IoD-Sim: an Open-Source Simulator for 6G Integrated Terrestrial/Non-Terrestrial Networks

Giovanni Grieco[a,b] (giovanni.grieco@poliba.it), Daniele Pugliese[a,b] (daniele.pugliese@poliba.it), Adnan Rashid[a,b] (adnan.rashid@poliba.it), Ilaria Cianci[a,b] (ilaria.cianci@poliba.it)

[a] Department of Electrical and Information Engineering, Politecnico di Bari, Via Orabona 4, 70126 BA, Bari, Italy
[b] Consorzio Nazionale Interuniversitario per le Telecomunicazioni, Viale G.P. Usberti, 181/A Pal.3, 43124 PR, Parma, Italy

Abstract
Integrated Terrestrial/Non-Terrestrial Networks (T/NTNs) are paving the way to ubiquitous connectivity in future Sixth Generation (6G) communication systems, as they enable novel heterogeneous environments with drones, High-Altitude Platforms (HAPs), and satellites. For the challenges brought by this diverse spectrum of mobile network entities, it is imperative to have tools capable of assessing such a complex network infrastructure before moving to a real-world deployment and testing phase. To this end, this work emphasizes the need for a comprehensive system-level communication simulation platform to study and develop these emerging architectures. It surveys existing simulators and introduces the Internet of Drones Simulator (IoD-Sim), an open-source platform designed for T/NTN simulations, including the envisioned 6G technology of Intelligent Reflective Surfaces (IRSs).

Keywords
ns-3, system-level, simulator, 6G, Non-Terrestrial Network, Internet of Drones

Code metadata

Nr	Code metadata description	Please fill in this column
C1	Current code version	V4.0.2 – ns-3.42
C2	Permanent link to code/repository used for this code version	https://telematics.poliba.it/iod-sim
C3	Permanent link to reproducible capsule	
C4	Legal code license	GPL-2.0
C5	Code versioning system used	git
C6	Software code languages, tools and services used	C++, Python, Bash, CMake
C7	Compilation requirements, operating environments and dependencies	Linux-based Operating System
C8	If available, link to developer documentation/manual	
C9	Support email for questions	giovanni.grieco@poliba.it

Body of the article

1. Motivation

Non-Terrestrial Networks (NTNs) are unlocking future Sixth Generation (6G) communications in achieving pervasive connectivity across the planet [1]. The traditional terrestrial network infrastructure, which has been massively enhanced and made flexible thanks to the Fifth Generation (5G) ecosystem, is further extended, and thus integrated, with several aerial and

space networking entities. Operating at different altitudes, Unmanned Aerial Vehicles (UAVs), High-Altitude Platforms (HAPs), and satellite platforms pave the way for an Integrated Terrestrial/Non-Terrestrial Network (T/NTN). To this end, it is essential to study and research heterogeneous environments, focusing on all the different peculiarities that distinguish this three-dimensional (3D) Internet infrastructure in terms of design and testing.

For instance, UAVs, also known as drones, can be categorized as multi-copters and fixed wing in structure and, according to their mechanical implementation, they are constrained in terms of the possible hardware that can be installed, thus limiting the computational, memory, energy, and communication capabilities. To some extent, HAPs are subject to similar constraints to maintain a stable flight in the stratosphere. Moreover, it is crucial to distinguish between the types of satellites involved in the communication system under consideration. These satellites vary widely, ranging from small CubeSats deployed in mega-constellations at Low Earth Orbit (LEO), which are affected by significant Doppler shifts, to Geostationary Earth Orbit (GEO) satellites, which move in sync with Earth's rotation [2].

Along with the physical properties of these network entities, more research on mobile communications is critical for the upcoming network infrastructure. Moreover, 6G is pushing to (i) improve sub-6 GHz spectrum efficiency, (ii) unlock mmWave and THz, and (iii) employ metasurfaces. The latter, and specifically Intelligent Reflective Surfaces (IRSs), are increasingly attracting attention due to their potential in transforming multi-path fading as an advantage [3].

As such communication architectures increase in complexity, it is of utmost importance to ensure that researchers have a tool able to study and understand how these devices would operate in an integrated context. At the same time, industries need a state-of-the-art platform to observe such advancements, track their performance, and iterate over their products in a fast-paced environment. To this end, in order to enable such use cases, a comprehensive system-level communication simulation platform is needed, which offers a balance between (i) a high-level scenario configuration language, (ii) an extensible model architecture, (iii) a high-quality foundation library, and (iv) a rich set of complementary tools for data analysis.

At the time of writing, it is difficult to find a simulator that integrates out of the box this excess of features to achieve the stated vision [4–10]. Most notably, Network Simulator 3 (ns-3) [11] with its 5G LENA module [12], OMNeT++ [13], and Vienna 5G [14] are well-known for their solid foundation in simulating terrestrial networks, based on the latest 3rd Generation Partnership Project (3GPP) and Institute of Electrical and Electronics Engineers (IEEE) standards on 5G. Furthermore, there is ongoing work to enable 6G communications in ns-3 with Terasim [15].

Regarding NTN entities, UAVs can be physically simulated through Robot Operating System (ROS) and Gazebo [7, 16, 17], but they lack tools for a comprehensive network simulation, to which CORNET 2.0 [9] accomplishes through a hybrid architecture with Mininet [18]. Alternatives, specifically designed for the design and implementation of Internet of Drones (IoD) [19] scenarios are FlyNetSim [4], CUSCUS [5], and AVENS [6].

As for satellites, there is an ongoing effort to extend ns-3 through its NTN module [20] and Satellite ns-3 (SNS3) [21], although these modules lack full end-to-end simulation for the former and the specific focus on Digital Video Broadcasting (DVB) for the latter. Finally, to design and test IRSs, WiThRay [22], SimRIS [23], and a Vienna 5G module [24] allow their modeling, phase shift optimization, and the evaluation of their fading loss.

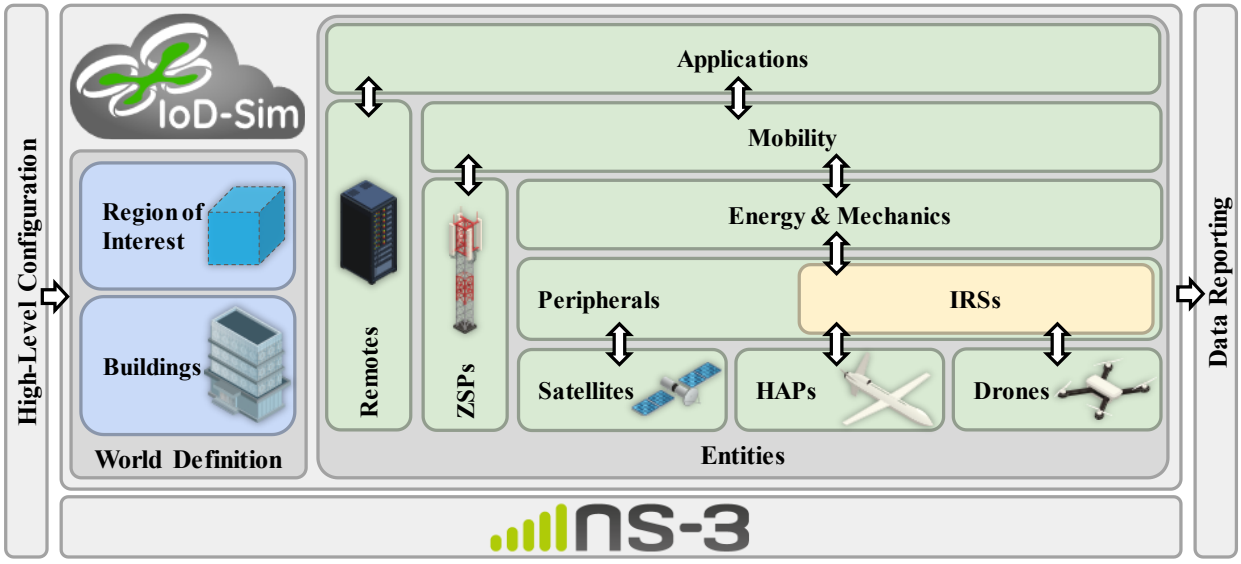

Figure 1. The current IoD-Sim core architecture.

Among these simulators, this contribution introduces the latest version of Internet of Drones Simulator (IoD-Sim), an open-source system-level communication simulation platform, written in C++ and based on the well-known ns-3 event-based simulator [25–28]. IoD-Sim represents a significant step forward in the design and evaluation of 6G-enabled T/NTNs, by integrating and extending the functionalities made for ns-3 with NTN entities, i.e., UAVs, HAPs, and satellites. Moreover, experimental 6G IRSs can be configured and attached to these mobile nodes to study use cases that involve passive relaying.

2. High-level description

IoD-Sim is an event-driven tool for network simulations, extending the notable ns-3 with over 200 C++ source and header files, 120 classes, and 34000 lines of code. Figure 1 provides an overview of the features offered by the platform, which are summarized hereby:

1. *High-Level Configuration* – A configuration abstraction reduces the effort to set up complex scenarios by hiding the complexity of (i) the integrations made in IoD-Sim, (ii) the definition of ns-3 scenarios, which requires C++ programming skills. To this end, in the proposed simulator, scenarios can be designed and configured through a Graphical User Interface (GUI) program named Airflow. As illustrated in Figure 2, this tool leverages a domain-specific visual programming language to configure the entities and link them together as graphical blocks and connections. Once configured, the scenario is exported in JavaScript Object Notation (JSON)-encoded files. These configuration files, generated via Airflow or written manually, are then parsed by the simulator. This approach eases the learning curve of all the features provided by the platform while keeping the configuration parameters in a data format that has an acceptable trade-off between human comprehension and ease of machine parsing.
2. *World Definition* – the simulator offers the possibility to define a simple 3D Cartesian space or a geographic one, enabling the choice to study simple networks or to reproduce realistic ones. If the geographic coordinate system is chosen, IoD-Sim automatically converts the system of reference to a geocentric Cartesian one or to a Mercator projection as needed. Given the chosen coordinate space, buildings and regions of interest can be defined. While the former are key for realistic experimentation in smart cities, the latter are 3D boxes that enable UAVs and HAPs to change their functions according to the current location.

3. *Drones and HAPs* – Drones and HAPs are a specialization of ns-3's Node [11,25,27] adding support to crucial characteristics of these 6G non-terrestrial entities, i.e., mechanical features, on-board peripherals, and applications. The essential properties that distinguish these entities are their mass, type of aircraft, and flight altitude. According to these details, a power consumption model can be configured to ensure a proper characterization of the energy depletion curve and hence estimate their battery residual. Furthermore, their altitude impacts on the channel model, due to atmospheric absorption and scintillation effects [29]. UAVs and HAPs can also be characterized with a mobility model. Among the ones already provided by ns-3, IoD-Sim offers specific models that simulate a curvilinear trajectory based on the point of interest. The curve points, generated through an enhanced Bézier equation, are followed by the entities in a constant acceleration or with a given parametric speed equation.
4. *Peripherals* – Each entity can be equipped with peripherals of different types, i.e., (i) a storage one that acts as a temporary buffer in case of loss of signal, (ii) a generic input peripheral that captures data, and (iii) IRSs 6G devices [28] for relaying use cases. As the input peripheral can be interleaved with the storage one to simulate buffered communications, the IRSs enable these entities to passively improve link efficiency between the ground users and the designed network infrastructure. Moreover, they can be logically subdivided into patches, each of which has a scheduling plan to dynamically serve certain nodes of interest or to just configure a fixed reflection angle.
5. *Zone Service Providers (ZSPs)* – In IoD-Sim, the terrestrial infrastructure is composed of base stations that can be enhanced with local edge services, namely ZSPs. These nodes can be interconnected with their core network and UAVs, which represent key enablers for the vision of internet-connected drones [30]. Behind the core network of choice, a backbone network simulates remote cloud services. Together with UAVs and HAPs, these entities can be configured with applications that communicate telemetry or send generic traffic.
6. *Satellites* – GEO satellites are one of the recent additions to IoD-Sim [27]. They represent a preliminary effort to embrace 6G satellite communications, especially in the mmWave spectrum. Currently, it is possible to define satellite position through its geographic coordinates and distance from the Earth's surface, giving the possibility to evaluate fundamental link-level performance metrics, such as the Signal-to-Interference-plus-Noise Ratio (SINR) [27].
7. *Data Reporting* – According to the configuration, data are extracted, aggregated, and summarized in a dedicated directory whose name includes the time of execution of the scenario and its name. Among the traditional text and PCAP-based trace files of ns-3, an eXtensible Markup Language (XML) summary is generated, which reports relevant data of the simulation, e.g., data traffic, nodes trajectories, and their telemetry. The file formats have been chosen to ease data pre-processing and analysis with other tools and languages, e.g., Python and MATLAB, for which some reference examples are provided in the source code.

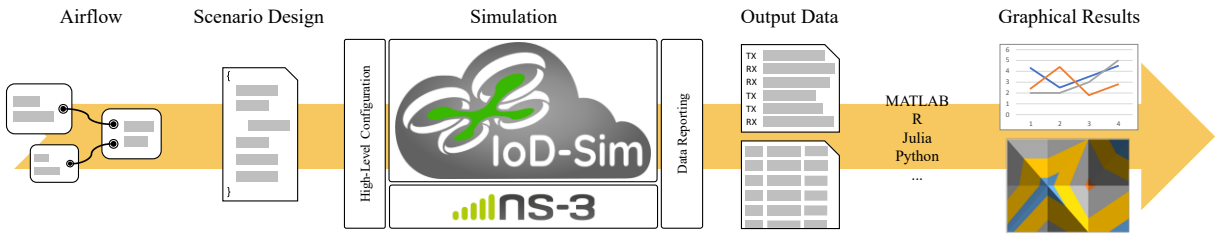

Figure 2. Scenario workflow in IoD-Sim, from its design to output data evaluation.

3. Impact overview

The ever-evolving landscape of 6G and Integrated T/NTN technologies demands robust and versatile tools for performance evaluation and experimentation. Addressing this need, IoD-Sim stands as an open-source system-level simulator that empowers researchers and practitioners to delve into the complexities of this field.

Catering to user convenience, IoD-Sim offers (i) pre-built scenarios to streamline research by leveraging preconfigured settings for typical use cases related to 6G and Integrated T/NTN; (ii) extensive customization options to accommodate research across diverse fields, thus fostering user adoption while simultaneously facilitating the exploration of emerging applications and services; (iii) integration with conventional Integrated Development Environments (IDEs), such as Visual Studio Code, to ensure efficient workflow and minimal learning curve through simple executable tasks; (iv) comprehensive log and data generation for full insight into simulation behavior, with detailed text traces capturing key events; and finally (v) a modular design to seamlessly extend the tool's capabilities in order to address diverse research needs by incorporating new mobility, communication, and application models.

The open-source nature of IoD-Sim is cultivating a community of users from both academia and industry. Its impact is demonstrably evident through successful use in IoD scenarios [25] as well as IRS research [28] and NTN [27]. The tool also aligns with the goals of the "RESTART" project, part of the Italian National Recovery and Resilience Plan (NRRP).

As a valuable tool for advancing 6G and Integrated T/NTN research and experimentation, IoD-Sim empowers users to explore a vast array of research questions and evaluate emerging applications and services. Its demonstrated impact within the research community solidifies its position as a cornerstone for future development and innovation.

4. Scholarly publications enabled by the software

The simulator architecture has been proven to be easily extensible through the years and a valuable tool for students and researchers in this field. As IoD-Sim started in its infancy to provide advanced mechanisms for IoD experimentation [25, 26], at the time of writing (December 2024) also provides further extensions to unlock research in NTNs [27] and IRSs [28].

5. Conclusion

An Integrated T/NTN simulator for future 6G communications is needed to enable academia and industry to approach the upcoming communication technologies, ever so complex and flexible. In this regard, IoD-Sim integrates some of the features discussed from the state of the art and it offers a configurable and extensible platform for ease of use and continuous improvement. In the future, more efforts will focus on implementing and experimenting with the 3D network architecture to demonstrate the feasibility and impact of the 6G emerging use cases.

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