As a Linux-based program, Gpredict might not be accessible to users on other operating systems without additional setup or virtualization.

As highlighted in this not exhaustive survey, existing simulation solutions are very heterogeneous in the provided features and the target KPIs. Therefore, in designing a unified platform for STINs servers, issues should be considered, such as i) discrepancies in programming languages, network structures, and data formats across different tools; ii) using software conceived for work either with satellite or terrestrial networks independently; iii) integrating these diverse networks by combining the strengths of multiple simulation platforms; iv) complements the existing solutions with specialized capabilities to smoothly solve communication and data format issues.

If some of these issues have already been successfully targeted in specific scenarios, such as indoor communications environments (Hussain et al., 2024), research is still needed to define a platform that can effectively analyze the communication and channel characteristics in integrated satellite-terrestrial networks. Therefore, the target of the paper is to combine the strengths of various simulation platforms to

[4] https://mathworks.com/products/simulink.html

overcome the complexities of integrating diverse networks and contribute to more comprehensive STIN evaluations.

3 METHODOLOGY

In this section, we introduce the methodology used for developing our simulation framework designed for STINs. This framework integrates different tools to offer a modular solution for simulating various satellite constellations and communication scenarios. Figure 2 depicts the STIN simulation framework. Our integrated STIN framework consists of three main components, similar to those found in most software. The input part involves feeding the framework with the initial data necessary for analysis and obtaining results. This part is responsible for providing the simulation with essential data and configurations, allowing users to customize parameters and input the required information for network representation. The core part processes the input data, closely observing the constellation to determine the distribution and movement of satellites to create an accurate representation of the real environment

Additionally, it generates a 3D version of the ground that closely resembles the real environment. Finally, it visualizes the communication between the obtained constellation and the ground. The output part of our framework presents the simulation events

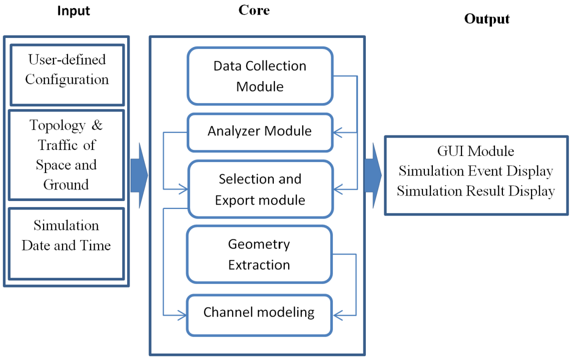


Figure 2: The STIN simulation framework.

and results, offering users useful information to explore, understand, and assess the performance of STIN under different scenarios and configurations.

To schematize the flow of data between different tools in our framework, we provide a sequence diagram (Figure 1) of the methodology execution using three commercial tools (Matlab, Blender, and Wireless InSite (WI)). As mentioned in the introduction, the selected tools were chosen due to their availability within our institution. Alternative tools with similar performance can also be utilized.

In this case, the diagram illustrates the step-by-step interactions between the main components of our proposed STIN framework, highlighting how the modules collaborate to simulate and analyze satellite constellations in a realistic environment. The user-

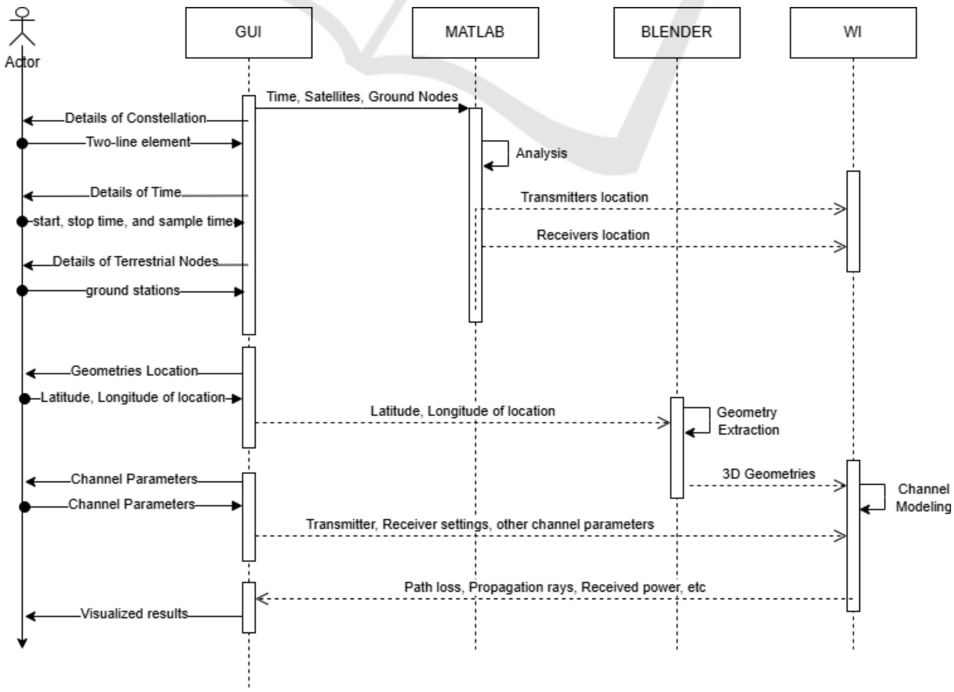


Figure 1: Sequence Diagram of proposed STIN simulation.

provided inputs are transferred to different tools based on their requirements. All data necessary for constellation analysis and data related to the simulation under investigation are transferred to MATLAB, where the core processes related to that are executed. Any data required for generating 3D models of the ground environment is sent to and handled in Blender, which performs the relevant processes. The data obtained from these tools, along with other parameters, are sent to Wireless InSite (WI) to compute the communication performance between terrestrial and non-terrestrial components. Finally, the simulation events and results are sent back to the framework for visualization and further analysis by the user. Considering the Core component of Figure 2, in the following sections, details of each of its modules are provided.

3.1 Data Collection Module

This module simulates a satellite communication scenario over time by iterating through several steps. As shown in Algorithm 1, it first defines the scenario's details, including date/time, locations, and the satellite constellation. Then, for each time step, it retrieves the current location of the ground node and collects a FeatureDataset containing the Date/Time, Azimuth, Elevation, and Distance for the entire constellation. The function repeats this process until the simulation is complete and returns the collected FeatureDataset for further analysis.

Algorithm 1. Collect-Data (TimeDetails).

```
Set Step ← 1

while Step ≤ TotalTime / SampleTime do
    Get the current location of Ground Node
    Get the FeatureDataset for the entire constellation
(Date/Time, Azimuth, Elevation, Distance)
    Increment Step
end while
return FeatureDataset
```

3.2 Analyser Module

The *Analyzer module* processes the collected features from the scenario simulation and analyzes the satellite constellation. Based on the Algorithm 2, in line 1, it begins by calculating the Line-of-Sight (LOS) satellites based on antenna orientation, which determines which satellites are within the line of sight of the ground nodes. Then in line 2, it computes the Mass distribution function for LOS satellites' Elevation, Azimuth, and Distance to estimate the probability distribution of these parameters.

The function then determines the count of non-line-of-sight locations in line 3 and calculates the number of time intervals without visibility (line 4). In line 5, it calculates the minimum and maximum satellites in the line of sight for each point on the ground, as well as the Access Interval - statistics of visibility duration of LOS satellites, including the minimum, maximum, and average values in line 6.

Based on line 7, the function identifies satellites with comprehensive coverage, which helps locate satellites that provide the most extensive coverage to the ground nodes. Finally, it visualizes the analysis to represent the findings of the satellite-ground node communication, such as coverage, visibility, and other essential characteristics (line 8). The function concludes by returning the calculated satellite statistics, providing valuable information for further analysis or decision-making.

Algorithm 2. Consellation-Analyzer (FeatureDataset).

```
1: SatStatistics (1) ← Calc-LOS ()
2: SatStatistics (2) ← Cal-Mass ()
3: SatStatistics (3) ← Comp-NLOS-count ()
4: SatStatistics (4) ← Calc-visibilityless ()
5: SatStatistics (5) ← Calc-LOS-Stat ()
6: SatStatistics (6) ← Calc-AcInterval-VisDuration ()
7: SatStatistics (7) ← Ident-Comp-Coverage ()
8: Visualize (SatStatistics)
9: Return SatStatistics
```

3.3 Selection and Export Module

The *Selection and Export module* performs satellite selection and data export for simulation purposes. In Algorithm 3,it takes the FeatureDataset and SatStatistics, ground location as input. In line 1 it selects representative satellites based on the analysis of the constellation. In line 2, it calculates the ground projection of the selected satellites on the ground and finally, it returns information about transmitter and receivers for further use in simulations.

Algorithm 3. Selection-AND-Export (Feature-Dataset, Sat-Statistics, Ground-data).

```
1: [El, Az, Dis] ← Select-Representative ()
2: Satloc ← Calc-Projection (El, Az, Dis)
3: Return SatLoc
```

3.4 Geometry Extraction Module

As depicted in Figure 2, the Core component also includes modules managing the geometry and the channels. The Geometry Extraction module is a crucial component for streamlining the CAD preparation process in simulating real-world environments using Blender. It integrates the Blosm3 add-on, which simplifies the creation of 3D CAD models for simulation purposes. Utilizing Blosm3's functionality, the module enables the following tasks: downloading real-world terrain data to ensure realistic simulations; generating 3D CAD models of buildings from the OpenStreetMap dataset; placing CAD models on the terrain while considering various building height and floor options; and importing forests and individual trees as 3D objects to enhance the simulation environment's realism.

3.5 Channel modeling Module

This module focuses on modeling the interaction of transmitted rays with surrounding geometries through reflections, diffractions, and transmissions. Channel models are incorporated to enable a realistic evaluation of integrated terrestrial and non-terrestrial network solutions' performance.

Algorithm 4. Channel-Modeling (Geometries, WaveDetails, AntennaDetails, TransmittersLoc, ReceiversLoc).

1: Geo3D ← Import (Geometries (Train, City, Foliage))
2: SetMaterials (Geometries)
3: TransceiverWave ← DefineWave (WaveDetails)
4: TransceiverAnten ← DefineAntenna (AntennaDetails)
5: Trans ← EstablishTransmitter (TransceiverWave, TransceiverAnten, TransmittersLoc)
6: Receiv ← EstablishReceiver (TransceiverWave, TransceiverAnten, ReceiversLoc)
7: SetStudyArea (Geo3D, Trans, Receiv)
8: SetCommunicationSystem ()
9: RunSimulation ()
10: Return (Result)

The location of the transceivers has been imported in line 1, and the geometric characteristics of the geometries' material, waves, antennas, transmitters, and receivers are defined in lines 2 to 6. Ray-tracing models have been employed in this module to simulate the scenario, facilitating a detailed analysis of the network's performance within the given study area, which is determined in lines 7 and 8. After running the simulation (line 9) with the specified settings, the module returns the results for further analysis.

4 VALIDATION OF EXECUTION

To validate our proposed framework, we applied it in a simulation involving a real-world satellite constellation and a defined terrestrial area, demonstrating its practicality and performance under realistic conditions. Specifically, we used the TLE (Two-Line Element) file of the Starlink constellation[5] and set the simulation to begin at 18:30:00 local time on 2025/02/22, with a total duration of 20 minutes and a sampling interval of 5 seconds. The terrestrial observation grid covered a rectangular area bounded by latitudes 43.7061 to 43.7277 and longitudes 10.3834 to 10.4357, representing a set of ground nodes for visibility analysis.

[5] https://celestrak.org/NORAD/elements/

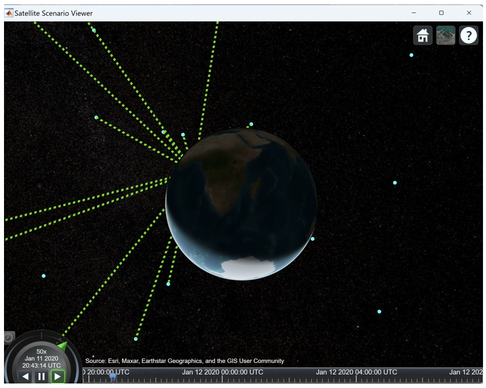


Figure 3: Access analyses between the satellites and the ground station using Matlab.

During the constellation observation phase, the framework monitored satellite movement and ground coverage over time. This allowed the system to record link availability and other spatial-temporal metrics relevant for connectivity assessment. Figures 3 illustrates the simulated satellite constellation and ground area setup. Figure 5 displays a portion of the dataset collected after executing Module 1, and were then passed to the next module for analysis.

Key features of the constellation were evaluated using the analysis module. Figure 6 presents a summary of the analyzed features, which contributed to the subsequent selection of an optimal set of constellations with the most coverage in the simulation area. Based on the extracted metrics, the simulation recorded 197 unique satellites observed during the defined time window. Each ground node maintained LOS with between 11 and 25 satellites, and no receiver was left without visibility throughout the observation period.

Furthermore, the visibility duration per satellite ranged from 5 to 150 seconds, offering insight into temporal coverage dynamics. These results guided the realistic selection of satellite subsets and their relative positions. With the analyzed features and other inputs, the next component selected an optimal set of constellations that provided the most comprehensive coverage in the simulation area. Figure 7 showcases the selected satellites and their projected locations on the ground. To accurately reflect the physical environment in our simulation, we configured and extracted the geometry of the target area bounded by latitudes 43.7061 to 43.7277 and longitudes 10.3834

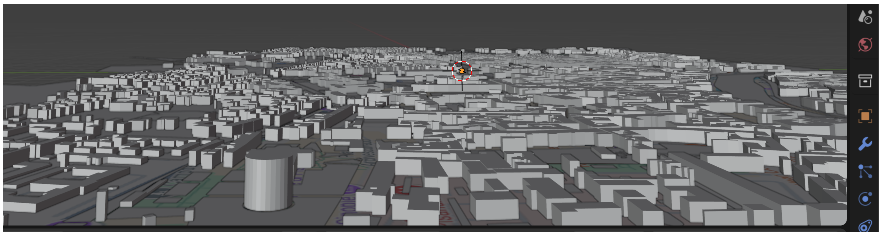
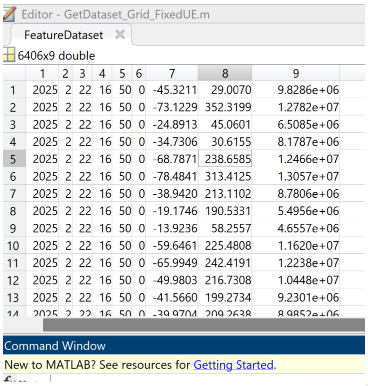


Figure 4: 3D CAD model of simulation area (Blender).



Editor - GetDataset_Grid_FixedUE.m

FeatureDataset

6406x9 double

	1	2	3	4	5	6	7	8	9
1	2025	2	22	16	50	0	-45.3211	29.0070	9.8286e+06
2	2025	2	22	16	50	0	-73.1229	352.3199	1.2782e+07
3	2025	2	22	16	50	0	-24.8913	45.0601	6.5085e+06
4	2025	2	22	16	50	0	-34.7306	30.6155	8.1787e+06
5	2025	2	22	16	50	0	-68.7871	238.6585	1.2466e+07
6	2025	2	22	16	50	0	-78.4841	313.4125	1.3057e+07
7	2025	2	22	16	50	0	-38.9420	213.1102	8.7806e+06
8	2025	2	22	16	50	0	-19.1746	190.5331	5.4956e+06
9	2025	2	22	16	50	0	-13.9236	58.2557	4.6557e+06
10	2025	2	22	16	50	0	-59.6461	225.4808	1.1620e+07
11	2025	2	22	16	50	0	-65.9949	242.4191	1.2238e+07
12	2025	2	22	16	50	0	-49.9803	216.7308	1.0448e+07
13	2025	2	22	16	50	0	-41.5660	199.2734	9.2301e+06
14	2025	2	22	16	50	0	-39.9704	209.2638	8.9852e+06

Command Window

New to MATLAB? See resources for Getting Started.

Figure 5: The output of Collect-Data module (Matlab).

Description	Value
{'NumberofTimeIntervalWithoutAnyVisibility'}	0
{'MinimumLatitudeAfterProjection' }	40.089
{'ManimumLatitudeAfterProjection' }	46.076
{'MinimumLongitudeAfterProjection' }	5.6369
{'MaximumLongitudeAfterProjection' }	15.261
{'MinimumAltitudeAfterProjection' }	4.5825e+05
{'MaximumAltitudeAfterProjection' }	6.2375e+05
{'MinimumNumberofLOS' }	11
{'MaximumNumberofLOS' }	25
{'NumberofTotalUniqueSatellites' }	197
{'MinimumVisibilityDurationofLOSSatellites'}	5
{'MaximumVisibilityDurationofLOSSatellites'}	150

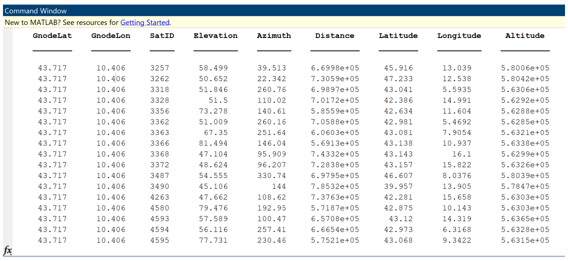
>

Figure 6: The output of Consellation-Analyzer module (Matlab).

to 10.4357 using Geometry Extraction Module. Figure 4 illustrates the resulting 3D representation of the simulation environment.

After completing the constellation selection and projection and geometry extraction, the data, consisting of transmitter and receiver locations in a CSV file, along with DAE files containing terrain, buildings, foliage, and other objects, is fed into the channel modeling module. Figure 8 depicts the channel modeling process, which generated results that could be used for further post-processing or AI-driven analysis.

For each ground node, we compute a normalized ray reception ratio, defined as the number of rays received with power above the NB-IoT receiver sensitivity threshold divided by the total number of rays traced to that node. These results are shown in Figure 9, where each cell corresponds to a specific



Command Window

New to MATLAB? See resources for Getting Started.

GnodeLat	GnodeLon	SatID	Elevation	Azimuth	Distance	Latitude	Longitude	Altitude
43.717	10.406	3257	58.499	39.513	6.6998e+05	45.916	13.039	5.8006e+05
43.717	10.406	3262	50.652	22.342	7.3059e+05	47.233	12.538	5.8042e+05
43.717	10.406	3318	51.846	260.76	6.9897e+05	43.041	5.5935	5.6306e+05
43.717	10.406	3328	51.5	110.02	7.0172e+05	42.386	14.991	5.6292e+05
43.717	10.406	3356	73.278	140.61	5.8559e+05	42.634	11.604	5.6288e+05
43.717	10.406	3362	51.009	260.16	7.0588e+05	42.981	5.4692	5.6285e+05
43.717	10.406	3363	67.35	251.64	6.0603e+05	43.081	7.9054	5.6321e+05
43.717	10.406	3366	81.494	146.04	5.6913e+05	43.138	10.937	5.6338e+05
43.717	10.406	3368	47.104	95.909	7.4332e+05	43.143	16.1	5.6299e+05
43.717	10.406	3372	48.624	96.207	7.2838e+05	43.157	15.822	5.6326e+05
43.717	10.406	3487	54.555	330.74	6.9795e+05	46.607	8.0376	5.8039e+05
43.717	10.406	3490	45.106	144	7.8532e+05	39.957	13.905	5.7847e+05
43.717	10.406	4263	47.662	108.62	7.3763e+05	42.281	15.658	5.6303e+05
43.717	10.406	4580	79.476	192.95	5.7187e+05	42.875	10.143	5.6303e+05
43.717	10.406	4593	57.589	100.47	6.5708e+05	43.12	14.319	5.6365e+05
43.717	10.406	4594	56.116	257.41	6.6654e+05	42.973	6.3168	5.6328e+05
43.717	10.406	4595	77.731	230.46	5.7521e+05	43.068	9.3422	5.6315e+05

Figure 7: The output of Selection-AND-Export module (Matlab).

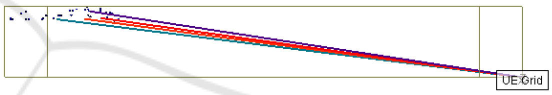


Figure 8: Visualize several propagation Rays obtained in the communication (WI).

ground location (defined by latitude and longitude) and indicates the link reliability or ray coverage quality at that point. Higher values (close to 1) indicate strong and consistent reception, while lower values suggest potential outages or weak coverage areas due to obstacles or poor link geometry. The generation of these comprehensive datasets through our framework paves the way for various data-driven applications in the field of STIN. These datasets can be used to develop, train, and test ML and AI tasks such as coverage prediction, outage detection, adaptive UAV placement, or dynamic beam steering. Furthermore, researchers use them to explore advanced applications, such as reinforcement learning for autonomous network management and deep learning for enhanced signal processing and interference mitigation.

5 CONCLUSION AND FUTURE WORK

Our STIN framework presents a comprehensive and modular approach for simulating and evaluating satellite constellations in realistic environments. By incorporating various modules for observation, analysis, and channel modeling, the framework offers valu-

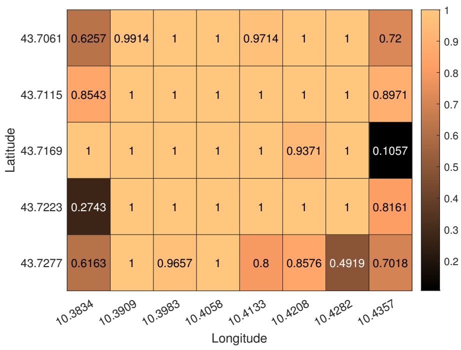


Figure 9: Normalized Link Quality per Ground Location in the Simulation Area.

able insights into the performance and behavior of integrated terrestrial and non-terrestrial communication systems. In future work, we will focus on further enhancing our STIN framework. Key areas of improvement include refining the efficiency of constellation selection algorithms and integrating advanced AI techniques for more in-depth data analysis. These advancements will enable more accurate and efficient simulation and evaluation of integrated 5G-satellite networks. Additionally, we will prioritize the development of an automated platform to facilitate seamless communication and information exchange between various simulation tools. This automation will streamline the simulation process, making it more accessible and efficient for a broader range of users. Furthermore, recognizing that reliance on commercial tools may not be feasible for all researchers, we will continue to explore alternative simulation tools and platforms. Our goal is to create a framework composed entirely of free and open-source tools, ensuring that the proposed methodology can be implemented and utilized by anyone, regardless of their access to commercial software.

ACKNOWLEDGEMENTS

We thank Tarun Chawla and Remcom Inc for the Wireless InSite X3D ray tracer numerical analysis. This work is supported by RESTART (PE00000001) under the PNRR of the Italian MUR program NextGenerationEU.

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