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Direct-to-satellite internet of things (DtS-IoT): a tutorial review on architectures, protocols, and future directions

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The Internet of Things (IoT) is increasingly used in agriculture, logistics, smart cities, environmental monitoring, and industrial automation. However, many remote, rural, maritime, and disaster-prone regions remain disconnected because deploying terrestrial infrastructure is prohibitively expensive or technically infeasible. Direct-to-Satellite IoT (DtS-IoT) addresses this gap by leveraging Low Power Wide Area Network (LPWAN) technologies, such as adapted LoRa and Narrowband IoT (NB-IoT), which both enable direct communication between IoT devices and Low Earth Orbit (LEO) satellites and provide the long-range, low-power operation required for such links. This tutorial paper provides a structured and accessible introduction to DtS-IoT. Building on recent literature, it covers seven major themes: (*i*) system architectures, (*ii*) constellation design, (*iii*) LPWAN protocols, (*iv*) key challenges, (*v*) simulation tools, (*vi*) experimental studies, and (*vii*) future directions and open research issues. The goal is to guide the reader through the foundational concepts, design principles, and current technological landscape of DtS-IoT, offering a comprehensive set of references for further study.

KEYWORDS

direct-to-satellite IoT, Internet of things, LORA, LPWAN, NB-IoT, satellite constellations

1 Introduction

1.1 From terrestrial IoT to satellite-enabled IoT

Terrestrial Internet of Things (IoT) networks based on Low Power Wide Area Network (LPWAN) technologies, Wi-Fi, and cellular systems have enabled large-scale deployments in urban and suburban areas. Nevertheless, sizeable parts of the world remain poorly covered or completely unserved.

It is estimated that more than 70% of the Earth's surface, including deserts, mountain regions, forests, large maritime areas, and sparsely populated rural zones, is not covered by terrestrial communication infrastructures. In these environments, installing base stations, fiber, or dense terrestrial backhaul is often economically unattractive or technically infeasible. Satellite systems have long been used to provide global connectivity; however, it was only in the last decade that they have become compatible with low-cost IoT devices.

This evolution has been driven by:

- The emergence of new constellations of small Low Earth Orbit (LEO) satellites, supported by the expansion of the NewSpace economy;
- Adaptation of LPWAN waveforms to long-range, low-power operation;
- Standardization efforts, notably in the 3GPP non-terrestrial networks (NTN) context (Kodheli et al., 2020).

In this scenario, Direct-to-Satellite IoT (DtS-IoT) refers to architectures in which IoT devices communicate directly with one or more LEO satellites using LPWAN or cellular technologies such as Narrowband IoT (NB-IoT), without the need for local terrestrial base stations.

1.2 Scope and intended audience

Research on DtS-IoT has grown significantly since about 2018. Existing works cover topics such as:

- Design of sparse and dense LEO constellations for delay-tolerant and near-real-time IoT services (Fraire et al., 2020; Capez Maiolini et al., 2022);
- Adaptation of LoRa, Long Range-Frequency Hopping Spread Spectrum (LR-FHSS), and NB-IoT to satellite channels (Alvarez et al., 2022; Scapin et al., 2024; Ullah et al., 2023; Gedara et al., 2023; Fraire et al., 2022a);
- Doppler modeling and mitigation techniques (Al-Hourani and Al Homssi, 2024; Subramanian et al., 2023; Zhou et al., 2023);
- New MAC protocols and scheduling policies for large populations of devices (Tondo et al., 2024; Jung et al., 2023);
- Simulation frameworks and validation methods for DtS-IoT networks (Fraire et al., 2022b; Schubert et al., 2022; Kassing et al., 2020);
- Experimental demonstrations and field trials of DtS-IoT links.

Many papers in the literature assume the reader is already familiar with satellite terminology, LPWAN operation, and basic performance metrics. The objective of this tutorial is to provide a more gradual introduction, with emphasis on:

- Explaining the main concepts;
- Highlighting design trade-offs;
- Pointing to key recent references for each topic.

The intended audience includes graduate students, early-stage researchers, and practitioners with a basic background in wireless communications and networking who want to understand how DtS-IoT systems are conceived, modeled, and evaluated.

1.3 Distinct contribution of this review

This review occupies a distinct niche by offering a tutorial-grade, system-level introduction to DtS-IoT, bridging foundational concepts with the most recent technological and commercial developments. Unlike (Centenaro et al., 2021; Le et al., 2024), which assume substantial prior knowledge and focus heavily on protocol-level technicalities, our survey is deliberately accessible while remaining rigorous. In comparison with the earlier synthesis in (Fraire et al., 2019), major advances since 2019 are incorporated, including the latest commercial constellations and new waveforms such as LR-FHSS. Even comprehensive recent overviews such as (Chen et al., 2023) do not jointly cover these cross-layer and cross-technology perspectives. Finally, unlike application-centric works such as (Chippalkatti and Biradar, 2021), this review provides an integrated view of architectures, protocols, technologies, and emerging trends, filling a gap in the literature with an up-to-date and accessible tutorial on DtS-IoT.

1.4 Structure of the tutorial

The rest of the paper is structured as follows. Section 2 introduces the main DtS-IoT architectures, including direct, indirect, and hybrid space-terrestrial configurations. Section 3 analyses sparse, dense, and regional LEO constellations, highlighting their trade-offs for IoT traffic. Section 4 reviews the principal waveforms and protocols used for DtS-IoT: LoRa, LR-FHSS, and NB-IoT. Section 5 discusses key transmission challenges, including Doppler mitigation, random access scalability, and energy constraints. Section 6 presents simulation tools and validation methodologies relevant for DtS-IoT research. Section 7 presents some examples of satellite constellations for Direct-to-Satellite IoT. Section 8 summarizes representative experimental results from in-orbit demonstrations and field testbeds. Section 9 outlines open problems and future research directions. Finally, Section 10 concludes the tutorial.

Throughout the text, a selection of works is referenced to offer deeper technical details. These references are not exhaustive, but they cover a broad range of approaches and viewpoints.

2 Satellite IoT architectures

This section describes the architectural structure of satellite IoT systems, focusing on how devices access the network and which communication paths are involved.

At a high level, three architectural configurations are typically considered: (*i*) direct-to-satellite (DtS), where devices communicate directly with a passing LEO satellite; (*ii*) indirect-to-satellite (ItS) or gateway-based, where devices connect to a terrestrial gateway that relays data to the satellite; and (*iii*) hybrid architectures, where devices can dynamically switch between terrestrial and satellite links depending on coverage, energy constraints, or service requirements.

In the following, these three architectures are compared. For each architecture, a brief description is first provided, followed by a discussion of the main advantages and the corresponding limitations.

2.1 Direct-to-satellite architectures

In a pure DtS architecture, each IoT device transmits directly to a LEO satellite, bypassing terrestrial base stations, making the satellite the first hop in the network (Fraire et al., 2019). Devices typically employ LPWAN waveforms such as LoRa or LR-FHSS in sub-GHz bands, or NB-IoT-like waveforms in licensed bands (Fraire et al., 2020; Alvarez et al., 2022; Ullah et al., 2023; Fraire et al., 2022a). This model naturally suits highly remote deployments, including maritime monitoring and environmental sensing in isolated or hard-to-access regions (Ullo and Sinha, 2020).

2.1.1 Advantages (DtS)

DtS architectures require minimal or no ground infrastructure, enabling operation in remote or inhospitable areas without local network deployment. In particular, they are well suited to oceans, deserts, forests, and sparsely populated rural areas (Susilo and Suryana, 2023; Scapin et al., 2024). Another important advantage lies in the immediate availability and resilience enabled by existing satellite coverage, which allow rapid activation during emergencies, infrastructure loss, or terrestrial outages, making DtS suitable for disaster response and seamless connectivity. Furthermore, short LEO slant ranges of 300–1200 km help reduce latency and path loss compared with GEO links, making DtS viable for massive machine-type communication (mMTC) in remote environments. Field studies (e.g., ocean sensing and flood-response monitoring) confirm that DtS systems can sustain stable operation and scale to large numbers of devices (Marin-de Yzaguirre et al., 2024; Bakhtiari et al., 2025).

2.1.2 Limitations (DtS)

Despite these advantages, maintaining high reliability remains challenging. Rapidly time-varying conditions due to satellite motion impose stringent requirements on channel tracking and Doppler compensation. In fact, Doppler shifts resulting from satellite velocities above (7 km/s) can distort waveforms and degrade decoding performance (Al-Hourani and Al Homssi, 2024). Without proper compensation, packet delivery ratios (PDR) may drop below 50% under adverse conditions, whereas advanced Doppler mitigation and timing strategies can raise PDR to about 80% in sparse deployments (Ullah et al., 2023; 2025). These observations highlight the need for robust synchronization mechanisms and adaptive MAC protocols to operate efficiently within short, bursty visibility windows (González et al., 2021). Other key challenges include intermittent visibility windows, since each satellite is in view for only a few minutes per pass, and stringent link budget requirements, as devices must communicate directly with satellites using limited transmit power.

2.2 Gateway-based and indirect architectures

Indirect or gateway-based architectures introduce a terrestrial relay between devices and the satellite. Devices communicate using short-range terrestrial LPWAN technologies (e.g., LoRaWAN), while the gateway aggregates traffic and forwards it to the satellite through a backhaul link (Ogbodo et al., 2022; Scapin et al., 2024). This approach mirrors traditional LPWAN deployments, with the key distinction that the gateway is connected to the network infrastructure via a satellite backhaul rather than a terrestrial one.

2.2.1 Advantages (ItS)

The main advantages of this architecture stem from the reduced complexity and power demand at the device level, as sensors communicate over short terrestrial ranges with a nearby gateway rather than transmitting directly to space. As a result, device energy consumption can be reduced by up to approximately 40% compared with direct-to-satellite (DtS) solutions (González et al., 2021). Furthermore, shorter communication hops enable tighter synchronization and improved quality-of-service (QoS) control, which is particularly beneficial for semi-real-time industrial and logistics applications. Additional benefits arise from the presence of local intelligence at the gateway, which enables on-site processing, caching, traffic filtering, and more efficient scheduling before forwarding data to the satellite segment. Finally, this approach allows operators to leverage existing LPWAN deployments, extending connectivity to semi-remote or industrial environments without the need to redesign the entire access network.

2.2.2 Limitations (ItS)

The main limitations of ItS architectures stem from their reliance on terrestrial infrastructure. This dependency introduces a potential single point of failure, as gateway outages can disconnect entire clusters of devices. Moreover, the overall architecture is generally more complex compared to pure DtS solutions. As a result, gateway-based architectures are best suited to scenarios in which limited infrastructure can be reliably deployed and maintained, such as offshore platforms, vessels, mining sites, or isolated villages (Ogbodo et al., 2022; Ledesma et al., 2024). Conversely, their scalability is inherently constrained in remote or disaster-prone regions, where the installation and maintenance of terrestrial gateways may be impractical or economically unjustified.

2.3 Hybrid space-terrestrial architectures

Hybrid architectures combine direct satellite connectivity with terrestrial communication paths. Depending on coverage, traffic conditions, or service requirements, devices may dynamically switch between:

- Direct DtS uplinks to satellites,
- Terrestrial LPWAN connectivity (e.g., LoRaWAN or NB-IoT),
- Reduced-capability 5G (RedCap) links when available (Gedara et al., 2023; Kodheli et al., 2020).

2.3.1 Advantages (hybrid architectures)

Hybrid architectures exploit the complementary strengths of DtS and ItS. This architecture enables operators to integrate both access types within a single operational model. Such architectures can still sustain connectivity during terrestrial outages or periods of congestion and have demonstrated strong resilience in smart-city and emergency scenarios. Studies report reductions in network downtime of up to 55% when hybrid mechanisms are adopted (Ledesma et al., 2024). Practical configurations often combine local LPWAN access (e.g., LoRa) with NB-IoT or RedCap for wide-area coverage, enabling seamless adaptation to varying connectivity conditions (Ogbodo et al., 2022).

2.3.2 Limitations (hybrid architectures)

This flexibility comes at the cost of *increased orchestration complexity*. Managing transitions across heterogeneous links

TABLE 1 Comparison of DtS-IoT architectural models.

Architecture	Description	Advantages	Limitations
Direct-to-satellite (DtS)	End devices communicate directly with LEO satellites	No ground infrastructure; wide-area coverage; resilience to terrestrial outages	Strong doppler; short visibility windows; stricter link budget.
Indirect-to-satellite (ItS)	Devices connect to a terrestrial gateway that relays traffic to the satellite	Lower device power consumption; tighter synchronization; improved QoS	Requires terrestrial infrastructure; the gateway is a single point of failure
Hybrid space–Terrestrial	Devices dynamically switch between DtS and terrestrial LPWAN/cellular links	Flexible operation; improved reliability; adaptive path selection	Complex integration; link orchestration; standardization challenges

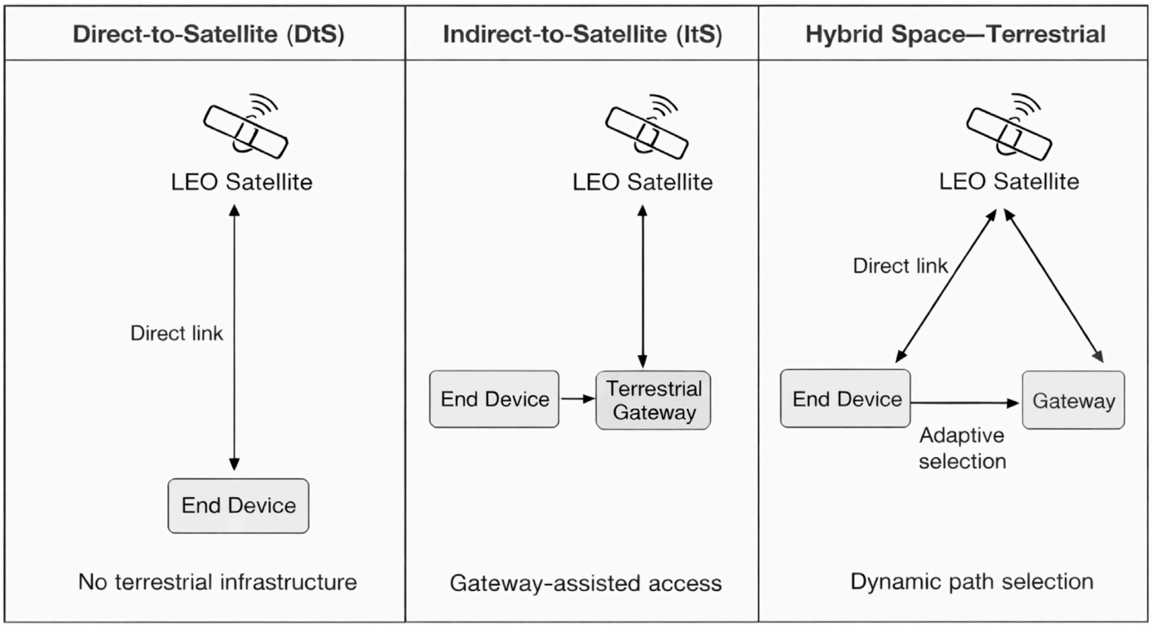

FIGURE 1
Conceptual comparison of Direct-to-Satellite (DtS), Indirect-to-Satellite (ItS), and Hybrid space–terrestrial IoT architectures.

requires sophisticated handover strategies, multi-link scheduling, and careful alignment with standardization frameworks such as 3GPP NTN. Reconfigurable antennas may be needed to support switching between terrestrial and satellite bands (Bouyedda et al., 2021). Furthermore, hybrid operation introduces additional interoperability and resource-allocation challenges across network domains (Queralta et al., 2019). Overall, hybrid architectures offer a powerful solution for environments where connectivity must remain operational despite partial coverage, variable link conditions, or stringent reliability requirements. Still, they demand careful system design and substantial control-plane support.

2.4 Summary

Table 1; Figure 1 summarizes the three architectural models considered in DtS-IoT systems: direct-to-satellite (DtS), indirect-to-satellite (ItS), and hybrid architectures, highlighting their operational principles, strengths, and main limitations.

3 Satellite constellations

Satellite constellation design is a central aspect of DtS-IoT systems, as it determines coverage, latency, revisit times, device energy consumption, and overall deployment cost. Although many orbital configurations exist, most DtS-IoT deployments fall into three broad categories:

- Sparse constellations, consisting of a small number of satellites that provide periodic access opportunities and are optimized for delay-tolerant sensing;
- Dense constellations, composed of tens to thousands of satellites across multiple orbital planes, supporting near-continuous visibility and low latency;
- Regional constellations, tailored to specific geographic areas with concentrated demand, offering a compromise between sparse global fleets and dense worldwide networks.

These three families reflect distinct design philosophies: sparse constellations minimize cost and energy usage, dense constellations maximize responsiveness and availability, and regional designs concentrate satellite resources where connectivity is most needed. The following subsections describe each category in detail.

3.1 Sparse constellations

Sparse constellations typically consist of approximately 4–25 satellites and provide periodic coverage rather than continuous connectivity. They naturally align with delay-tolerant IoT applications, in which devices buffer measurements and transmit only during predicted satellite passes (Fraire et al., 2020; 2022b). Sparse Walker-type layouts, when optimized, can achieve substantial regional or global coverage while drastically reducing deployment and operational costs compared with dense fleets (Capez et al., 2022).

Studies demonstrate that sparse constellations can reach up to ~ 90% regional coverage under suitable orbital tuning and contact-scheduling strategies (Capez et al., 2022). Lightweight visibility-prediction algorithms allow devices to wake only during expected access windows, reducing idle listening and achieving success rates above 80%-85% even in constrained environments (Ortigueira et al., 2024). Delay-tolerant networking (DTN) techniques further enable buffer-and-forward operation across long periods of offline connectivity, ensuring eventual delivery in remote field deployments (Koukis et al., 2024; Marin-de Yzaguirre et al., 2024).

The main limitation of sparse constellations lies in their long revisit times, which often exceed tens of minutes or hours, making them unsuitable for services that require timely reporting or continuous monitoring. Nevertheless, their scalability, simplicity, and excellent alignment with low-duty-cycle IoT traffic make them ideal for agriculture, wildlife tracking, structural monitoring, and other applications where periodic updates suffice (Fraire et al., 2020; Capez et al., 2022).

3.2 Dense constellations

Dense constellations range from several tens to thousands of satellites and are engineered for near-continuous visibility and low end-to-end latency, often below 50 ms (Capez et al., 2022). Prominent deployments include Starlink, the largest operational broadband constellation; OneWeb, providing polar-inclusive global coverage; Amazon Kuiper, now entering its deployment phase; and China's Guowang system, envisioned as a multi-thousand-satellite national LEO infrastructure (Laniewski et al., 2025; Osoro and Oughton, 2021; Delkowski et al., 2025). By distributing satellites across many orbital planes and employing inter-satellite links (ISLs) Radhakrishnan et al. (2016), dense fleets maintain persistent access and reduce queuing delays, enabling real-time or near-real-time IoT services.

Such architectures are well-suited for safety-critical telemetry, environmental alerting, industrial monitoring, and other applications requiring continuous connectivity. However, the associated costs are substantial: multi-plane deployments, ISL meshes, and complex routing frameworks impose high capital and operational expenditures (Deng et al., 2021; He et al., 2023). For typical IoT workloads, which are characterized by small payloads and sporadic transmissions, dense constellations often provide more capacity than necessary, leading to inefficiencies (Capez et al., 2022).

In practice, dense constellations excel in latency-critical or availability-driven use cases, but they are often economically and operationally unsuitable for cost-sensitive DtS-IoT deployments (He et al., 2023).

3.3 Regional constellations

Regional constellations represent an intermediate solution between sparse global fleets and dense worldwide networks. Instead of offering universal coverage, these systems focus their capacity on specific geographic areas with the highest IoT demand, such as maritime corridors, polar regions, or rural areas in developing countries.

From an orbital perspective, regional constellations typically rely on high-inclination LEO orbits for enhanced *polar visibility*, equatorial planes for *tropical areas*, or a small number of Walker planes tuned to the *target region*. In some cases, elliptical or highly inclined orbits provide extended dwell time over selected latitudes.

A key design tool for such regional systems is the use of *repeating ground-track orbits*, in which a satellite's ground path repeats exactly after a fixed number of days and revolutions. By synchronizing the orbital period with Earth's rotation, the satellite overflies the exact geographic locations at regular intervals. This property allows operators to concentrate revisit frequency and pass timing over specific areas without deploying large numbers of satellites, while still maintaining predictable, schedulable access windows, highly valuable for IoT traffic planning, contact-plan generation, and power-constrained devices.

These configurations enable frequent access in the region of interest while keeping the number of satellites and the associated costs significantly lower than in dense global constellations.

Regional designs offer shorter revisit times than sparse global fleets and avoid the cost and complexity of dense deployments, making them attractive for maritime monitoring, ice-management, fisheries control, or regional logistics.

Their main limitation is geographic selectivity: performance degrades quickly outside the target zone, making them unsuitable for globally mobile assets.

3.4 Summary

Sparse, dense, and regional constellations provide complementary trade-offs for DtS-IoT deployments. Sparse constellations minimize cost and energy consumption, dense constellations maximize availability and responsiveness, and regional systems concentrate resources where demand is geographically localized. Selecting a constellation type depends on latency requirements, coverage objectives, traffic patterns, and the economic constraints of the target application.

Table 2 summarizes the key characteristics of the three approaches.

TABLE 2 Summary of sparse, dense, and regional constellation characteristics.

Type	Description	Advantages	Limitations
Sparse	Small fleets (~ 4-25 satellites) offering periodic access with long revisit times	Low cost; energy-efficient scheduling; well-suited to delay-tolerant sensing	Long latency; limited temporal coverage; unsuitable for time-sensitive data
Dense	Large fleets (tens to thousands of satellites) enabling near-continuous visibility	Low latency; high availability; supports real-time or high-frequency reporting	High cost; complex ISLs and routing; often overprovisioned for typical IoT traffic
Regional	Constellations tailored to specific geographic zones with concentrated demand	Frequent access in target areas; lower cost than dense global fleets	Poor coverage outside the region; not suited for globally mobile assets

4 Protocols

Communication protocols play a central role in determining the feasibility, performance, and scalability of DtS-IoT systems. Their behavior over LEO links differs substantially from terrestrial operation due to substantial Doppler shifts, intermittent visibility, and the large number of devices contained within a single satellite footprint. This section reviews the main protocol families considered for DtS-IoT, i.e., LoRa, LR-FHSS, and NB-IoT, highlighting physical-layer characteristics, Doppler resilience, scalability, and practical limitations.

These protocols represent complementary design points. LoRa and LR-FHSS dominate low-power LPWAN connectivity; NB-IoT extends 3GPP cellular technology to satellite environments. Their differences illustrate key performance and cost trade-offs in DtS-IoT design.

4.1 LoRa

LoRa employs chirp-spread-spectrum (CSS) modulation and is widely adopted in terrestrial LPWAN deployments because of its long range, low power consumption, and tunability through spreading factor (SF), bandwidth, and coding rate (Scapin et al., 2024).

Although often used interchangeably, LoRa and LoRaWAN refer to distinct components of the communication stack, and their roles must be carefully differentiated when analyzing DtS-IoT systems. LoRa defines a physical-layer (PHY) modulation scheme based on chirp spread spectrum, which specifies how information is encoded and transmitted over the wireless channel. As a PHY technology, LoRa can in principle be employed in different network architectures and does not inherently impose assumptions on network topology, access control, or higher-layer procedures. LoRaWAN, on the other hand, specifies a MAC and network-layer protocol originally designed for terrestrial LPWAN deployments. It introduces gateway-based architectures, centralized network servers, device classes, adaptive data rate mechanisms, and specific assumptions on uplink-downlink asymmetry and network control. These features are closely tied to the presence of terrestrial infrastructure and to the availability of relatively frequent downlink opportunities, which may not always be guaranteed in DtS-IoT scenarios. In the context of DtS-IoT, the use of LoRa modulation does not necessarily imply full compliance with the LoRaWAN protocol. While LoRa modulation can be directly adapted to satellite channels, LoRaWAN may require modifications or partial re-interpretation to account for satellite-specific constraints such as long propagation delays, limited downlink capacity, intermittent visibility, and Doppler effects. As a result, the scalability, network control mechanisms, and overall system behavior of LoRa-based DtS-IoT solutions can differ significantly depending on whether LoRa is employed as a standalone physical layer solution. In-orbit demonstrations confirm its DtS feasibility: CubeSat experiments reported received powers between −112 and −127 dBm at 400 – 600 km altitudes (Khamsah et al., 2024).

Over LEO satellites, LoRa faces three main challenges:

- Strong and fast-varying Doppler shifts, especially for high SFs with long symbol durations;
- Significant evolution of elevation angle and path loss during each pass;
- Scalability limitations stemming from pure ALOHA access.

Ullah et al. show that Doppler effects can drive PDR below 50% without compensation (Ullah et al., 2023), while Subramanian et al. demonstrate that Doppler shift is the primary source of packet loss in LoRa communications at *higher spreading factors* and propose a transmitter-side hardware-assisted compensation technique (Subramanian et al., 2023). Parameter tuning, including moderate SFs, narrower bandwidths, and suitable carrier frequencies, significantly improves reliability under LEO dynamics (Ullah et al., 2025).

In addition, LoRa's ALOHA-based MAC (Class A), ideal for sparse terrestrial deployments, saturates quickly in DtS scenarios: with more than 100 contending devices under a satellite footprint, collision probabilities may exceed 60% (Testi and Paolini, 2024). While Class A offers minimal power consumption, its uncoordinated uplink limits scalability. LoRaWAN's other device profiles provide alternatives: Class B introduces beacon-synchronized ping slots that could help coordinate access if satellites broadcast timing signals, and Class C offers near-continuous downlink reception suited to power-rich terminals such as gateways or mobile assets. These modes do not remove the need for Doppler or contention management, but they expand LoRa's applicability in DtS-IoT beyond pure ALOHA operation.

4.2 LR-FHSS

LR-FHSS (Long-Range Frequency Hopping Spread Spectrum) extends the LoRaWAN family by enabling coordinated frequency hopping to increase the scalability and robustness offered by CSS-based LoRa modulation Boquet et al. (2021). Each packet is spread over many time-frequency slots (e.g., ~ 137 hops in a 125 kHz channel), reducing collision probability and improving resilience Ullah et al. (2021).

Key properties include:

- High scalability: up to ~ 75 × more devices per pass than LoRa (Alvarez et al., 2022);
- Improved Doppler tolerance: short symbol durations reduce frequency-offset sensitivity;
- Resilience to narrowband interference through hopping diversity.

Empirical studies report PDR values above 95% in high-density settings (Jung et al., 2023). Unlike LoRa's pure ALOHA access, LR-FHSS inherently reduces contention by dispersing transmissions across many time-frequency resources, mitigating saturation effects in large satellite footprints. As research on enhancing LR-FHSS scalability progresses (Maldonado et al., 2025), the waveform has emerged as a strong candidate for large-scale DtS deployments, supporting applications such as logistics, maritime tracking, and wildlife telemetry (Maleki et al., 2024).

4.3 NB-IoT

Narrowband IoT (NB-IoT), a cellular technology integrated into the 3GPP ecosystem, contrasts sharply with LoRa/LoRaWAN by offering a more controlled (thus more sophisticated), reservation-based access rather than pure ALOHA. Built on OFDMA with 15kHz subcarrier spacing, NB-IoT provides stronger reliability, standardized security, and QoS mechanisms inherited from LTE/5G system design. Its adaptation to NTN has been extensively studied within 3GPP (Kodheli et al., 2020), making it a natural fit for operators seeking tight integration between terrestrial and satellite segments.

Main strengths:

- Robust QoS and link-layer reliability, inherited from cellular resource scheduling and HARQ mechanisms;
- Coverage Enhancement (CE) modes enabling operation in long-range, high-loss, or obstructed environments typical of NTN;
- Beacon-aided Doppler and timing tracking, significantly improving synchronization and random-access success in LEO scenarios (Zhou et al., 2023).

In DtS experiments, NB-IoT provides uplink rates of 20 – 60 kbps, well above LoRa-based technologies (Ali et al., 2023). However, its active-mode consumption (up to ~ 300 mAh/day) limits suitability for battery-powered mobile sensors. As such, NB-IoT is appropriate for QoS-driven DtS deployments involving fixed or mains-powered devices.

4.4 Summary

The protocols used in DtS-IoT span a wide range of complexity, energy cost, and Doppler resilience. Low-power LPWAN solutions (LoRa, LR-FHSS) offer simplicity and excellent energy efficiency; NB-IoT provides QoS and higher throughput at increased power cost.

Table 3 summarizes the main qualitative differences across protocols.

While the technologies and protocols discussed in this section enable DtS-IoT operation, their performance is influenced by several system-level and physical-layer challenges, which are discussed in the next section.

5 Protocol challenges in DtS-IoT

Protocols designed for DtS-IoT environments must operate under substantially more challenging PHY and MAC layers conditions than terrestrial LPWAN or cellular deployments. Four challenges dominate LEO operation: (*i*) large and rapidly varying Doppler shifts; (*ii*) short, intermittent contact windows; (*iii*) severe MAC-layer contention within vast satellite footprints; and (*iv*) tight device constraints on energy, computation, and synchronization overhead. These factors jointly shape reliability, throughput, energy efficiency, and scalability. This section reviews each challenge and summarizes representative mitigation strategies.

5.1 High doppler and frequency dynamics

The Doppler frequency shift introduced by satellite motion is given by $\Delta f = \frac{v}{c} f_c$, where v is the relative satellite-terminal velocity, c is the speed of light, and f_c is the carrier frequency. The high relative velocity of LEO satellites (often > 7 km/s) induces Doppler shifts up to ± 40 kHz at sub-GHz carriers. Doppler varies rapidly over a pass, typically peaking at mid-elevation, and affects:

- Carrier and timing synchronization,
- Symbol orthogonality (critical for CSS),
- Packet detection and demodulation,
- Effective SNR and link budget,
- MAC timing accuracy for slot-based protocols.

TABLE 3 Qualitative comparison of protocols for DtS-IoT.

Protocol	Modulation	Scalability	Doppler resilience	Typical use
LoRa	CSS	Medium	Low–Medium	Sparse sensors
LR-FHSS	FHSS	High	Medium–High	Dense devices
NB-IoT	OFDMA	Medium	Medium	QoS-critical

TABLE 4 Summary of protocol challenges and mitigation strategies in DtS-IoT.

Challenge	Impact	Representative mitigation
High Doppler	Synchronization loss; degraded PDR; increased overhead	SF/BW tuning; hardware-assisted tracking; beacon-based prediction; Doppler-assisted decoding
Short contact windows	Bursty access; latency spikes; energy inefficiency	Visibility-aware scheduling; deterministic or adaptive slotting; pass prediction
MAC contention	High collision probability; throughput limits	Multi-channel SA/SALSA; TDMA hybrids; SCHC compression; learning-based access
Device constraints	Limited compute/energy; complexity trade-offs	Lightweight synchronization; simplified Doppler models; cross-layer co-design

Stochastic Doppler models parameterized by elevation angle, orbital geometry, and altitude provide predictive tools for PHY/MAC adaptation (Al-Hourani and Al Homssi, 2024).

5.1.1 LoRa Doppler sensitivity

In LoRa systems, the symbol duration is given by $T_{\mathrm{sym}} = \frac{2^{\mathrm{SF}}}{\mathrm{BW}}$, where SF is the spreading factor and BW is the signal bandwidth. As the spreading factor increases, the symbol duration grows exponentially, making the signal more sensitive to Doppler-induced frequency offsets and time variations.

LoRa's CSS modulation is particularly vulnerable at high spreading factors (SF11-SF12), where symbol durations approach 1 s. Residual frequency offset disrupts chirp orthogonality, reducing PDR below 50% without mitigation (Ullah et al., 2023).

Mitigation strategies include:

- Reducing SF to SF7-SF9,
- Widening bandwidth (e.g., 250 kHz),
- Shortening payloads,
- Optimizing center frequency to minimize mid-pass Doppler.

When properly tuned, LoRa can achieve PDR values around ~ 82% at ~ 560 km altitude (Ullah et al., 2023; 2025). Hardware-assisted Doppler tracking with SX1262-class radios provides gains of ~ 22% under peak Doppler (Subramanian et al., 2023).

5.1.2 NB-IoT synchronization

NB-IoT benefits from OFDMA-based synchronization channels. Beacon-aided Doppler pre-compensation has achieved ~ 89% synchronization success within 10-min passes (Zhou et al., 2023). Differential resource allocation and uplink power control help mitigate distortion in dense access periods, though at the cost of additional processing and timing overhead that may challenge ultra-low-power devices.

5.1.3 Emerging Doppler-Aware techniques

Recent research treats Doppler as a usable signal:

- Doppler-assisted decoding tracks frequency trajectories, improving PDR by ~ 15% at low SNR (Singh et al., 2024);
- geOmetry-based Doppler prediction informs adaptive PHY/MAC behavior (Al-Hourani and Al Homssi, 2024);
- Joint Doppler-MAC alignment adjusts slot timing to match Doppler phases.

These methods offer performance gains but require additional computation and memory.

5.2 Short contact windows and temporal constraints

A LEO satellite is visible for only 5–15 min per pass, with 6–14 passes per day depending on geometry. This intermittent connectivity imposes temporal constraints:

- Traffic becomes highly bursty at pass boundaries,
- Devices must schedule wake-up and transmission precisely,
- Downlink opportunities for synchronization are limited,
- Applications must tolerate store-and-forward operation.

Visibility-aware scheduling is therefore essential. Devices often rely on:

- Predicted pass schedules derived from TLE data,
- Wake-up timers aligned with expected elevation thresholds,
- Reduced duty cycles to avoid wasted idle listening.

When combined with Doppler models, prediction-based scheduling minimizes energy usage and increases packet success probability.

Deterministic-access protocols (e.g., SL-MAC, LST-MAC) exploit these windows by aligning slots to pass geometry, providing latency and energy benefits in structured traffic patterns (Wang et al., 2018; Wang et al., 2019). Irregular or asynchronous traffic, however, may require adaptive strategies that react dynamically to missed or shortened passes.

5.3 MAC contention and scalability limits

A single satellite footprint can cover hundreds of thousands of devices. During each visibility window, many may attempt uplink transmission simultaneously. This creates severe contention, especially under ALOHA-like protocols.

5.3.1 ALOHA limitations

Pure ALOHA, widely used in LoRaWAN, exhibits collision rates exceeding 60% with more than 100 active devices (Testi and Paolini, 2024; Chabou et al., 2024). Given the footprint size of LEO satellites, classical ALOHA is unsuitable for large-scale DtS deployments.

5.3.2 Enhanced slotted ALOHA

Multi-channel Slotted ALOHA (e.g., SALSA) leverages frequency diversity and coordinated rescheduling:

- Throughput improvements up to 80%,

- Support for ~ 50% more devices per pass,
- Normalized throughput improvements from 0.52 to 0.82 under multi-satellite awareness (Chabou et al., 2024).

These schemes preserve low complexity while improving performance in moderate-density scenarios.

5.3.3 TDMA and adaptive slotting

TDMA-based MACs assign deterministic slots aligned with predicted visibility windows (Wang et al., 2018; 2019). Advantages include predictable latency and reduced energy expenditure. Adaptive schemes (e.g., LoRa-OCI) estimate network load online and dynamically tune slot allocations and backoff strategies, reducing collisions under heavy traffic (Maldonado et al., 2023). However, for ultra-dense regimes ($\gtrsim 5,000$ devices per pass), contention remains problematic.

5.3.4 Learning-based and predictive access

Learning-based scheduling predicts device activity or traffic patterns to optimize slot assignments and access probabilities. Preliminary results show collision reductions around 50% (Tondo et al., 2022; Jung et al., 2023). Practical adoption requires lightweight models suitable for nanosatellite payloads and battery-powered devices.

5.4 Device constraints and cross-layer trade-offs

DtS devices often operate on small batteries, with limited processing capability and strict duty-cycle budgets. Mitigation techniques must therefore balance performance with resource constraints.

Key device-level limitations include:

- Limited CPU and memory for complex synchronization,
- Power restrictions that limit active-mode duration,
- Hardware oscillator instability affecting Doppler tracking,
- Constraints on antenna size and orientation.

Cross-layer approaches help address these constraints:

- SCHC compression reduces IPv6 overhead by ~ 75%, enabling ~ 35% energy savings (Ortigueira et al., 2021);
- Simplified Doppler models reduce compute load while preserving accuracy;
- Coordinated PHY/MAC/NET design minimizes redundant signaling during short passes.

The fundamental trade-off is clear: more substantial compensation and scheduling improve reliability but increase energy consumption and hardware complexity. Future designs must optimize mitigation overhead jointly with device constraints.

5.5 Summary

Table 4 summarizes the most important challenges discussed in this section. High Doppler, intermittent visibility, heavy MAC contention, and strict device constraints represent the four core protocol challenges in DtS-IoT. Doppler-aware tuning, hardware-assisted tracking, and predictive models mitigate frequency dynamics. Visibility-aware scheduling and TDMA hybrids improve temporal efficiency, while enhanced Slotted ALOHA and learning-based access reduce contention. Cross-layer design remains essential for balancing reliability with device-level energy and complexity constraints.

6 Simulation tools and validation methodologiesa

Simulation plays a central role in DtS-IoT research. Large-scale experimental testbeds requiring multiple satellites, thousands of devices, and controlled mobility are costly and complex to operate. Consequently, most studies rely on simulation environments that combine orbital dynamics, propagation models, protocol behavior, and device-level constraints. This section reviews the main categories of tools used in DtS-IoT research, as well as validation methodologies that ensure model reliability.

6.1 Categories of simulation tools

Simulation tools for DtS-IoT can be broadly grouped into four families:

- Orbit and coverage simulators for geometry, access windows, and revisit time analysis;
- Link-level simulators for physical-layer performance under Doppler, noise, and interference;
- System- and network-level simulators for large-scale access, congestion, and protocol behavior;
- Integrated or multi-domain frameworks combining orbital, PHY, and MAC/NET modelling.

These categories differ in fidelity, scalability, and purpose; in practice, hybrid workflows are often required.

6.2 Orbit and coverage simulators

These tools model satellite trajectories, coverage footprints, visibility windows, and access opportunities. They are essential for estimating pass durations, latency distributions, and the number of contact opportunities per day.

- STK (Ansys) Analytical GraphicsInc Now Ansys (2025) provides high-precision orbit propagation, coverage maps, and communication link modules. It is a licensed tool yet widely used in industry for mission design.
- GMAT (NASA) NASA Goddard Space Flight Center (2022) is a free and open-source astrodynamics tool supporting trajectory optimization and spacecraft modelling; often used to compute access times.
- Orekit CS Group and the Orekit Project Team (2025) is a free and open-source Java library that enables high-fidelity orbital analyses.

- Poliastro Poliastro Development Team (2025) is a Python toolkit suited for rapid prototyping of constellation geometries and access windows for LEO IoT scenarios.

These tools provide accurate orbital dynamics but do not model device traffic or MAC behavior.

6.3 Link-level simulators

Link-level simulators evaluate physical-layer waveforms under Doppler, noise, fading, and terminal constraints. They are crucial for analyzing waveform robustness and link budget feasibility.

- MATLAB/Python parametric simulators support narrowband waveform modeling, Doppler analysis, and link-budget evaluation for LoRa, LR-FHSS, NB-IoT, and proprietary waveforms.
- GNU Radio enables real-time prototyping of modulation schemes (e.g., LoRa and OFDMA adaptations), hardware-in-the-loop testing, and Doppler emulation.
- 3GPP-inspired PHY simulators adapt NB-IoT/LTE-M link models to LEO conditions, including extended propagation delay and Doppler.

These simulators generally operate at a small scale but provide high physical fidelity.

6.4 System- and network-level simulators

System-level tools model interactions among large device populations, random access mechanisms, duty-cycle constraints, and delay-tolerant traffic.

- ns-3 ns-3 Consortium (2025) supports satellite modules and IoT traffic models. Extensions such as `ns-3-leo` model LEO constellations, device access cycles, and transport behavior (Schubert et al., 2022).
- OMNeT++ OMNeT++ Community (2025) provides a modular discrete-event platform suited for MAC protocol evaluation, large-scale IoT populations, and scheduling strategies.
- OpenSAND OpenSAND Steering Committee (2025), originally GEO-focused, can emulate LEO links with adapted propagation delays, enabling protocol and application-level evaluation.
- Custom Python-based simulators are widely used for DtS-IoT, modeling satellite pass schedules, device sleep cycles, random access collisions, and duty-cycle compliance.

While less accurate at the PHY layer, these tools scale to millions of devices.

6.5 Integrated or multi-domain platforms

Multi-domain frameworks integrate orbital, physical-layer, and network-layer models into unified workflows, supporting end-to-end evaluation.

- Hybrid toolchains: STK for orbit and coverage, MATLAB/Python for link-level analysis, and ns-3/OMNeT++ for system-level behavior.
- Operator-developed simulators model end-to-end service performance, terminal energy consumption, and traffic patterns using proprietary architectures.
- ML-enhanced frameworks incorporate machine-learning models for device traffic prediction, Doppler estimation, power adaptation, or dynamic access control.

These platforms help explore cross-layer interactions but often incur high computational costs.

6.6 FLoRaSAT and LoRa-Based simulators

FLoRaSAT (Fraire et al., 2022b; Choquenaira-Florez et al., 2025) extends LoRaWAN simulations to satellite contexts and is among the most widely used open-source frameworks for DtS-IoT. Its capabilities include:

- Modelling of satellite orbits (SGP4 propagator) and visibility windows,
- LoRa physical-layer models including path loss, interference, and regulatory constraints,
- ALOHA-based MAC behavior under duty-cycle limits.
- Custom Link and Network protocols sandbox.

FLoRaSAT allows large-scale evaluation of:

- Packet delivery ratio (PDR) over long time horizons,
- Collision probability under dense access,
- How spreading-factor distributions impact performance,
- How sparse a constellation may be for a target application.

Its abstraction of orbital and PHY dynamics enables rapid design exploration with realistic MAC behavior.

6.7 Ns-3-leo and geometry-centric tools

The `ns-3-leo` framework (Schubert et al., 2022) augments ns-3 with detailed models for LEO mobility, Doppler, satellite routing, and handover. It supports multi-layer evaluation spanning:

- Random access and congestion control,
- Transport and routing mechanisms under intermittent links,
- Hybrid terrestrial-satellite architectures and handover strategies.

Geometry-centric tools such as Hypatia (Kassing et al., 2020) complement ns-3 by focusing on constellation geometry, contact opportunities, and scheduling, and can be integrated with network simulators for end-to-end evaluation.

6.8 Validation, datasets, and reproducibility

Simulation-based research must be validated against empirical observations whenever possible. Common validation sources include:

- In-orbit CubeSat measurements, e.g., RSSI and Doppler profiles reported in (Khamsah et al., 2024);
- Laboratory testbeds, using real LoRa or NB-IoT transceivers under controlled Doppler emulation;
- Analytical models–such as the Doppler and link-budget formulations in (Al-Hourani and Al Homssi, 2024);
- Public datasets and open-source code, increasingly common but still not universal (Fraire et al., 2022b; Schubert et al., 2022).

Reproducibility remains a challenge: many studies rely on custom simulators that are not publicly released. A more systematic approach, based on standardized datasets, common simulation templates, and open-source toolchains, would greatly benefit the community.

6.9 Summary

Table 5 summarizes the simulation tools discussed in this section. Orbit-level simulators such as STK, GMAT, Orekit, and Poliastro provide high-fidelity access and visibility predictions. Link-layer tools like MATLAB and GNU Radio enable detailed waveform and robustness evaluations. System-level platforms, including ns-3 and OMNeT++, support large-scale studies of congestion, scheduling, and protocol behavior. Increasingly, integrated frameworks combine these layers to deliver end-to-end performance assessment. Robust validation ultimately requires blending simulation results with analytical models, in-orbit measurements, and hardware-in-the-loop experiments.

7 Satellite constellations for direct-to-satellite IoT

Several commercial initiatives have deployed or are deploying low Earth orbit constellations specifically tailored for DtS-IoT. These systems typically operate narrowband links, support ultra-low-power terminals, and target delay-tolerant applications such as environmental sensing, asset tracking, agriculture, and logistics. The following subsections summarize the most representative constellations and their technical characteristics.

7.1 Swarm technologies (SpaceX)

Swarm operates one of the largest DtS-IoT constellations, consisting of UHF picosatellites in near-polar LEO (450–550 km). It offers two-way low-rate messaging using a proprietary narrowband protocol and ultra-low-power terminals. Thanks to its large fleet, revisit times are short, enabling quasi-global coverage with latencies suitable for delay-tolerant applications and extremely low service cost.

7.2 Astrocast

Astrocast deploys L-band CubeSats providing bidirectional IoT connectivity. Its waveform employs adaptive spreading and Doppler-resilient modulation, enabling higher robustness and data rates than UHF-based systems. The constellation is expanding toward improved revisit times and denser multi-plane coverage.

7.3 Lacuna space

Lacuna offers DtS connectivity based on LoRa/LoRaWAN adaptations for LEO, operating in ISM bands. The system aims for interoperability between terrestrial LoRaWAN networks and space-based uplinks, allowing standard LoRaWAN devices (with minor adaptations) to communicate via satellite. Coverage is global, with moderate latency that improves as new spacecraft are added.

7.4 OQ technology

OQ Technology focuses on NB-IoT-based DtS services, using L-band frequencies and 3GPP-compliant waveforms adapted to address LEO Doppler and extended propagation delay. Its long-term vision is complete integration of satellite NB-IoT into the broader 5G ecosystem.

7.5 Kepler communications

Originally focused on data backhaul, Kepler has expanded its offerings to include narrowband IoT services. Operating S-band spacecraft, the system supports medium-rate IoT messaging and targets industrial and logistics applications requiring high link reliability.

7.6 Hiber

Hiber deployed UHF and L-band narrowband IoT satellites before being acquired and integrated into Astrocast's infrastructure. It represents one of the earliest European efforts in DtS IoT, demonstrating feasibility and providing initial commercial services.

7.7 Apogeo space

Apogeo Space is deploying an Italian constellation of UHF picosatellites targeting low-cost, ultra-low-power IoT terminals. The architecture emphasizes simplicity, minimal terminal requirements, and scalability through multi-plane deployments aimed at reducing revisit times and approaching continuous global service.

7.8 Kinéis (Argos)

Kinéis, evolution of the long-running Argos programme, is deploying a LEO constellation dedicated to global environmental and asset monitoring. The system operates in VHF/UHF with a proprietary narrowband protocol optimized for ultra-low-power terminals used in wildlife tracking, oceanography and scientific missions. Its architecture targets global coverage, low terminal cost and long battery life, leveraging decades of Argos ecosystem deployment.

7.9 Myriota

Myriota operates a constellation of UHF nanosatellites providing direct-to-satellite messaging using a proprietary spread-spectrum protocol. The system employs extremely low-power terminals and an opportunistic uplink scheme enabling very long battery life. It addresses industrial, agricultural and environmental IoT applications requiring delay-tolerant but highly energy-efficient links.

7.10 SatellioT (NB-IoT)

SatellioT focuses on providing direct-to-satellite connectivity using standard 3GPP NB-IoT waveforms. Its LEO architecture aims to minimize modifications on terrestrial NB-IoT devices while ensuring global coverage. The system is aligned with the long-term vision of integrating satellite NB-IoT within the broader 5G ecosystem.

7.11 Echostar mobile (starlink)

Echostar Mobile has provided S-band narrowband IoT services through GEO platforms covering Europe and surrounding regions. These activities were later integrated into a broader portfolio following the acquisition by SpaceX. The GEO architecture offers high availability and reliable messaging despite the intrinsic higher latency.

7.12 Skylo (GEO lease)

Skylo offers IoT connectivity through leased GEO payloads in L/S-band, using a proprietary protocol aligned with 3GPP NTN concepts. The system is designed for very low-cost terminals and integrates with smartphones and terrestrial modules via a cloud-based NTN core. Coverage is currently regional with ongoing expansion plans.

7.13 Iridium SBD

Iridium SBD leverages the LEO cross-linked Iridium NEXT constellation to provide global short-burst messaging services. Operating in L-band, it offers robust low-latency connectivity with rugged terminals widely used in maritime, aviation and critical IoT. It remains one of the most mature and reliable narrowband satellite messaging systems.

7.14 General considerations

Across these constellations, several trends are evident: reliance on small LEO platforms, use of narrowband and energy-efficient waveforms, and increasing interest in standardized protocols (LoRaWAN, NB-IoT) to simplify terminal integration. The market is transitioning from demonstration missions to operational large-scale constellations with improved reliability, reduced latency, and growing alignment with terrestrial IoT standards.

7.15 Summary table

Table 6 summarizes orbit characteristics, frequency bands, waveform choices, and service profiles for the most relevant DtS-IoT constellations.

8 Experimental demonstrations of direct-to-satellite IoT

While large-scale testbeds with many satellites and thousands of devices are still rare, A growing number of in-orbit experiments and controlled field trials have validated the feasibility of DtS-IoT using LoRa, LR-FHSS, NB-IoT, and proprietary narrowband waveforms. These demonstrations are essential to complement simulation studies, providing ground truth on link budgets, Doppler tolerance, timing uncertainties, and real-world access opportunities.

8.1 LoRa and LoRaWAN-based in-orbit experiments

Several CubeSat missions have tested LoRa uplinks from ground devices to LEO spacecraft. The MicroOrbiter-1 mission reported successful LoRa uplinks with received signal strengths between −112 and −127 dBm at altitudes of 450–600 km, even under rapidly varying Doppler conditions (Khamsah et al., 2024). These measurements confirm that CSS modulation remains decodable in space, provided that carrier frequency error and frame duration are properly matched to pass geometry.

Lacuna Space has conducted multiple field campaigns using modified LoRaWAN stacks for LEO, demonstrating two-way messaging with standard LoRaWAN terminals and providing public telemetry datasets used for validation in several simulation studies (Scapin et al., 2024). Results show robust operation at spreading factors up to SF11, with Doppler compensation performed at the gateway side.

Experimental studies of LR-FHSS demonstrate its practicality for real DtS-IoT conditions. Field measurements in urban and semi-urban environments (Mardones et al., 2025) show that LR-FHSS maintains high packet-delivery ratios under interference, mobility, and cluttered propagation, confirming its ability to scale to large device populations. Complementary transceiver-level evaluations (Jung et al., 2025) validate the waveform's Doppler robustness and frequency-hopping resilience through a full hardware implementation and laboratory verification over LEO-like channels.

8.2 NB-IoT NTN and 5G-based trials

NB-IoT has also been experimentally validated in LEO conditions through a combination of laboratory trials, prototype

TABLE 5 Categories of simulation tools used for DtS-IoT analysis.

Tool category	Purpose	Examples
Orbit and coverage simulators	Access windows, visibility, constellation geometry	STK, GMAT, orekit, poliastro
Link-level simulators	Waveform robustness, doppler, link budget	MATLAB/Python, GNU radio, 3GPP PHY models
System/network simulators	MAC behavior, congestion, routing, large-scale traffic	Ns-3, ns-3-leo, OMNeT++, OpenSAND, custom python
Integrated frameworks	End-to-end multi-domain evaluation	Hybrid STK + MATLAB + ns-3, operator tools, ML-based frameworks

TABLE 6 Overview of satellite constellations deployed for DtS-IoT.

Constellation	Orbit	Bands	Waveform/ Standard	Terminal	Coverage	Notes
Swarm (SpaceX)	LEO 450–550 km	UHF	Proprietary narrowband	Ultra-low-power sensors	Global, short revisit	Large picosatellite fleet; very low-cost service
Astrocast	LEO 500–600 km	L-band	Adaptive proprietary NB waveform	Low-power IoT devices	Global, improving	Robust link; constellation expanding
Lacuna space	LEO 500–600 km	ISM	LoRa/LoRaWAN adapted for LEO	LoRaWAN devices	Global	Interoperable with terrestrial LoRaWAN
OQ technology	LEO	L-band	3GPP NB-IoT adapted for LEO	3GPP IoT terminals	Global (ongoing)	5G NTN-oriented architecture
Kepler communications	LEO	S-band	Narrowband IoT protocols	Industrial IoT terminals	Global	Backhaul heritage; now supports NB-IoT
Hiber (Astrocast)	LEO	UHF/ L-band	Proprietary narrowband	Simple sensors	Global (sparse)	Early European system; now part of Astrocast
Apogeo space	LEO picosats	UHF	Proprietary narrowband IoT	Ultra-low-power sensors	Global (expanding)	Italian picosatellite constellation; low-cost
Kinéis (Argos)	LEO	VHF/UHF	Proprietary Argos-based narrowband	Low-power environmental sensors	Global	Evolution of Argos; highly optimized for scientific and tracking payloads
Myriota	LEO nanosats	UHF	Proprietary spread-spectrum IoT	Ultra-low-power sensors	Global (scheduled)	Opportunistic uplink; very long battery life
SatelioT (NB-IoT)	LEO	L-band	3GPP NB-IoT (standard)	Standard NB-IoT terminals	Global (expanding)	Direct-to-satellite NB-IoT with minimal device modifications
Echostar mobile (starlink)	GEO	S-band	Proprietary narrowband	Industrial terminals	Regional (Europe)	GEO IoT services later integrated after acquisition by SpaceX
Skylo (GEO lease)	GEO	L/S-band	Proprietary NTN-oriented protocol	Low-cost IoT terminals	Regional (Asia, expanding)	Cloud-based NTN core; smartphone-oriented IoT
Iridium SBD	LEO	L-band	Short burst data (SBD)	Rugged IoT terminals	Global continuous	Very mature system; cross-linked constellation enables low latency

payloads, and commercial demonstrations. Beacon-aided Doppler pre-compensation achieved synchronization success rates near 89% during 10-min passes in controlled environments (Zhou et al., 2023), confirming the suitability of OFDMA-based narrowband cellular waveforms for DtS operation. OQ Technology has demonstrated end-to-end NB-IoT connectivity over multiple in-orbit campaigns, showing uplink stability and integration with standard 3GPP core networks.

Pre-commercial tests of 5G NTN (Release 17) using airborne platforms and experimental payloads indicate the feasibility of RedCap (Reduced Capability) and New Radio-Light waveforms for hybrid terrestrial-satellite IoT. Though full DtS demonstrations remain limited and highly dependent on terminal power constraints.

8.3 Ground testbeds, hardware impairments, and channel replay

Laboratory testbeds using hardware-in-the-loop setups (e.g., LoRa SX1262 transceivers, NB-IoT development kits) allow controlled emulation of Doppler trajectories, oscillator instability, multipath, and scheduling policies. These platforms have been used to assess:

- Residual frequency offset after hardware Doppler tracking (Subramanian et al., 2023);
- Payload decoding under low SNR and non-ideal chirp orthogonality;

- Packet delivery under ALOHA-like contention with replayed satellite passes;
- Device sleep/wake synchronization with satellite visibility predictions.

Such testbeds bridge the gap between analytic models and on-orbit data, enabling repeatable evaluation of PHY and MAC techniques under realistic impairments.

8.4 Key insights from experimental literature

Existing experiments, although limited in scale, provide several consistent insights:

- Doppler compensation is essential. Hardware tracking and beacon-aided methods significantly improve LoRa and NB-IoT performance.
- Short passes amplify timing uncertainty. Experiments show that precise wake-up scheduling is critical to reduce energy waste and maintain reliability.
- Real devices underperform ideal PHY models. Measured sensitivity, CFO, drift, and burst timing variability degrade performance relative to clean simulations.
- Proprietary systems outperform generic LPWANs. Purpose-built waveforms (Astrocast, Swarm, Apogeo) achieve higher robustness in difficult LEO dynamics.
- Public datasets accelerate reproducibility. Lacuna and MicroOrbiter datasets are widely used to calibrate simulation frameworks.

Overall, experimental results confirm the viability of DtS-IoT and highlight the importance of integrated PHY/MAC design, realistic Doppler modelling, and hardware-aware protocol tuning.

9 Future directions and open challenges

Direct-to-satellite IoT (DtS-IoT) has progressed rapidly thanks to low-cost launch opportunities, the emergence of small-satellite constellations, and the adaptation of terrestrial IoT technologies to non-terrestrial propagation conditions. Despite these advances, several scientific and engineering challenges remain open. They span the physical, link, network, and system layers, and will shape the next-generation of satellite IoT services in terms of reliability, scalability, latency, and energy consumption.

9.1 Physical-layer challenges

Narrowband uplinks from simple sensors to fast-moving LEO satellites remain constrained by Doppler dynamics, link asymmetry, and extremely tight power budgets. While Doppler-resilient waveforms and compensation techniques have been proposed (Ullah et al., 2023; Subramanian et al., 2023; Zhou et al., 2023), their integration into standardized frameworks (e.g., 3GPP NTN) remains incomplete.

Key open problems include:

- Design of ultra-low-complexity Doppler-resilient waveforms suitable for battery-powered nodes;
- Low-power synchronization mechanisms under highly variable elevation angles;
- Interference management and coexistence among multiple constellations sharing L/S/ISM bands;
- Analytical and stochastic Doppler models applicable across satellite geometries (Al-Hourani and Al Homssi, 2024).

9.2 Random access and massive connectivity

DtS-IoT random access is traditionally optimized for sparse traffic and relies on long revisit times to spread contention. As constellations scale and access windows become more frequent, new contention-management strategies will be required.

Open research directions include:

- Contention resolution for extremely uncoordinated traffic and short access windows;
- Collision-aware or visibility-aware scheduling exploiting predicted pass geometries;
- Learning-based access schemes capable of adapting to device density and traffic patterns (Jung et al., 2023; Tondo et al., 2024);
- Probabilistic or coded random access adapted to intermittent coverage.

9.3 Energy efficiency and device lifetime

Most DtS-IoT sensors operate for years without maintenance. While low-duty-cycle transmission helps, further advances are needed to extend device lifetime, especially in remote or harsh environments.

Open research topics include:

- Wake-up strategies synchronized with satellite visibility (Ortigueira et al., 2024);
- Adaptive power control under uncertain link conditions and Doppler variability;
- Tightly integrated PHY/MAC co-design for energy minimization;
- Energy harvesting and long-term battery health modeling.

9.4 Interoperability with terrestrial IoT standards

Although LoRaWAN and NB-IoT adaptations for LEO exist, full interoperability with terrestrial IoT ecosystems remains limited by timing, Doppler, and propagation asymmetries. A

TABLE 7 Summary of open problems and research directions in Direct-to-Satellite IoT.

Challenge area	Key open problems and research directions
Physical layer	Doppler-resilient waveforms; low-power synchronization; interference management; coexistence between constellations; PHY schemes for ultra-low-complexity devices
Random access and massive connectivity	Scalable contention resolution; probabilistic and visibility-aware access; learning-based random access; handling ultra-dense device populations
Energy efficiency and lifetime	Wake-up optimization; energy-aware scheduling; adaptive duty cycles; power control under uncertain conditions; integration of energy harvesting
Interoperability and 3GPP NTN integration	Unified protocol stacks; standardized doppler/timing procedures; transparent mobility; coexistence of LoRaWAN, NB-IoT, and RedCap across terrestrial-satellite domains
Constellation and network management	Scalable constellation design; inter-plane coordination; autonomous orbit maintenance; traffic prediction; on-board intelligence for routing and congestion control
Security and robustness	Lightweight authentication; key management with intermittent visibility; jamming/spoofing resilience; anomaly detection; secure SCHC-compatible frameworks

unified IoT stack spanning terrestrial and non-terrestrial domains is still an open goal.

Important directions include:

- Unified protocol layers supporting seamless mobility across terrestrial and satellite networks;
- Standardized timing and Doppler procedures for NTN within 3GPP (Kodheli et al., 2020);
- Coexistence mechanisms for LoRaWAN, NB-IoT, and 5G RedCap in hybrid deployments (Gedara et al., 2023; Ogbodo et al., 2022);
- Addressing, roaming, and session continuity across heterogeneous infrastructures.

9.5 Constellation design and scalable network management

As IoT constellations grow to dozens or hundreds of satellites, design and management become increasingly complex. Open problems include:

- OPTIMAL selection of orbital planes, altitude, and inter-plane spacing (Capez et al., 2022);
- Dynamic orbit maintenance using miniaturized propulsion and autonomous control;
- Large-scale routing and congestion control using inter-satellite links (ISLs);
- Machine-learning-based prediction of traffic, visibility, and link quality.

These challenges highlight the importance of multi-domain optimization that spans orbital geometry, physical-layer modeling, and large-scale traffic dynamics.

9.6 Security, authentication, and robustness

Security remains underdeveloped in DtS-IoT, particularly due to constrained devices, long round-trip times, and intermittent visibility. Challenges include:

- Uncertainty regarding whether the Static Context Header Compression and Fragmentation (SCHC) standard can effectively function in DtS-IoT environment (Munoz-Lara et al., 2024);
- Jamming and spoofing detection in unlicensed or weakly protected bands;
- Anomaly detection and distributed trust mechanisms for massive device populations;
- Integration of SCHC-compressed IPv6 with secure DTN-style protocols.

9.7 Summary of open research directions

Table 7 summarizes the main open problems across all layers. Each category provides opportunities for innovation in physical-layer design, access protocols, battery-aware algorithms, security frameworks, and large-scale constellation management.

10 Conclusion

This work has presented a tutorial-grade, system-level overview of Direct-to-Satellite IoT (DtS-IoT), guiding readers through core concepts and relevant recent literature. By providing an integrated and up-to-date entry point, the tutorial covers architectural models, constellation configurations, waveform and protocol adaptations, MAC and scalability challenges, simulation methodologies, and emerging research directions. The goal has been to offer a structured introduction to the fundamental engineering principles underlying DtS-IoT, rather than an exhaustive survey of the literature.

DtS-IoT systems have the potential to extend connectivity to regions that remain underserved or completely unconnected, supporting applications in environmental monitoring, logistics, agriculture, maritime observation, and critical infrastructure sensing (Ullo and Sinha, 2020). At the same time, their design introduces a number of open challenges across multiple layers, including Doppler and synchronization issues, scalable medium access during short satellite visibility windows, battery lifetime constraints, coexistence and spectrum management, security and authentication, and integration with terrestrial IoT and 3GPP NTN ecosystems.

Looking ahead, DtS-IoT is expected to play a relevant role within future 6G NTN, where seamless integration of terrestrial, aerial, and satellite segments and global coverage will be key design objectives. In this context, DtS-IoT technologies can be seen as a building block toward 6G NTN visions, potentially benefiting from enhanced support for massive connectivity and improved cross-layer optimization. As research in this field continues to accelerate, progress will likely come from cross-layer approaches that jointly consider waveform design, access schemes, constellation geometry, energy constraints, and system-level management. The references cited throughout this tutorial provide further entry points for exploring these topics in depth and for contributing to the next-generation of global, energy-efficient, and interoperable non-terrestrial IoT systems.

Author contributions

SA: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review and editing. AC: Writing - review and editing, Conceptualization, Investigation. JF: Conceptualization, Investigation, Supervision, Writing – original draft, Writing – review and editing. RG: Conceptualization, Investigation, Supervision, Writing – original draft, Writing – review and editing.

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References

Al-Hourani, A., and Al Homssi, B. (2024). Doppler shift distribution in satellite constellations. *IEEE Commun. Lett.* 28 (9), 2131–2135. doi:10.1109/LCOMM.2024.3434433

Ali, M. M., Hashim, S. J., Chaudhary, M. A., Ferré, G., Rokhani, F. Z., and Ahmad, Z. (2023). A reviewing approach to analyze the advancements of error detection and correction codes in channel coding with emphasis on LPWAN and IoT systems. *IEEE Access* 11, 127077–127097. doi:10.1109/access.2023.3331417

Alvarez, G., Fraire, J. A., Hassan, K. A., Cespedes, S., and Pesch, D. (2022). Uplink transmission policies for LORA-based direct-to-satellite IoT. *IEEE Access* 10, 72687–72701. doi:10.1109/access.2022.3189647

Analytical Graphics, Inc. (AGI), now Ansys (2025). Systems tool kit (stk) – digital mission engineering software. Available online at: https://www.ansys.com/products/missions/ansys-stk (Accessed November 20, 2025).

Bakhtiari, V., Kerchi, H. D., Piadeh, F., Behzadian, K., and Nasirzadeh, F. (2025). Role of the internet of things in flood risk management: a critical review on current practices and future directions. *Nat. Hazards* 121, 19473–19505. doi:10.1007/s11069-025-07589-2

Boquet, G., Tuset-Peiró, P., Adelantado, F., Watteyne, T., and Vilajosana, X. (2021). LR-FHSS: overview and performance analysis. *IEEE Commun. Mag.* 59, 30–36. doi:10.1109/mcom.001.2000627

Bouyedda, A., Barelaud, B., and Gineste, L. (2021). Design and realization of an UHF frequency reconfigurable antenna for hybrid connectivity LPWAN and LPWAN satellite networks. *Sensors* 21, 5466. doi:10.3390/s21165466

Capez Maiolini, G., Henn, S., Fraire, J. A., and Garello, R. (2022). Sparse satellite constellation design for global and regional direct-to-satellite IoT services. *IEEE Trans. Aerosp. Electron. Syst.* 58, 3786–3801. doi:10.1109/taes.2022.3185970

Centenaro, M., Costa, C. E., Granelli, F., Sacchi, C., and Vangelista, L. (2021). A survey on technologies, standards and open challenges in satellite IoT. *IEEE Commun. Surv. and Tutorials* 23, 1693–1720. doi:10.1109/comst.2021.3078433

Chabou, Z., Addaim, A., and Ait Madi, A. (2024). Enhancing performance of slotted aloha protocol for iot covered by constellation low-earth orbit satellites. *Bull. Electr. Eng. Inf.* 13, 4030–4040. doi:10.11591/eei.v13i6.8158

Chen, X., Xu, Z., and Shang, L. (2023). Satellite internet of things: challenges, solutions, and development trends. *Front. Inf. Technol. and Electron. Eng.* 24, 935–944. doi:10.1631/FITEE.2200648

Chippalkatti, V. S., and Biradar, R. C. (2021). Review of satellite based internet of things and applications. *Turkish J. Comput. Math. Educ.* 12, 758–766.

Choquenaira-Florez, A. Y., Ohs, R., Fraire, J. A., and Rivano, H. (2025). "Florasat 2: simulating cross-linked direct-to-satellite IoT LEO constellations," in *2025 12th advanced satellite multimedia systems conference and the 18th signal processing for space communications workshop (ASMS/SPSC)* (IEEE), 1–8.

CS Group and the Orekit Project Team (2025). Orekit: a free low-level space dynamics library. Available online at: https://www.orekit.org/overview.html (Accessed November 20, 2025).

Delkowski, M., Urbonas, J., Eiskowitz, S., Cameron, B. G., Crawley, E. F., Belobaba, P., et al. (2025). Evaluating the strategic intent and competitive dynamics of China's satellite communications constellations. *Aerosp. Sci. Technol.* 10, 1511–1524.

Deng, R., Di, B., Zhang, H., Kuang, L., and Song, L. (2021). Ultra-dense leo satellite constellations: how many LEO satellites do we need? *IEEE Trans. Wireless Communications* 20, 4843–4857. doi:10.1109/twc.2021.3062658

Fraire, J. A., Céspedes, S., and Accettura, N. (2019). "Direct-to-satellite IoT-a survey of the state of the art and future research perspectives: backhauling the IoT through leo satellites," in *International conference on Ad-Hoc networks and wireless* (Springer), 241–258.

Fraire, J. A., Henn, S., Dovis, F., Garello, R., and Taricco, G. (2020). "Sparse satellite constellation design for LORA-based direct-to-satellite internet of things," in GLOBECOM 2020-2020 IEEE global communications conference *(IEEE)*, 1–6.

Fraire, J. A., Iova, O., and Valois, F. (2022a). Space-terrestrial integrated internet of things: challenges and opportunities. *IEEE Commun. Mag.* 60, 64–70. doi:10.1109/mcom.008.2200215

Fraire, J. A., Madoery, P., Ait Mesbah, M., Iova, O., and Valois, F. (2022b). "Simulating lora-based direct-to-satellite iot networks with florasat," in 2022 IEEE 23rd international symposium on a World of wireless, mobile and multimedia networks (WoWMoM) *(IEEE)*, 464–470.

Gedara, C. D., Khattak, M. D., Ullah, M. A., and Mikhaylov, K. (2023). "Direct-to-satellite connectivity for IoT: overview and potential of reduced capability (redcap)," in 2023 IEEE 9th world forum on internet of things (WF-IoT) *(IEEE)*, 1–8.

González, T. N., Salamanca, J. L., Sánchez, S. M., Meza, C. A., and Céspedes, S. (2021). "Analysis of channel models for LORA-based direct-to-satellite IoT networks served by LEO nanosatellites," in *2021 IEEE international conference on communications workshops (ICC workshops)* (IEEE), 1–6.

He, Y., Chen, H., Wang, C., Li, Y., and Niu, Z. (2023). "Challenges and developments of routing techniques for dense LEO constellations," in *Proceedings of the 2023 2nd international conference on networks, communications and information technology*, 122–126.

Jung, S., Jeong, S., Kang, J., Ryu, J. G., and Kang, J. (2023). Transceiver design and performance analysis for LR-FHSS-based direct-to-satellite IoT. *IEEE Commun. Lett.* 27, 3310–3314. doi:10.1109/LCOMM.2023.3325052

Jung, S., Jeong, S., Kang, J., Im, G., Lee, S., Oh, M.-K., et al. (2025). LR-FHSS transceiver for direct-to-satellite IoT communications: design, implementation, and verification. *IEEE Open J. Veh. Technol.* 6, 1920–1942. doi:10.1109/OJVT.2025.3585160

Kassing, S., Bhattacherjee, D., Águas, A. B., Saethre, J. E., and Singla, A. (2020). "Exploring the "internet from space" with hypatia," in *Proceedings of the ACM Internet measurement conference*, 214–229.

Khamsah, N. M. N., Moumni, F., Nobayashi, D., Ikenaga, T., and Cho, M. (2024). "In-orbit performance of lora for internet of things communication on microorbiter-1 satellite," in *2024 IEEE international conference on communication, networks and satellite (COMNETSAT)*, 48–54. doi:10.1109/COMNETSAT63286.2024.10862081

Kodheli, O., Lagunas, E., Maturo, N., Sharma, S. K., Shankar, B., Montoya, J. F. M., et al. (2020). Satellite communications in the new space era: a survey and future challenges. *IEEE Commun. Surv. and Tutorials* 23, 70–109. doi:10.1109/comst.2020.3028247

Koukis, G., Safouri, K., and Tsaoussidis, V. (2024). All about delay-tolerant networking (DTN) contributions to future internet. *Future Internet* 16, 129. doi:10.3390/fi16040129

Laniewski, D., Lanfer, E., and Aschenbruck, N. (2025). Measuring mobile starlink performance: a comprehensive look. *IEEE Open J. Commun. Soc.* (6), 1266–1283. doi:10.1109/OJCOMS.2025.3539836

Le, T. T. T., Hassan, N. U., Chen, X., Alouini, M.-S., Han, Z., and Yuen, C. (2024). A survey on random access protocols in direct-access LEO satellite-based IoT communication. *IEEE Commun. Surv. and Tutorials* 27, 426–462. doi:10.1109/comst.2024.3385347

Ledesma, O., Lamo, P., and Fraire, J. A. (2024). Trends in LPWAN technologies for LEO satellite constellations in the newspace context. *Electronics* 13, 579. doi:10.3390/electronics13030579

Maldonado, D., Fraire, J. A., Ilabaca, P., Rivano, H., and Céspedes, S. (2023). "Network size estimation for LORA-based direct-to-satellite IoT," in *2023 IEEE cognitive communications for aerospace applications workshop (CCAAW)* (IEEE), 1–6. doi:10.1109/CCAAW57883.2023.10219363

Maldonado, D., Kaneko, M., Fraire, J. A., Guitton, A., Iova, O., and Rivano, H. (2025). Enhancing LR-FHSS scalability through advanced sequence design and demodulator allocation. *IEEE Trans. Green Commun. Netw.* 9, 1716–1729. doi:10.1109/TGCN.2025.3570185

Maleki, A., Nguyen, H. H., Bedeer, E., and Barton, R. (2024). Outage probability analysis of LR-FHSS and D2D -aided LR-FHSS protocols in shadowed-rice fading direct-to-satellite iot networks. *IEEE Internet Things J.* 11, 11101–11116. doi:10.1109/JIOT.2023.3329361

Mardones, M. R., Fraire, J. A., Iova, O., Dobler, F., Alphand, O., Donsez, D., et al. (2025). "From the city to the clouds: an experimental performance evaluation of LR-FHSS," in *International conference on distributed computing in smart systems and the internet of things (DCOSS-IoT)*.

Marin-de Yzaguirre, M., Fuste, O., and Ruiz-de Azua, J. A. (2024). Study to integrate delay-tolerant network protocols in IoT LEO constellations for flood prevention. *Acta Astronaut.* 225, 968–977. doi:10.1016/j.actaastro.2024.09.004

Munoz-Lara, R., Céspedes, S., and Diaz, M. (2024). "Schc over DtS-IoT: performance of schc confirmation modes in satellite IoT," in 2024 IEEE 10th world forum on internet of things (WF-IoT) *(IEEE)*, 678–683.

NASA Goddard Space Flight Center (2022). General mission analysis tool (gmat) version r2022a. Available online at: https://software.nasa.gov/software/GSC-19097-1 (Accessed November 20, 2025).

ns-3 Consortium (2025). ns-3: discrete-event network simulator. Available online at: https://www.nsnam.org (Accessed November 20, 2025).

Ogbodo, E. U., Abu-Mahfouz, A. M., and Kurien, A. M. (2022). A survey on 5G and LPWAN-IoT for improved smart cities and remote area applications: from the aspect of architecture and security. *Sensors* 22, 6313. doi:10.3390/s22166313

OMNeT++ Community (2025). Omnet++: discrete event simulator. Available online at: https://omnetpp.org (Accessed November 20, 2025).

OpenSAND Steering Committee (2025). Opensand: a satellite network emulation platform. Available online at: https://www.opensand.org/overview.html (Accessed November 20, 2025).

Ortigueira, R., Fraire, J. A., Becerra, A., Ferrer, T., and Cespedes, S. (2021). RESS-IoT: a scalable energy-efficient MAC protocol for direct-to-satellite IoT. *IEEE Access* 9, 164440–164453. doi:10.1109/access.2021.3134246

Ortigueira, R., Montejo-Sánchez, S., Henn, S., Fraire, J. A., and Céspedes, S. (2024). Satellite visibility prediction for constrained devices in direct-to-satellite IoT systems. *IEEE Sensors J.* 24, 26630–26644. doi:10.1109/jsen.2024.3418728

Osoro, O. B., and Oughton, E. J. (2021). A techno-economic framework for satellite networks applied to low earth orbit constellations: assessing starlink, oneweb and kuiper. *IEEE Access* 9, 141611–141625. doi:10.1109/access.2021.3119634

Poliastro Development Team (2025). Poliastro: python library for astrodynamics and orbital mechanics. Available online at: https://www.poliastro.space (Accessed November 20, 2025).

Queralta, J. P., Gia, T. N., Zou, Z., Tenhunen, H., and Westerlund, T. (2019). Comparative study of LPWAN technologies on unlicensed bands for M2M communication in the IoT: beyond lora and lorawan. *Procedia Comput. Sci.* 155, 343–350. doi:10.1016/j.procs.2019.08.049

Radhakrishnan, R., Edmonson, W. W., Afghah, F., Rodriguez-Osorio, R. M., Pinto, F., and Burleigh, S. C. (2016). Survey of inter-satellite communication for small satellite systems: physical layer to network layer view. *IEEE Commun. Surv. and Tutorials* 18, 2442–2473. doi:10.1109/comst.2016.2564990

Scapin, G. L., Alvarez, G., Quiroga, N., Collado, F., and Fraire, J. A. (2024). "Performance assessment of LORA-WAN DtS-IoT networks: operation modes and server placement," in *2024 IEEE biennial congress of Argentina (ARGENCON)*. IEEE, 1–8.

Schubert, T., Wolf, L., and Kulau, U. (2022). NS-3-LEO: evaluation tool for satellite swarm communication protocols. *IEEE Access* 10, 11527–11537. doi:10.1109/access.2022.3146770

Singh, V., Chakraborty, T., Jog, S., Chabra, O., Vasisht, D., and Chandra, R. (2024). Exploiting satellite doppler for reliable and faster data download in IoT satellite networks. *Getmob. Mob. Comput. Commun.* 27, 11–14. doi:10.1145/3640087.3640091

Subramanian, V., Karunamurthy, J. V., and Ramachandran, B. (2023). "Hardware doppler shift emulation and compensation for LORA LEO satellite communication," in *2023 international conference on IT innovation and knowledge discovery (ITIKD)* (IEEE), 1–6.

Susilo, H. E., and Suryana, J. (2023). "Research on LPWAN direct to satellite IoT: a survey technology and performance on LEO satellite," in *2023 29th international conference on telecommunications (ICT)* (IEEE), 1–7.

Testi, E., and Paolini, E. (2024). Packet collision probability of direct-to-satellite IoT systems. *IEEE Internet Things J.* 12 (2), 1843–1855. doi:10.1109/JIOT.2024.3470113

Tondo, F. A., Souto, V. D. P., Lopez, O. L. A., Montejo-Sanchez, S., Cespedes, S., and Souza, R. D. (2022). Optimal traffic load allocation for ALOHA-based IoT LEO constellations. *IEEE Sensors J.* 23, 3270–3282. doi:10.1109/JSEN.2022.3230796

Tondo, F. A., Afhamisis, M., Montejo-Sánchez, S., López, O. L. A., Palattella, M. R., and Souza, R. D. (2024). Multiple channel LORA-to-LEO scheduling for direct-to-satellite IoT. *IEEE Access* 12, 30627–30637. doi:10.1109/access.2024.3368872

Ullah, M. A., Mikhaylov, K., and Alves, H. (2021). Analysis and simulation of LORAWAN LR-FHSS for direct-to-satellite scenario. *IEEE Wirel. Commun. Lett.* 11, 548–552. doi:10.1109/lwc.2021.3135984

Ullah, M. A., Pasolini, G., Mikhaylov, K., and Alves, H. (2023). Understanding the limits of LORA direct-to-satellite: the Doppler perspectives. *IEEE Open J. Commun. Soc.* 5, 51–63. doi:10.1109/OJCOMS.2023.3337004

Ullah, M. A., Mikhaylov, K., and Alves, H. (2025). Experiment-based models for air time and current consumption of LORAWAN LR-FHSS. *IEEE Internet Things J.* 12 (24), 52621–52631. doi:10.1109/JIOT.2025.3616034

Ullo, S. L., and Sinha, G. R. (2020). Advances in smart environment monitoring systems using IoT and sensors. *Sensors* 20, 3113. doi:10.3390/s20113113

Wang, C., Liu, L., Ma, H., and Xia, D. (2018). "Sl-MAC: a joint TDMA MAC protocol for LEO satellites supported internet of things," in *2018 14th international conference on Mobile Ad-Hoc and sensor networks (MSN)* (IEEE), 31–36.

Wang, C., Liu, L., Ma, H., and Xia, D. (2019). "Lst-MAC: a low-latency hybrid MAC protocol for LEO satellite supported IoT," in *2019 IEEE 25th international conference on parallel and distributed systems (ICPADS)* (IEEE), 480–487.

Zhou, Z., Accettura, N., Prévost, R., and Berthou, P. (2023). "Lightweight synchronization to NB-IoT enabled LEO satellites through doppler prediction," in *2023 19th international conference on wireless and Mobile computing, networking and communications (WiMob)*, 218–223. doi:10.1109/WiMob58348.2023.10187879