Satellite IoT in Practice: A First Measurement Study on Network Availability, Performance, and Costs

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Abstract

Low Earth Orbit (LEO) satellites have emerged as a space-based infrastructure to offer networking services anywhere on Earth. Satellite IoTs enable novel Direct-to-Satellite (DtS) connectivity, allowing IoT devices in remote areas to connect to the Internet via LEO satellites using existing terrestrial technologies like LoRa. This paper presents the first-of-its-kind measurement study on satellite IoTs, investigating the practical characteristics of DtS communications and their suitability for IoT applications. We deployed 27 low-cost ground stations across eight locations worldwide to passively measure the network availability of multiple constellations. Our findings reveal a significant gap between the effective durations of DtS connectivity and their theoretical durations, leading to intermittent connections for satellite IoTs. Additionally, we examine the performance of the Tianqi constellation in supporting real-world IoT traffic (agriculture application). We observed longer delays and higher power consumption in satellite IoTs compared to terrestrial IoTs. Our study identifies the bottlenecks and sheds light on potential optimizations for satellite IoTs.

CCS Concepts

• **Networks → Network measurement**; **Network performance analysis**; *Network services.*

Keywords

Network measurement, Satellite IoT, Direct-to-Satellite connectivity

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1 Introduction

The Internet of Things (IoT) has progressed rapidly over the past decades, with successful applications in various fields. Most IoT systems deploy terrestrial infrastructure, specifically IoT gateways, to serve numerous sensors/actuators installed on-site. These gateways provide low-power, low-cost network access for IoT end devices and require backhaul networking infrastructure, such as wired or cellular networks, to connect end devices to the Internet. Despite their successes, the terrestrial IoT market has reached saturation. It faces challenges in expanding to areas like remote farms, forest fire alarms, and ocean observatories, where there is a pressing need for IoT solutions. However, the lack of backhaul Internet infrastructure (wired network, LTE, and 5G) poses a significant obstacle in these scenarios.

Driven by recent advancements in Low Earth Orbit (LEO) satellite networks [5, 15], companies like SWARM [1], FOSSA [3], and Tianqi [6] start operating LEO satellites as space-based infrastructure to facilitate IoT connectivity anywhere on the planet. Unlike geostationary (GEO) satellites, which are 36,000 km away and require expensive specialized ground stations for space-ground communications, LEO satellites operate at altitudes between 200 km and 2,000 km. These altitudes can be reached directly using IoT technologies like NB-IoT [30, 31] and LoRa [13, 26], thus enabling a novel paradigm of *Direct-to-Satellite (DtS) IoT connectivity.* In DtS, IoT devices on the ground transmit data directly to overhead satellites, which serve as gateways. The satellites carry the received data and forward it to the ground when flying over ground stations that have backhaul connections to the Internet. Benefiting from the fast orbit traveling of LEO satellites, a small constellation of a few hundred satellites and tens of terrestrial ground stations can provide global coverage effectively. The IoT industry is increasingly embracing LEO satellites as a cheaper complementary solution to terrestrial IoT connections, potentially pushing the boundaries of IoT development and applications to new heights.

Despite its promising potential, LEO satellite IoT remains in its infancy. Some major issues concerning the IoT community are: How does the DtS model of satellite IoT perform in practice? Can a space-based infrastructure deliver network performance that fulfills the requirements for IoT connectivity? To answer these questions, this paper presents the first comprehensive measurement study on LEO satellite IoT in the wild, with a particular emphasis on assessing how well their practical performance aligns with IoT requirements.

LEO satellite IoTs share some common characteristics with the existing satellite systems for broadband Internet services such as Starlink [25] and OneWeb [18], particularly regarding satellite orbiting motions, Doppler effects, link variations, and weather impacts, which have been addressed in recent measurement studies [9, 14, 16, 17]. In contrast, our study focuses on the unique network characteristics of LEO satellites in supporting IoT traffic. Unlike Internet traffic, which requires low latency and high throughput to ensure Quality of Experience (QoE) for users, IoT communications typically prioritize low cost in terms of battery consumption and data charges over traffic delays. Additionally, the DtS techniques in satellite IoTs differ from those of satellite Internet and, for compatibility reasons, typically use existing terrestrial IoT technologies featuring narrow bandwidth and low data rates. For instance, most operational satellite IoTs employ LoRa for DtS links, where the bandwidth is a few hundred kilohertz, and a single transmission can last for hundreds to thousands of ms. How terrestrial IoT technologies perform over DtS links with practical LEO satellite settings (*e.g.*, Doppler effects, link dynamics) remains unknown to the community, necessitating a systematic measurement study.

In this paper, we conduct in-depth investigations to characterize the network availability, reliability, cost, and energy performance of satellite IoTs. We built a low-cost, tiny ground station using off-the-shelf modules to passively receive signals from LEO IoT satellites that use LoRa (400–450 MHz) for DtS communications. We deployed 27 ground stations across eight locations on four continents (Asia, Europe, Australia, and North America). We received Beacons from 39 satellites across four constellations (*i.e.*, Tianqi, FOSSA, PICO, and CSTP). Our measurements span over six months and collect 121,744 packet traces, from which we examine the global accessibility of satellite IoTs.

To complement the passive measurements, we conducted a one-month active measurement using three satellite IoT nodes from Tianqi, the largest commercial satellite IoT operator. We installed the Tianqi nodes in a remote farmland to regularly monitor and upload agricultural data through the Tianqi constellation. We compare the practical performance of satellite IoT against terrestrial IoT in terms of reliability, latency, energy consumption, and cost.

Our measurements confirm that LEO satellites enable ubiquitous IoT connectivity globally. However, existing constellations only provide intermittent services. We observed high Beacon losses over the DtS links, significantly reducing the effective duration of each contact with a constellation to less than 20% of their theoretical durations. This can impact strategy designs, including transmission scheduling, collision management, and congestion control for satellite IoTs. Compared to terrestrial IoTs, satellite IoTs save on infrastructure construction costs but incur higher data charges and suffer from 643.6× longer delays, and 14.9× greater battery drain. The intermittent contact windows and lossy DtS links serve as the major performance bottleneck. Our study calls for a specific focus on optimizing communication for DtS.

2 Background and Methodology

2.1 LEO Satellite as IoT Gateway

The industry is expanding the use of LEO satellites to offer global network connectivity for IoTs. Unlike satellites for Internet services, which require expensive high-end hardware, IoT satellites are built from a low price point, typically of small size, and use simple hardware such as dipole antennas with no beamforming capabilities or inter-satellite links. As of December 2024, over 2,500 nano-satellites have been launched [2], and IoT ranks as the top application for those satellites [11]. Companies like SWARM (SpaceX), FOSSA, Tianqi, and Lacuna are leading this satellite IoT trend.

Figure 1 illustrates the architecture of a typical satellite IoT system. Satellites and terrestrial Ground Stations (GS) form a backbone. Ground stations download data from satellites and forward it to subscribers via the Internet. A Satellite Network Operator (SNO) may build specialized ground stations and use mature technologies (*e.g.*, Ka and Ku bands) for satellite-to-GS communications. Alternatively, a low-cost distributed ground station architecture [23, 24, 29] is increasingly being adopted. The satellites are mounted with gateway transceivers and orbit the Earth to serve as access points for IoT devices on the ground. Satellite IoTs support Direct-to-Satellite (DtS) communications from IoT devices using terrestrial IoT technologies such as LoRa. This enables prevalent plug-and-play deployment of IoT devices even in remote areas lacking terrestrial backhaul. End users can simply install IoT devices on-site, turn them on, and connect to the overhead satellite for data service. A LEO satellite passes over a given spot several times a day, with each pass lasting around 10 minutes. A constellation of many satellites is required to provide global coverage.

2.2 Global Measurements across Multiple Constellations

We have developed a testbed for measurement experiments based on an open platform TinyGS [27]. TinyGS offers open-source hardware and software for setting up a ground station to directly receive signals from LEO satellites that utilize LoRa for DtS links. The hardware comprises affordable and versatile off-the-shelf modules (*e.g.*, ESP32 board, LoRa SX126x radio) with a cost of approximately 30 US dollars. TinyGS employs a crowd-sourced approach, enabling global enthusiasts to deploy ground stations and voluntarily contribute data. As of April 2025, over 1,800 active ground stations are distributed worldwide, and 2,276 satellites from 11 constellations are compatible with TinyGS [27]. The DtS links of these satellites operate in sub-GHz unlicensed ISM bands (*e.g.*, 137 MHz, 433 MHz, 868 MHz). Similar to terrestrial LoRa gateways, these satellites periodically broadcast Beacons. TinyGS ground stations receive these

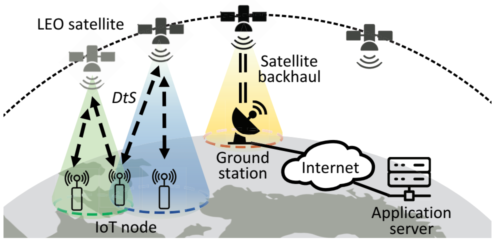


Figure 1: Satellite IoT Architecture.

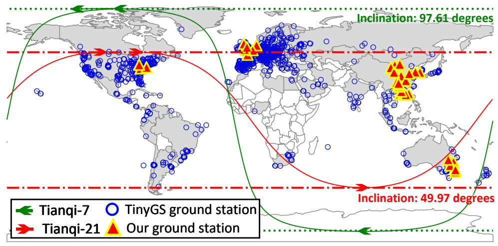


Figure 2: Measurement node map.

City	# GS	Start time	# Traces
PGH	3	2025/02	15,612
LDN	5	2025/02	799
SH	2	2024/10	2,731
GZ	2	2024/09	18,488
SYD	4	2025/01	15,258
HK	6	2024/09	31,330
NC	1	2024/11	328
YC	4	2024/09	37,198

Table 1: Dataset overview.

Beacons, from which packet timestamps, RSSI, SNRs, and metadata of the sender satellite, including altitude, elevation angle, and Doppler frequency shift, can be extracted. We use the information extracted from received Beacons to passively measure characteristics of network availability, such as the presence and duration of DtS connectivity for satellite IoTs.

However, a practical issue with the vanilla TinyGS is that the assignment of which ground station listens to which satellite is determined by an internal scheduling algorithm, which is not accessible to us. It prevents us from precisely identifying the network availability of a specific constellation. To mitigate the problem, we replaced TinyGS's scheduling algorithm with a customized scheduler that allows manual assignment of ground stations to the satellites of interest. The customized scheduler tracks the real-time locations of satellites and schedules ground stations in advance to work with the target satellite's DtS frequency and Beacon parameters. This enables us to precisely measure the starting and ending points of a satellite's contact window when it flies over.

We have deployed 27 ground stations across 8 selected locations worldwide, as shown in Figure 2. The measurement sites are located across different latitudes and longitudes with diverse climate conditions, which ensures our measurements have good representativeness of satellite IoT service in major areas on Earth.The ground station hardware uses the LILYGO board embedded with an SX1262 LoRa radio operating in 400–450 MHz. Eight constellations with 68 satellites operate in this spectrum. Our measurements span seven months, from September 2024 to March 2025, during which we collected over 121,744 packet traces in total. A brief overview of our dataset is summarized in Table 1.

2.3 Active Measurements with Tianqi Constellation

While passive measurements offer insights into the global network accessibility of satellite IoTs, they do not provide information on end-to-end delays and DtS power characteristics. Obtaining such data requires IoT devices on the ground to actively send data using a satellite IoT infrastructure. To complement the passive measurements, we have acquired equipment and data services from Tianqi, a Chinese satellite IoT operator. We conducted active measurements with the Tianqi constellation to comprehensively investigate the network characteristics of satellite IoTs.

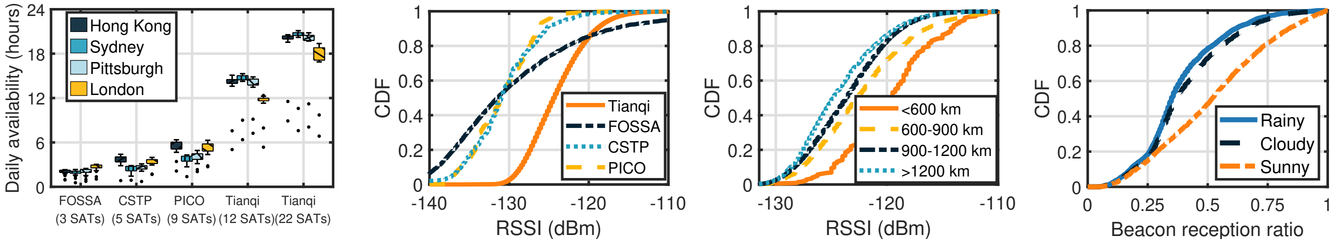
The Tianqi constellation consists of 22 satellites orbiting Earth at altitudes ranging from 441.9 km to 897.5 km. Tianqi operates 12 large ground stations, all located in China. Figure 7 in Appendix B displays Tianqi's standard IoT device (termed *Tianqi node*) for DtS communications. It is embedded with a commercial 400 MHz LoRa radio without dedicated hardware or software design. A Tianqi IoT node monitors for Tianqi satellites flying overhead. Upon receiving Beacons from a satellite, the node sends IoT data directly to the satellite. The data is later transferred from the orbital satellites to Tianqi's data center when a Tianqi ground station is within range, and finally forwarded to subscriber users via the Internet. We deployed three battery-powered Tianqi nodes in a coffee plantation in Yunnan, China (see detailed setup in Appendix B).

3 Measurement Results

3.1 Network Availability

This section explores the prevalence of IoT connectivity provided by LEO satellite constellations. We use a passive measurement dataset collected with our customized TinyGS platform. Specifically, we analyze the top four most active constellations operating in the 400–450 MHz bands: Tianqi from China, PICO from the US, FOSSA from the EU, and CSTP from Russia. We examine the measurement data of these constellations across four continents: Hong Kong (Asia), Sydney (Australia), London (Europe), and Pittsburgh (North America). An overview of the data is summarized in Table 3. Our primary focus is on whether existing LEO constellations can offer IoT connectivity anytime, anywhere. We investigate the characteristics and major factors impacting the time windows of contact with these satellite constellations.

Global Accessibility. We examine the availability of IoT satellites across various locations on Earth to determine if a constellation delivers effective global services. We first assess the time duration that a constellation is available for a specific location. Note that an LEO satellite flies over a spot multiple times a day, and each pass can have different azimuth and elevation angles with varying durations. To this end, we use the Two-Line Element (TLE) data of our targeted constellation satellites to track their orbiting trajectories. A TLE file contains the orbital parameters of a satellite, which are used by prediction algorithms such as the simplified perturbations models (*e.g.*, SGP8/SDP8 [28]) to project the position and velocity of satellites. We input the orbital parameters of the four constellations' satellites collected from one month's traces into the



(a) Time duration of satellite presence across different locations **(b) Signal strength of different constellations** **(c) Tianqi signal strength vs. satellite distance** **(d) Beacon reception performance per contact of Tianqi**

Figure 3: Global accessibility of IoT constellations and impacting factors (constellation size, distance, and weather).

prediction algorithms to theoretically calculate the daily presence duration for each satellite. By aggregating all satellites, we obtain the daily duration of a constellation and display their statistics in Figure 3a.

The results show that the availability duration of a constellation remains relatively stable across the four locations, and a larger constellation size generally contributes to longer daily durations. For instance, the FOSSA constellation has only three satellites operating at 433 MHz, providing services to a spot for only 1.1~3.0 hours per day. In comparison, the daily duration of PICO (nine satellites) is 5.7 hours. The availability of Tianqi improves from 13.4 hours to 19.1 hours while the number of active satellites increases from 12 to 22.

We further investigate the quality of network services provided by satellite constellations, indicated by the signal strength of satellites, which can be extracted from the RSSI of Beacon frames received by our TinyGS hardware. As shown in Figure 3b and Figure 3c, signals from LEO satellites are typically of low strength, *e.g.*, -140 dBm to -110 dBm, due to power fading over distant transmissions. Although LoRa employs optimized designs to enhance weak signal receptions, high reception failures can still be observed. For instance, >50% of the Beacons are dropped for Tianqi even on sunny day, as shown in Figure 3d.

Per-Constellation Contact Window. To investigate the practical communication opportunities of satellite IoTs, we perform detailed examinations of the constellations' contact windows, during which a satellite flies over a spot and communicates with ground devices. For each constellation, we assess *the theoretical duration* and *the effective duration* of every contact window. The theoretical duration is calculated from the TLE data of satellites and describes how long a satellite stays in overhead orbit visible to a ground station. The effective duration is calculated from our measurement data as the time span between the first and the last received Beacons within a contact window, indicating how long a ground IoT device can effectively communicate with the overhead satellite. The results are presented in Figure 4a.

Surprisingly, the effective durations of contact windows are observed to be shorter than the theoretical durations by 73.70%–89.23% across all constellations. An in-depth investigation reveals that DtS links experience high packet losses at the beginning and end of a contact window, primarily due to small elevation angles and long communication distances with the satellite (see Figure 9 in Appendix C). Consequently, the time intervals between two contacts with a constellation are enlarged by 6.1–44.9 times longer than theoretical values, as shown in Figure 4b. The aggregated daily contact duration of a constellation shrinks by 85.74%–92.20%. For instance, the daily availability of the Tianqi constellation is 18.5 hours in theory, but the effective duration is only 1.8 hours, with each contact lasting for 3.8 minutes and the contact intervals averaging 15.6 minutes.

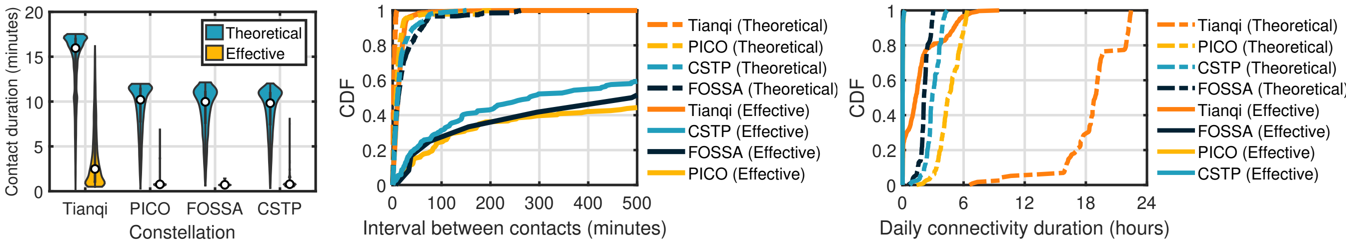
Regarding the intermittent connections with a constellation, a store-and-forward data transmission paradigm is necessary for satellite IoTs. In this paradigm, IoT data is stored in a local buffer while waiting for a satellite to pass by. The buffer size should be determined based on the duration and interval characteristics of a constellation's contact windows. Additionally, since a satellite's footprint covers thousands of km^2 with many IoT devices deployed, bursty concurrent communications from numerous devices can be expected when a satellite flies over. This imposes pressure on the processing capacity and capabilities of the satellite. For constellations with insufficient satellite numbers or processing capabilities, high packet losses may occur due to collisions, satellite resource constraints, or congestion.

Takeaways. Existing LEO constellations for IoTs do not provide continuous, all-hour networking services. The effective service time of a constellation is 85.9% shorter than theoretical numbers due to weak signals and high packet losses over DtS links. The intermittent characteristics of satellite connections necessitate collision management and congestion control strategies for satellite IoTs.

3.2 Tianqi for Agriculture Application

This section evaluates the practical performance of satellite IoT in supporting real-world traffic for an agriculture application (*i.e.*, coffee plantation environment monitoring). In our application, on-site sensors generate 20-byte data every 30 minutes. We installed three Tianqi nodes to transfer sensory data to an Internet server through the Tianqi satellite constellation. For comparative studies, we also deployed a terrestrial LoRaWAN consisting of three RAKwireless gateways using LTE for backhaul connections with the Internet. We compare the terrestrial and satellite IoT systems in terms of application-layer data reliability, latency, energy consumption, and costs.

End-to-End Performance. Figure 5a compares the end-to-end packet reliability of terrestrial and satellite IoT systems. By default, retransmission is disabled in both systems. The terrestrial LoRaWAN system achieves nearly 100% reliability, whereas Tianqi



(a) Contact window durations **(b) Contact window intervals** **(c) Effective connectivity time**

Figure 4: Characteristics of constellation contact windows: the effective duration of a contact window is significantly shorter than the theoretical duration, resulting in intermittent connections.

averages 91% reliability. An in-depth analysis of Tianqi's log data reveals that most packet losses occur at the DtS links. We then configure the Tianqi nodes to allow a maximum of five retransmissions for DtS. This adjustment significantly improves reliability, reaching up to 96%, as shown in Figure 5a.

Figure 5b displays the DtS retransmission times of packets under different weather conditions and antenna types. The 5/8 wavelength antenna under sunny conditions achieves the best performance. More retransmissions are observed with 1/4 wavelength antennas and rainy days. Notably, around 50% of the packets are received without DtS retransmission, whereas Figure 5a shows that the end-to-end reliability without retransmissions exceeds 90%. These contradicting results are caused by the failure of ACK messages, which are transmitted by a satellite to confirm received packets (*i.e.*, ACK loss over DtS links causes unnecessary retransmissions).

Figure 5c examines the end-to-end latency, measured as the time elapsed from when data is generated by sensors to when it is received by our server. The Tianqi system exhibits an average latency of 135.2 minutes—remarkably, this is 643.6 times longer than that of the terrestrial IoT system, which averages just 0.2 minutes. Figure 5d further decomposes the latency within the Tianqi system into three segments: (1) *waiting for a satellite pass*, (2) *DtS (re)transmissions*, and (3) *Tianqi delivery via satellite-to-GS and terrestrial backhaul*. The average delays for the three segments are 55.2 minutes, 10.4 minutes, and 56.9 minutes, respectively.

Energy Consumption. To meet the low-power requirements of IoT applications, Tianqi IoT nodes introduce three operating modes: remaining in sleep mode for power saving, where only the Microcontroller Unit (MCU) stays in operation, and switching to active mode for Transmit (MCU+Tx) or Receive (MCU+Rx) only when necessary. Figure 6a - 6c plot the power consumption, hang-on time, and accumulated battery drain of a Tianqi node across these three modes. Compared to the power profile of a terrestrial LoRa node (see Figure 10 in Appendix D), a satellite IoT node consumes 2.2 times more power to enable Transmit for DtS. Additionally, the Tianqi node spends 39.4% more time and incurs 31.2% greater overall battery drain in radio active (MCU+Rx) mode. This is because satellites move rapidly, which requires a node to keep its Rx radio on while waiting for a satellite pass, and thus enables a quick switch to transmit mode. In contrast, terrestrial IoT nodes do not face such constraints and can implement additional operating modes (*e.g.*, Standby and Rx, as detailed in Appendix D) to further optimize power consumption. As estimated in Figure 6d, a 5,000 Ampere-hour battery can only power a Tianqi node for 48 days, compared to 718 days for a terrestrial IoT node.

Cost Assessment. Table 2 compares the expenditures of our terrestrial and satellite IoT systems in terms of network construction and monthly operational costs. For satellite IoT, a satellite IoT node (*i.e.*, the Tianqi IoT node) is required, with each unit costing 220 USD. In contrast, terrestrial IoT construction involves both end-node and gateway installations, costing 35 USD per end-node and 219 USD per gateway, respectively. The two IoT paradigms differ in data pricing models. Tianqi adopts a per-packet billing scheme, charging 16.5 USD per thousand packets, with each packet carrying up to 120 bytes. In our application, each sensor generates 48 packets per day, resulting in a monthly cost of 23.76 USD per sensor. For terrestrial IoT, an LTE data plan from China Mobile is utilized to empower backhaul connectivity between gateways and the Internet. This plan provides 42 Mbps of bandwidth at a monthly cost of 4.9 USD.

Takeaways. The Tianqi constellation achieves over 90% packet delivery reliability, but with hour-level latency. The DtS communication leads to heavy battery drain, primarily due to the extended active duration of the radio while waiting for satellite passes and the high power consumption required for DtS transmissions. Our study highlights the need for improvements in energy efficiency and operational cost to enable the large-scale, practical adoption of satellite IoT.

4 Related Work

While there is a rich body of measurement studies on LEO satellite Internet, few studies are available on investigating the characteristics of satellite IoTs. Our paper addresses this knowledge gap by presenting multifaceted measurements on LEO satellite IoTs, with a specific focus on the different network requirements between Internet and IoT traffic.

Existing measurement studies on satellite Internet primarily investigate latency and throughput performance. [10] analyzed connection bandwidth and path delays for Starlink, Kuiper, and Telesat through simulations. [16] examined transport protocols (TCP and QUIC) over Starlink connections by using real-world measurements from a single vantage point. Kassem *et al.* [9] created a browser extension to study the web page loading time of Internet connections over Starlink. Ma *et al.* [14] conducted measurements with Starlink in Canada to explore end-to-end latency and throughput characteristics across various terrains and weather

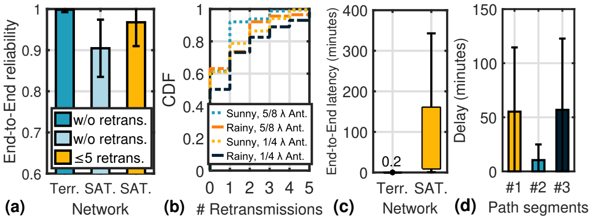


Figure 5: Terrestrial IoT vs. Satellite IoT: (a) reliability, (b) DtS retransmissions under varying weather and antenna conditions, (c) latency; and (d) path delays.

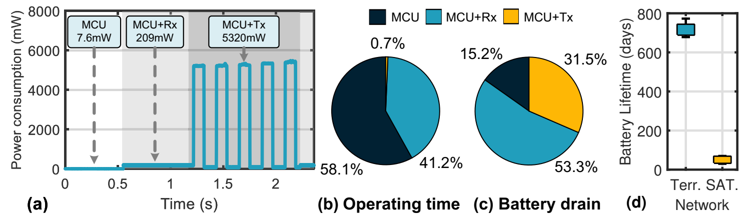


Figure 6: Tianqi node energy performance: (a) power consumption, (b) operating time, and (c) battery drains across different working modes, (d) battery lifetime of terrestrial node vs. satellite IoT node.

Network	Device cost	Infrastructure cost	Operational cost
Terrestrial IoT	$35 per unit	$219 per gateway	$4.9 per month
Satellite IoT	$220 per unit	–	$23.76 per month

Table 2: System expenditure comparison.

conditions. [17] presented a longitudinal study of Starlink to assess its performance in supporting real-time web applications such as video conferencing and cloud gaming. [8, 19] performed large-scale measurements on LEO satellite networks using worldwide crowd-sourced public datasets. However, none of these studies addressed the characteristics of satellite IoTs.

A few pioneering studies have incorporated measurements of specific aspects of satellite IoTs. For example, the Doppler effects due to the orbital movement of LEO satellites and their implications on LoRa-based IoT communications are reported in [4, 22–24]. [20] revealed the spatial and temporal variation characteristics of Direct-to-Satellite (DtS) IoT links using measurements with SpaceX's SWARM devices. [21] demonstrated that traditional MAC mechanisms cannot mitigate collisions among distant IoT nodes spanning the large footprint of an LEO satellite and presented a new MAC paradigm to coordinate constellation-wide communications. Heine *et al.* [7] conducted a latency analysis of SpaceX's SWARM IoT constellation. To the best of our knowledge, we are the first to perform systematic measurements to study whether or not LEO satellite networks can satisfy the core requirements of IoT.

5 Conclusion

In this paper, we conduct both passive and active measurements with satellite IoTs in the wild, providing insights from global network connectivity down to the performance of satellite IoT nodes deployed in a real-world application. We demonstrate that existing IoT satellite constellations can provide network connectivity worldwide. However, the DtS connections exhibit intermittent characteristics. Our real-world case study reveals that while the satellite-based solution generally meets IoT requirements, it produces lower reliability, longer delays, and higher power consumption than terrestrial IoTs.

Limitations and Future Work: Given the limited time between the commercial operation of the Tianqi constellation (launched in Q1 2025) and this study, our active measurements with Tianqi nodes are still in the early stages. Our study identifies the prolonged contact intervals and lossy DtS links as performance bottlenecks for satellite IoTs and calls for optimization of DtS communications. In practice, DtS packet losses can be attributed to many factors, including ultra-low SNRs, interference, packet collisions, congestion, resource constraints, or hardware incapability. More measurements and in-depth investigations are required to identify the key impacting factors and find potential improvement solutions.

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References

[1] eoPortal Directory. 2025. *Swarm (Geomagnetic LEO Constellation)*. Retrieved Apr 9, 2025 from https://directory.eoportal.org/satellite-missions/swarm

[2] Erik Kulu, Nanosats. 2025. *World's largest database of nanosatellites,over 4400 nanosats and CubeSats*. Retrieved Mar 15, 2025 from https://www.nanosats.eu/

[3] FOSSA Systems. 2025. *SATELLITE IOT: Empowering global industries with accessible IoT and Space Technologies, boosting sustainability and operational efficiency*. Retrieved Apr 10, 2025 from https://fossa.systems/

[4] Akshay Gadre, Zachary Machester, and Swarun Kumar. 2024. Adapting LoRa Ground Stations for Low-latency Imaging and Inference from LoRa-enabled CubeSats. *ACM Trans. Sen. Netw.* 20, 5, Article 102 (July 2024), 30 pages. doi:10.1145/3675170

[5] Grand View Research. 2025. *LEO Satellite Market Size, Share & Trends Analysis Report By Satellite Mass, By Frequency Band, By Propulsion Type, By Application, By End-use, By Region, And Segment Forecasts, 2024 - 2030*. Retrieved Apr 10, 2025 from https://www.grandviewresearch.com/industry-analysis/leo-satellite-market-report

[6] Guodian Gaoke. 2025. *Tianqi Constellation Introduction*. Retrieved Apr 10, 2025 from http://www.guodiangaoke.com/web/dist/index.html#/tianqixingzuo

[7] Simon Heine, Christian Hofmann, and Andreas Knopp. 2023. End-to-end latency evaluation of LEO satellite IoT systems. In *IET Conference Proceedings CP873*, Vol. 2023. IET, 216–221.

[8] Liz Izhikevich, Manda Tran, Katherine Izhikevich, Gautam Akiwate, and Zakir Durumeric. 2024. Democratizing LEO Satellite Network Measurement. *SIGMETRICS Perform. Eval. Rev.* 52, 1 (June 2024), 15–16. doi:10.1145/3673660.3655052

[9] Mohamed M. Kassem, Aravindh Raman, Diego Perino, and Nishanth Sastry. 2022. A browser-side view of starlink connectivity. In *Proceedings of the 22nd ACM Internet Measurement Conference* (Nice, France) *(IMC '22)*. Association for Computing Machinery, New York, NY, USA, 151–158. doi:10.1145/3517745.3561457

[10] Simon Kassing, Debopam Bhattacherjee, André Baptista Águas, Jens Eirik Saethre, and Ankit Singla. 2020. Exploring the "Internet from space" with Hypatia. In *Proceedings of the ACM Internet Measurement Conference* (Virtual Event, USA)

(IMC '20). Association for Computing Machinery, New York, NY, USA, 214–229. doi:10.1145/3419394.3423635

[11] Erik Kulu. 2024. Satellite Constellations—2024 Survey, Trends and Economic Sustainability. In *Proceedings of the International Astronautical Congress, IAC, Milan, Italy*. 14–18.

[12] LautOS. 2025. *IoT Power - CC*. Retrieved Apr 12, 2025 from https://wiki.luatos.org/iotpower/cc/index.html

[13] Jansen C. Liando, Amalinda Gamage, Agustinus W. Tengourtius, and Mo Li. 2019. Known and Unknown Facts of LoRa: Experiences from a Large-Scale Measurement Study. *ACM Trans. Sen. Netw.* 15, 2, Article 16 (feb 2019), 35 pages. doi:10.1145/3293534

[14] Sami Ma, Yi Ching Chou, Haoyuan Zhao, Long Chen, Xiaoqiang Ma, and Jiangchuan Liu. 2023. Network Characteristics of LEO Satellite Constellations: A Starlink-Based Measurement from End Users. In *IEEE INFOCOM 2023 - IEEE Conference on Computer Communications*. 1–10. doi:10.1109/INFOCOM53939.2023.10228912

[15] MarketsandMarkets. 2025. *Low Earth Orbit Satellite Market by Type (Small, Medium, Large), Subsystem (Payload, Structure, Telecommunication, On-board Computer, Power System, Attitude Control, Propulsion), Application, End User and Region - Global Forecast to 2029*. Retrieved Apr 10, 2025 from https://www.marketsandmarkets.com/Market-Reports/leo-satellite-market-252330251.html

[16] François Michel, Martino Trevisan, Danilo Giordano, and Olivier Bonaventure. 2022. A first look at starlink performance. In *Proceedings of the 22nd ACM Internet Measurement Conference* (Nice, France) *(IMC '22)*. Association for Computing Machinery, New York, NY, USA, 130–136. doi:10.1145/3517745.3561416

[17] Nitinder Mohan, Andrew E. Ferguson, Hendrik Cech, Rohan Bose, Prakita Rayyan Renatin, Mahesh K. Marina, and Jörg Ott. 2024. A Multifaceted Look at Starlink Performance. In *Proceedings of the ACM Web Conference 2024* (Singapore, Singapore) *(WWW '24)*. Association for Computing Machinery, New York, NY, USA, 2723–2734. doi:10.1145/3589334.3645328

[18] OneWeb. 2025. *Delivering LEO connectivity for new network solutions*. Retrieved Apr 10, 2025 from https://oneweb.net/

[19] Aravindh Raman, Matteo Varvello, Hyunseok Chang, Nishanth Sastry, and Yasir Zaki. 2023. Dissecting the Performance of Satellite Network Operators. *Proc. ACM Netw.* 1, CoNEXT3, Article 15 (Nov. 2023), 25 pages. doi:10.1145/3629137

[20] Yidong Ren, Amalinda Gamage, Li Liu, Mo Li, Shigang Chen, Younsuk Dong, and Zhichao Cao. 2024. SateRIoT: High-performance Ground-Space Networking for Rural IoT. In *Proceedings of the 30th Annual International Conference on Mobile Computing and Networking*.

[21] Jayanth Shenoy, Om Chabra, Tusher Chakraborty, Suraj Jog, Deepak Vasisht, and Ranveer Chandra. 2024. CosMAC: Constellation-Aware Medium Access and Scheduling for IoT Satellites. In *Proceedings of the 30th Annual International Conference on Mobile Computing and Networking* (Washington D.C., DC, USA) *(ACM MobiCom '24)*. Association for Computing Machinery, New York, NY, USA, 724–739. doi:10.1145/3636534.3690657

[22] Vaibhav Singh, Tusher Chakraborty, Suraj Jog, Om Chabra, Deepak Vasisht, and Ranveer Chandra. 2024. Spectrumize: Spectrum-efficient Satellite Networks for the Internet of Things. In *21st USENIX Symposium on Networked Systems Design and Implementation (NSDI 24)*. USENIX Association, Santa Clara, CA, 825–840. https://www.usenix.org/conference/nsdi24/presentation/singh-vaibhav

[23] Vaibhav Singh, Akarsh Prabhakara, Diana Zhang, Osman Yağan, and Swarun Kumar. 2021. A community-driven approach to democratize access to satellite ground stations. In *Proceedings of the 27th Annual International Conference on Mobile Computing and Networking* (New Orleans, Louisiana) *(MobiCom '21)*. Association for Computing Machinery, New York, NY, USA, 1–14. doi:10.1145/3447993.3448630

[24] Vaibhav Singh, Osman Yağan, and Swarun Kumar. 2022. SelfieStick: Towards Earth Imaging from a Low-Cost Ground Module Using LEO Satellites. In *2022 21st ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN)*. 220–232. doi:10.1109/IPSN54338.2022.00025

[25] Starlink. 2025. *HIGH-SPEED INTERNET AROUND THE WORLD*. Retrieved Apr 10, 2025 from https://www.starlink.com/

[26] Zehua Sun, Huanqi Yang, Kai Liu, Zhimeng Yin, Zhenjiang Li, and Weitao Xu. 2022. Recent Advances in LoRa: A Comprehensive Survey. *ACM Trans. Sen. Netw.* (jun 2022). https://doi.org/10.1145/3543856 Just Accepted.

[27] TinyGS. 2025. *Unleash Your Inner Explorer: Build a Tiny Ground Station and Help Secure Our Space Future*. Retrieved Apr 10, 2025 from https://tinygs.com/

[28] David Vallado, Paul Crawford, Ricahrd Hujsak, and TS Kelso. 2006. Revisiting spacetrack report# 3. In *AIAA/AAS astrodynamics specialist conference and exhibit*. 6753.

[29] Deepak Vasisht, Jayanth Shenoy, and Ranveer Chandra. 2021. L2D2: low latency distributed downlink for LEO satellites. In *Proceedings of the 2021 ACM SIGCOMM 2021 Conference* (Virtual Event, USA) *(SIGCOMM '21)*. Association for Computing Machinery, New York, NY, USA, 151–164. doi:10.1145/3452296.3472932

[30] Y.-P. Eric Wang, Xingqin Lin, Ansuman Adhikary, Asbjorn Grovlen, Yutao Sui, Yufei Blankenship, Johan Bergman, and Hazhir S. Razaghi. 2017. A Primer on 3GPP Narrowband Internet of Things. *IEEE Communications Magazine* 55, 3 (2017), 117–123. doi:10.1109/MCOM.2017.1600510CM

[31] Deliang Yang, Xianghui Zhang, Xuan Huang, Liqian Shen, Jun Huang, Xiangmao Chang, and Guoliang Xing. 2020. *Understanding Power Consumption of NB-IoT in the Wild: Tool and Large-Scale Measurement.* Association for Computing Machinery, New York, NY, USA.

A Ethics

This work does not directly interact with human subjects, and an IRB review is not required for our study. For the passive measurement dataset, our devices only passively receive the beacons broadcast by satellites, which are openly accessible to the public. No sensitive information about the sender satellites can be accessed or exposed. For the active measurement dataset, we deploy standard commercial IoT nodes with a subscribed service plan. Other Tianqi customers are not affected by our measurements. In addition, we have established an agreement with the farmland owner. All data analysis in our study complies with this agreement. Any information or data related to their detailed agricultural crops has been removed or masked before being sent to us for analysis. The collected raw data has been reviewed and validated by the farmland owner.

The dataset of the project can be accessed with https://github.com/CCMKCCMK/SINet.

B Active measurements setup

We installed three battery-powered Tianqi devices at a coffee plantation near the border of China (Yunnan province) to facilitate a smart agriculture application. The nodes collect and store on-site planting data, and send the data to our application server located in Hong Kong through Tianqi's satellite constellation. We use the data collected in March 2025, with 5,385 packet traces in total, for measurement study. Each data packet has a unique sequence ID. We compare the sequence IDs of packets sent by the nodes with those received by our server to estimate the reliability of end-to-end packet delivery with Tianqi. The timestamps of packets (*i.e.*, sending by nodes, receiving by Tianqi satellites, and arriving at our server) are recorded to measure traffic delays. The power consumption of the nodes is measured using a Hezhou power meter (*i.e.*, DC Analyzer Air9000 [12]), as presented in Figure 7.

C Causes of Beacon losses

The high Beacon losses observed during our passive measurements can be attributed to three main factors:

(1) **Weak signals due to long communication distances**. While LEO satellites orbit at altitudes of 500 km above the ground, the communication distance can be longer than 500 km due to varying elevation angles. Our measurements show that 80% of DtS communication links range from 600 km to 2,000 km (see Figure 8). Tianqi has higher orbit altitudes (900 km). 80% of the received Beacons are sent from 1,100 km – 3,500 km away. Long communication distance subjects to strong signal power attenuation, resulting in poor SNRs of Beacon reception. This is empirically validated by the measurement results shown in Figure 9. We note that approximately 70.4% of successful receptions occur during the middle portion of a contact window (*i.e.*, between 30% and 70% of its duration). Only 29.6% of the Beacon receptions happen at the beginning and end of the window. The results reveal that Beacon losses are relatively high at the beginning and end of every contact window, during

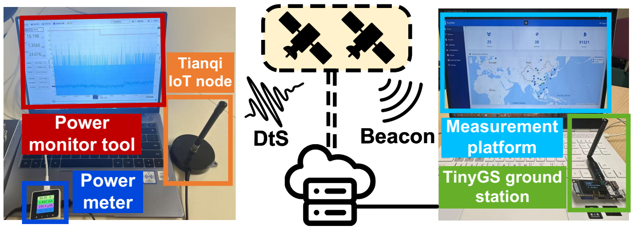

Figure 7: Measurement devices and setup.

SNO	Region	# SATs	Orbit Altitude	SAT. Footprint	Inclination	DtS Frequency	# Traces
Tianqi	China	16	815.7-897.5 km	3.27×10^7 km^2	49.97°	400.45 MHz	108,767
		4	544.0-556.9 km	2.39×10^7 km^2	35.00°		
		2	441.9-493.0 km	1.49×10^7 km^2	97.61°		
FOSSA	EU	3	508.7-512.0 km	1.27×10^7 km^2	97.36°	401.7 MHz	2,715
PICO	US	9	507.9-522.1 km	1.31×10^7 km^2	97.72°	436.26 MHz	3,186
CSTP	Russia	5	468.3-523.7 km	1.24×10^7 km^2	97.45°	437.985 MHz	3,766

Table 3: Overview of measured constellations.

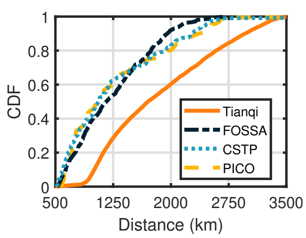

Figure 8: DtS communication distances.

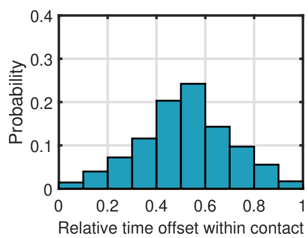

Figure 9: Beacon receptions within a contact window.

which satellites typically operate at low elevation angles with long communication distances.

(2) **Doppler effect due to fast speeds of LEO satellites**. LEO satellites at 500 km orbit move at 7.6 km/s relative to the ground, which can introduce Doppler frequency shifts and impair Beacon reception.

(3) **Limited capability of IoT devices**. The satellite IoT devices are featured with restricted capability in terms of transmit power, packet decoding capability, *etc.* These devices are unable to recover packets from errors caused by low SNRs and Doppler frequency shifts.

D Energy consumption of terrestrial LoRaWAN node

Terrestrial LoRaWAN nodes can operate in four modes: sleep, standby, transmit, and receive. Figure 10 displays the measured power consumption associated with each mode. The Tx mode exhibits the highest power consumption at 1,630 mW, followed by the Rx mode at 265 mW, Standby at 146 mW, and Sleep at just 19.1 mW. A detailed breakdown of the time spent and energy consumed by our deployed nodes across these modes is shown in Figure 11. Our observations indicate that 95% of the nodes' operational time is spent in the low-power Sleep and Standby modes, highlighting their energy-saving design. However, over 70% of the total battery consumption is attributed to Tx and Rx modes that are associated with actual communication activities.

E Additional measurements on Tianqi's reliability

Varying payload sizes. This experiment varies the payload of packets from 10, 60, to 120 bytes and measures the end-to-end packet reliability. The results are presented in Figure 12a. In general, higher reliability is observed for smaller payload sizes. Specifically, more than 75% of transmissions with 10-byte payloads and over 70% of transmissions with 60-byte payloads reach 90% end-to-end reliability. In contrast, for transmissions with 120-byte payload size, only 40% of the transmissions achieve the same reliability.

Simultaneous transmissions. This experiment examines the impact of simultaneous transmissions from multiple Tianqi nodes on end-to-end packet reliability. We deploy three Tianqi nodes and extract the transmission timestamps of each data packet from their logs. By comparing packet transmission periods, we identify simultaneous transmissions and evaluate their end-to-end reliability. The results are shown in Figure 12b. Tianqi's satellite IoT system maintains high reliability under simultaneous transmissions, with most cases achieving above 80% reliability. Single-node transmissions provide the highest packet reliability at 94%. When two and three nodes transmit simultaneously, the reliability decreases to 92% and 89%, respectively.

F Discussion

Generalizability of findings. We note that the network availability characteristics of satellite IoT (*e.g.*, intermittent connectivity, shortened effective service hours) are generally observed across all four constellations. Although our active measurements are performed with the Tianqi constellation only (other constellations do not provide service in our region), the key findings in terms of power consumption and operational costs can be extended to a broader satellite IoT ecosystem, because current LEO satellite IoT providers typically follow the same store-and-forward data transmission paradigm as that of Tianqi. Our measurement results reveal the common characteristics of this system design and are not restricted to a single operator.

High Beacon loss vs. low application data loss. According to the communication protocol of satellite IoT, application data is allowed to be transmitted upon receiving a Beacon successfully. This protocol ensures that application data is typically transmitted when the DtS link conditions become good enough (*i.e.*, a Beacon can be successfully received). In other words, Beacon communications occur under both good link conditions and bad conditions. Whereas, application data communications occur only when a good link condition is available. A detailed analysis of the causes of Beacon loss is provided in Appendix C.

Practical choice of terrestrial IoT or satellite IoT. Our measurements showcase that terrestrial IoT solutions outperform DtS satellite IoT in terms of power consumption, reliability, and operational cost. Existing terrestrial solutions, however, cannot provide coverage to hard-to-reach and hostile scenarios, such as wild forests

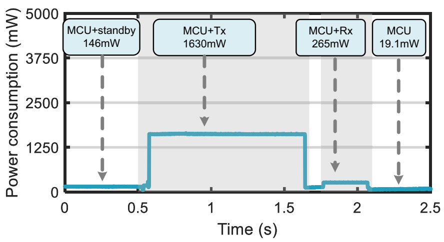

Figure 10: Power consumption of terrestrial IoT node.

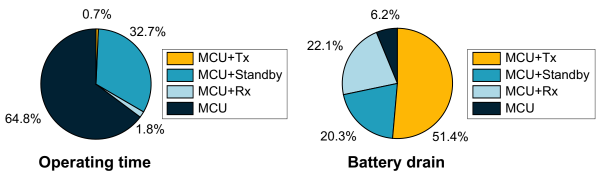

Figure 11: Breakdown of terrestrial LoRa node's operating time and energy consumption across different working modes.

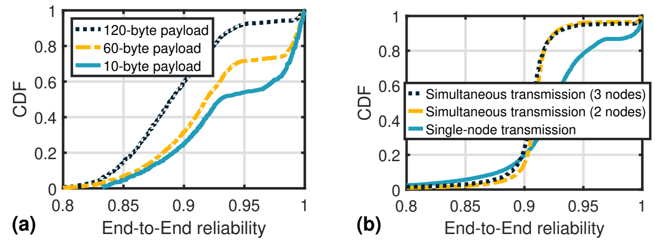

Figure 12: End-to-End reliability of Tianqi constellation under (a) varying payload sizes and (b) concurrent transmissions.

and oceans far away from shores, where wired network infrastructure cannot be accessed. In these scenarios, satellite IoT can be the only way to provide network connectivity despite the limitations of higher power consumption and costs.