Stochastic Modeling of Satellite Aging and its Impact on PDOP Reliability in Hybrid Satellite-Terrestrial Networks

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Abstract. *Satellite-assisted LoRaWAN networks are evolving toward collaborative technologies (3C: communication, coordination, cooperation) that enable coordinated and adaptive IoT connectivity. However, satellite aging, geometric degradation, and propagation losses significantly impact reliability, energy efficiency, and service continuity. This article summarizes a doctoral research contribution that integrates stochastic Petri Nets (SPN), Continuous-Time Markov Chains (CTMC), Erlang-distributed aging processes, and computational geometry to develop a unified analytical framework. The proposed model incorporates collaborative behavior among distributed nodes, capturing the causal chain linking satellite availability, geometric dilution of precision (PDOP), signal quality, packet delivery ratio, energy consumption, and device lifetime. Experimental validation demonstrates that collaborative adaptation improves resilience, availability, and Quality of Service (QoS) in aging-aware scenarios.*

1. Introduction and Research Vision

Satellite-assisted LoRaWAN systems are evolving toward collaborative technology architectures that enable coordinated connectivity in remote and infrastructure-limited regions. In these hybrid satellite–terrestrial environments, satellite availability is a key enabler for positioning, communication reliability, and IoT sustainability. However, long-term satellite aging increases failure probability, reduces constellation availability, and degrades geometry, directly impacting PDOP, link conditions, and network performance.

Despite its importance, most availability models based on CTMC or SPN assume constant failure rates and neglect degradation, maintenance, and collaborative behavior. This research addresses these gaps by proposing an aging-aware stochastic–geometric framework where satellite degradation is a primary design variable, incorporating cooperative interactions. The SPN-based model captures deterioration, integrates maintenance, and evaluates its impact on availability and PDOP.

The framework is extended to hybrid IoT ecosystems supported by LEO satellites, where link budget, SNR, and propagation losses define LoRa/LoRaWAN reliability. A collaborative localization strategy combining satellite trilateration, LoRa-based positioning, and computational geometry (Graham's algorithm) enhances spatial coordination. The main contribution is a cross-layer relationship linking satellite aging to availability, PDOP, link degradation, energy consumption, and device lifetime within a collaborative context, enabling predictive tools for resilient hybrid networks.

2. Objectives and Scientific Relevance

The main objective is to develop a predictive and optimization-oriented collaborative framework capable of quantifying the cascading impact of satellite aging on:

- Satellite availability (AvSat)
- Geometric positioning precision (PDOP)
- Signal-to-noise ratio (SNR)
- Packet delivery ratio (PDR)
- Energy consumption (E)
- Device lifetime (L)

The research is scientifically relevant because it unifies reliability engineering, stochastic modeling, computational geometry, and wireless propagation theory into a single analytical and collaborative methodology, enabling coordinated adaptation among distributed nodes to improve resilience, efficiency, and Quality of Service (QoS) in aging-aware hybrid satellite–terrestrial IoT systems.

2.1. Research General Objective

To develop and validate an integrated stochastic–geometric collaborative framework that models satellite aging, constellation-level availability, and hybrid LoRa–satellite communication performance, explicitly linking degradation dynamics with PDOP evolution, maintenance strategies, and link reliability, while enabling coordinated adaptation among distributed nodes in satellite-assisted IoT systems.

2.2. Specific Objectives

1. To develop an aging-aware SPN-based availability model incorporating Erlang degradation and collaborative system behavior, enabling realistic assessment of satellite and constellation-level availability.
2. To integrate preventive and corrective maintenance strategies into the stochastic framework, evaluating their impact on availability and continuity through coordinated network response.
3. To model LoRa link reliability under satellite propagation conditions, incorporating RSSI, SNR, FSL, and link budget dynamics within collaboratively adaptive hybrid environments.
4. To establish a mathematical relationship between satellite aging and PDOP degradation, quantifying its effects on localization accuracy, PDR, and energy consumption in collaboratively operating devices.
5. To apply computational geometry techniques for satellite selection and acquisition, improving signal robustness and spatial coordination in collaborative systems.
6. To evaluate the combined impact of aging, maintenance, geometry, and propagation on network resilience through analytical modeling and scenario-based validation with collaborative adaptation.

These objectives enable a unified collaborative framework for resilient and adaptive satellite-assisted IoT systems.

3. Research Relevance

The rapid expansion of satellite-assisted IoT and LEO-based hybrid systems demands reliability models beyond traditional steady-state analyses. Existing literature treats availability, networking, geometry, and stochastic reliability as separate domains, whereas real-world satellite-IoT systems operate under tightly coupled spatial, temporal, degradation-dependent, and collaborative constraints. This research is highly relevant because it:

- Introduces aging as a first-class variable in satellite-assisted IoT modeling, moving beyond homogeneous lifetime assumptions and enabling collaborative system awareness.
- Bridges availability theory and localization accuracy by explicitly linking satellite degradation with PDOP escalation, incorporating cooperative adaptation mechanisms.
- Integrates constellation-level reliability with physical-layer LoRa behavior, enabling cross-layer and collaborative performance evaluation.
- Addresses lifecycle resilience by combining degradation modeling, maintenance scheduling, signal optimization, and coordinated node adaptation within a unified framework.
- Responds to challenges in LEO megaconstellations, where sustainability, redundancy management, collaborative operation, and positioning accuracy are critical for mission continuity.

From both academic and operational perspectives, this work advances the state of the art by unifying stochastic reliability, computational geometry, hybrid communications, and collaborative system design into a cohesive and scalable paradigm, providing decision-support tools for optimizing satellite-assisted IoT networks under aging, uncertainty, and cooperative operation.

In summary, this research introduces a lifecycle-oriented collaborative modeling architecture that enhances resilience, availability prediction, localization precision, and communication efficiency in next-generation hybrid satellite-IoT systems, addressing a critical gap in high-impact literature.

4. State of the Art

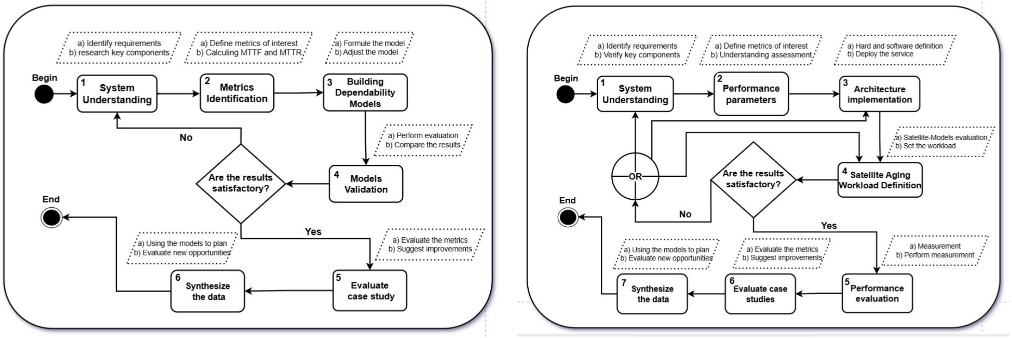
Recent advances in satellite system reliability and availability modeling have largely relied on stochastic frameworks such as Stochastic Petri Nets (SPN) and Continuous-Time Markov Chains (CTMC). Works such as [Li et al. 2018], [Ryan 2023], [Trivedi and Bobbio 2017], [Zeng et al. 2023], and [Fan et al. 2020] provide rigorous probabilistic foundations for constellation availability and signal continuity analysis. However, these studies generally assume homogeneous lifetimes and neglect long-term satellite aging, environmental variability, and collaborative IoT dynamics. Similarly, formal verification efforts in mission-critical systems [NASA 2022, NASA 2014, GNSS 2023, NAVSTAR 2020b, U. S. FAA 2022] emphasize system validation and fault detection but do not integrate degradation-aware stochastic modeling with hybrid communication performance or cooperative system behavior. From the perspective of hybrid and non-terrestrial networks, contributions such as [Oszczypała et al. 2024], [Shakhov et al. 2025], [Talgat et al. 2024], and [Wang et al. 2022] employ CTMC, Monte Carlo methods, and stochastic geometry to model redundancy, coverage, and uplink performance in LEO and FSO/RF systems. Likewise, spatial and geometric analyses in [Al-Hourani 2024] and [Ferre and Lohan 2021] evaluate Line-of-Sight (LoS) probability and GDOP-related positioning errors, while [Lee et al. 2022] highlights navigation limitations in urban safety contexts. Although these works advance hybrid communication modeling, they do not relate geometric degradation, localization accuracy, and collaborative adaptation to satellite aging processes or constellation-level availability constraints.

Advanced structural and decision-based reliability approaches further enrich the field. Multi-State System (MSS) modeling and uncertainty management using multi-valued logic and decision diagrams are presented in [Zaitseva et al. 2022], [Zaitseva and Vitaly 2017], [chang Mo et al. 2017], and [chang Mo et al. 2020], while economic optimization in steady-flow systems is discussed in [Natvig 2011]. Game-theoretic, Markov decision, and Bayesian redundancy frameworks are introduced in [Baouya et al. 2024], [Li et al. 2022], [Chen et al. 2024], and [Pan et al. 2023], and hybrid MBSE–LSTM predictive models are explored in [Alandihallaj et al. 2024]. Despite their mathematical rigor, these approaches focus primarily on structural reliability, cost efficiency, or redundancy, without jointly addressing aging-aware localization degradation, cross-layer QoS, and collaborative resilience in hybrid satellite–IoT systems.

Overall, the literature demonstrates substantial progress in stochastic reliability modeling, hybrid communication analysis, geometric positioning evaluation, and uncertainty management. Nevertheless, no prior work integrates satellite aging dynamics, preventive and corrective maintenance, constellation-level availability (e.g., four-satellite GNSS constraints), LoRa-specific propagation behavior (RSSI, SNR, FSL), computational geometry optimization, PDOP degradation, and collaborative node adaptation within a unified framework. This gap underscores the need for a holistic lifecycle-oriented model capable of linking stochastic aging, spatial signal optimization, and cooperative LoRa–satellite communication performance to enhance resilience, positioning accuracy, and operational efficiency. However, no prior framework integrates satellite aging dynamics with LoRaWAN performance metrics through a formal stochastic–geometric–collaborative coupling. This thesis bridges that gap.

5. Scientific Methods

It was necessary to use two methodologies, the first for the proposed availability model or SPN model, and the second methodology for evaluating the availability of models describes the environment in which we will test the proposed models (Figure 1). The methodological structure of the thesis is organized into chapters, and each chapter is linked in a cascade to arrive at results from a causal chain, as shown in Figure 2.



(a) Dependability Methodology **(b)** Performance Methodology

Figure 1. Methodologies

This research proposes a unified analytical–stochastic and collaborative framework for satellite-assisted LoRa systems under aging, integrating availability, geometry, propagation, and energy modeling into a single causally coupled structure. It quantifies how satellite degradation propagates from constellation availability to positioning accuracy, communication performance, and device lifetime, enabling cross-layer sensitivity analysis.

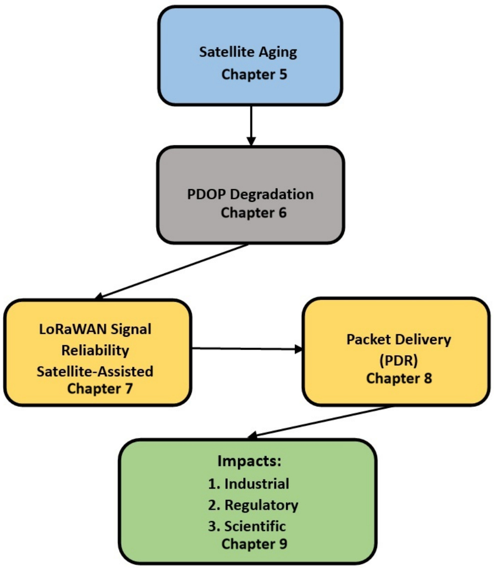


Figure 2. Cascading Effects of Satellite Aging in Collaborative Technologies for Satellite-Assisted LoRaWAN Networks

6. Experiment set-up environment

This section describes the location, environment, and devices used in the experiment, providing context for the research and highlighting the role of collaborative technologies in enabling coordinated system evaluation.

The architecture is composed of three subsystems, as follows: (i) LSM, Land Sky Module; (ii) GPS constellation, Global Positioning System constellation; and (iii) the GS, Ground Station, as shown in Figure 3.

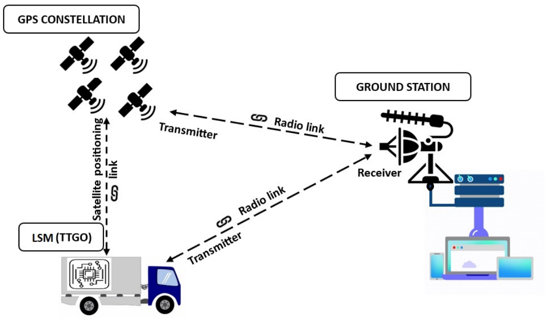


Figure 3. Architecture of Collaborative Technology for Satellite Telecommunications Systems.

As explained in the thesis, in the section titled "System Architecture," the data on all satellite maintenance and outage information is provided by NAVSTAR and NASA [NAVSTAR 2020a], [NASA 2022],. With these data, a new Petri net (SPN) aging model is generated for the GPS Constellation subsystem. Then inserted the obtained data into the proposed general architectural model and determined how it behaves within the overall architecture. That is, the impact that this new aging model has on the system architecture.

6.1. Device Configuration GPS Constellation and Position Dilution of Precision (PDOP)

It should be noted that, although we do not have access to the internal components of the satellites in orbit, as they are like a "black box" for the end user, we do know the types of maintenance and the time-frames involved during the space vehicle useful life. This experiment uses a 20 dBm TTGO LoRa ESP32 module with a frequency of 915 MHz, which adopts the LoRa (SX1276, SX1278) chip from the SEMTECH company. The module is equipped with an 2.4 GHz omnidirectional antenna that has a gain of 3 dBi integrated with the NEO-M8N GNSS, which is called LSM TTGO (Figure 3) and the second module with the RTL-SDR Blog Active L-Band 1525-1660 Inmarsat to Iridium Patch Antenna Set in the Ground Station (GS). Figure 4 shows the architecture of the system.

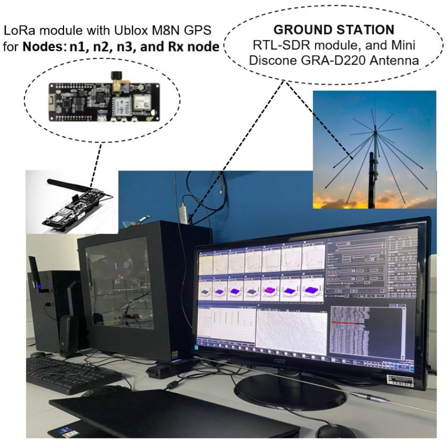


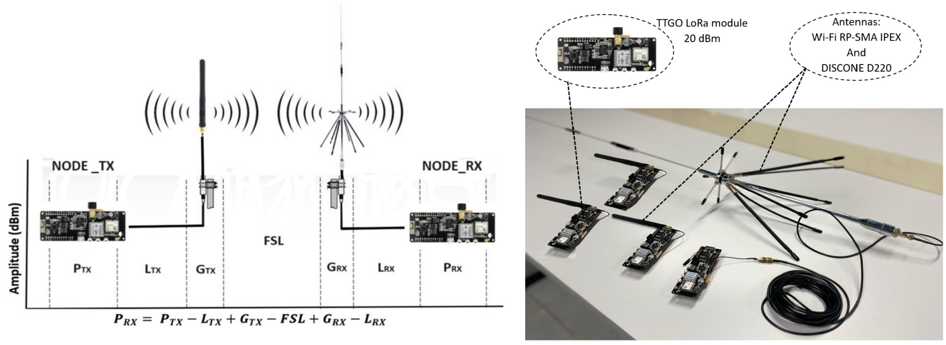
Figure 4. Ground Station and LSM LoRa Module in Collaborative Systems.

Figure 4 also shows the set of devices used for the analysis of the signal tests. Furthermore, in this figure, on the Ground Station monitor, you can see the images of the spectrograms of the signals received by the satellites when they are visible to it (GS), which will be explained later in the section: Case studies. In addition to the previously mentioned devices, two software tools were used: Mercury 5.1, to model the SPN, and GNSS SDR software, to take the data provided by the antenna and monitor the satellite coverage.

7. LoRa Architecture and Infrastructure Devices

This section aims to provide a comprehensive overview of the infrastructure and experimental setup employed in testing LoRa performance.

The experiment utilized a 20 dBm LILYGO TTGO LoRa ESP32 module operating at a frequency of 915 MHz, integrating the LoRa (SX1278, SX1276) chip from SEMTECH. Figure 5 illustrates the link diagram showcasing the antennas' configurations and interconnections.



(a) Antennas Link Diagram

(b) TTGO LoRa Propagation system nodes

Figure 5. General LoRaWAN network model

In the experiment, the module (nodes T_X) featured an omnidirectional antenna operating at 2.4 GHz with a gain of 3 dBi, integrated with the NEO-M8N GNSS. Conversely, the module (R_X), incorporated a GRA-D220 Mini Discone Antenna with a gain of 2.15 dBi, serving as the base station [Erturk et al. 2019]. These specifications are instrumental in understanding the capabilities and limitations of the equipment deployed. In addition, Figure 5b represents the TTGO TBeam LoRa ESP32 propagation system.

7.1. Location

Satellite performance testing was conducted at the coordinates 8.0555° S and 34.9513° W, since this area is categorized as obstacle-dense areas (NLoS), where propagation of the signal can sometimes present difficulties due to the structure of the obstacles that it must face, such as buildings and trees, in addition to the inherent attenuations of the environment. The node RX in Figure 6, shows the location of the Ground station and its previously mentioned coordinates.

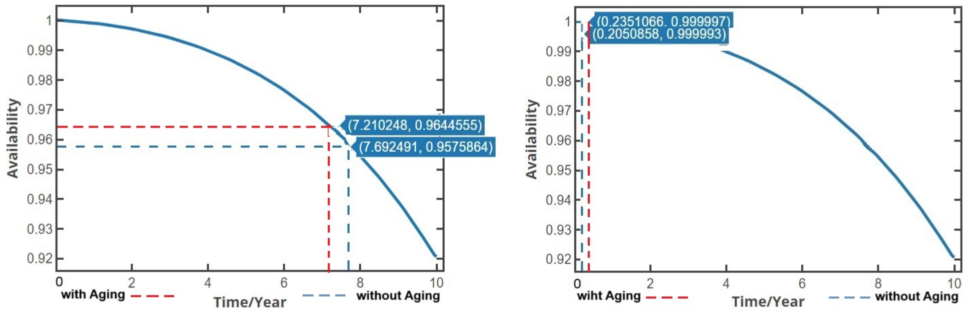
Figure 6. Experiment Area.

8. Results and Discussion

Figure 7 shows that the SPN model with aging (red line) performs better than the model proposed by NAVSTAR NASA (blue line), with an availability of 0.964 compared to 0.957 for a single satellite (Figure (a)), with a marginal difference of only 0.007. This confirms that geometric integrity and overall signal service quality remain stable and reliable. The same is true when four satellites are incorporated Figure (b).

Table 1. Causal analysis of packet delivery performance in satellite-assisted LoRaWAN networks

d (m)	Policy i	$\mathbf{Av_{Sat}}^{(i)}(d)$	$\mathbf{PDOP}^{(i)}(d)$	$\mathbf{SNR}^{(i)}(d)$	$\mathbf{PDR}^{(i)}(d)$	$\mathbf{E}^{(i)}(d)$	$\mathbf{Lifetime}^{(i)}(d)$
50	G	High	Low / Stable	High	1.00	0.73	338.5
50	NG	Moderate	Moderate	High	1.00	0.73	338.5
100	G	High	Low / Stable	High	1.00	0.73	338.5
100	NG	Moderate	Moderate	High	1.00	0.73	336.7
200	G	High	Low	High	1.00	0.73	338.5
200	NG	Reduced	Elevated	Moderate	0.80	0.81	302.3
300	G	High	Moderate	Moderate	0.95	0.75	330.1
300	NG	Reduced	Elevated	Lower	0.85	0.78	313.2
400	G	High	Moderate	Low–Moderate	0.85	0.78	313.2
400	NG	Low	High	Low	0.83	0.79	308.6
500	G	High	Moderate	Low–Moderate	0.83	0.79	308.6
500	NG	Low	High	Low	0.80	0.81	302.7
600	G	High	Moderate	Near limit	0.80	0.81	304.7
600	NG	Very Low	Severe	Near limit	0.78	0.82	301.5
700	G	High	Moderate	Near limit	0.79	0.82	302.0
700	NG	Very Low	Severe	Near limit	0.77	0.83	298.4



(a) Avail. Single Sat with and withoutAging.

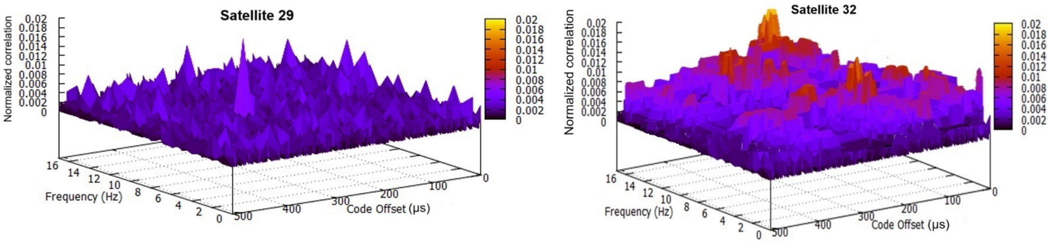
(b) A least 4 Single Sat with and without Aging.

Figure 7. Comparison of a Single satellite and at least 4 satellites: available with and without aging. (a) Case I. (b) Case II.

Figures 8a and 8b present normalized correlation values ranging from 0 to 0.02, representing the relative alignment between the satellite-received signal and the locally generated signal in the GNSS receiver (rover or LSM LoRa module). These values are unitless, as they quantify signal coincidence rather than physical magnitude, where 0 indicates no correlation and 0.02 denotes perfect correlation within the analyzed frequency band and code offset.

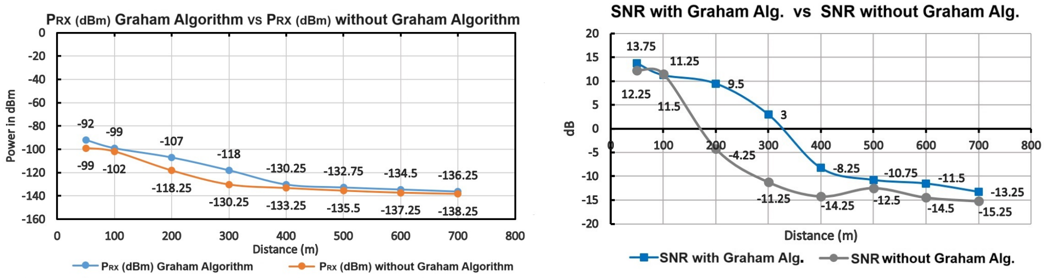
On the other hand, Figure 9a shows the comparison between the two signal scenarios, showing that the blue line, the scenario with the Graham algorithm, has better link behavior than the orange line, which is the scenario without the Graham algorithm. Similarly, Figure 9b of the signal-to-noise ratio (SNRs) increases with distance and causes the signal received at the R_X node to be affected even though the antennas have a dBi proportional to the link budget.

Figure 10a and Figure 10b, together demonstrate that Graham's algorithm significantly enhances Quality of Service (QoS) at a transmission rate of 20 packets/min. As shown in Figure 10a, without optimization the PDR falls below 85% at 200 m, whereas the Graham



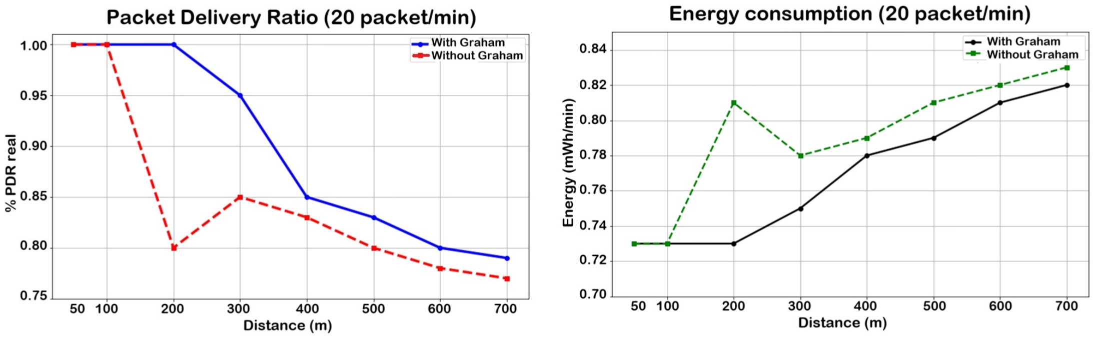
(a) Low satellite signal reception. **(b)** High satellite signal reception.

Figure 8. Satellite Signal Analysis LoRa Network



(a) Comparison Between Reception of P_{RX} Signals. **(b)** Comparison Between the SNRs.

Figure 9. Analysis of P_{RX} and SNR with and without Graham's Algorithm.



(a) Packet Delivery Ratio **(b)** Comparison Between the SNRs.

Figure 10. Packet Delivery Ratio and Energy Consumption in LoRaWAN Networks

policy maintains over 90% up to 400 m and greater stability even at 700 m (see Figure 10). Consistently, Figure 10b shows that the optimized strategy reduces retransmissions and idle listening, resulting in lower and more stable energy consumption compared to the non-optimized case, which exhibits fluctuations and energy spikes. These results confirm that geometric optimization directly improves link reliability, energy efficiency, and overall QoS.

9. Scientific and Technical Products

This section presents the scientific and technical products derived from the proposed framework, highlighting how collaborative technologies enable coordinated system design, cross-layer optimization, and resilient performance in satellite-assisted IoT environments. Thus

- Integrated Stochastic Availability Model with Satellite Aging based on Stochastic Petri Nets (SPN), extending reliability framework incorporating preventive and corrective maintenance strategies under degradation conditions.
- Analytical aging model linking satellite degradation with Quality of Service (QoS) metrics with QoS optimization strategy for satellite-assisted LPWAN networks.
- PDOP-based positioning accuracy assessment model considering satellite aging effects.
- Stochastic modeling framework for GNSS performance degradation over time.
- Experimental LoRaWAN-over-satellite testbed using TTGO GNSS modules for real-world validation, and simulation environment for long-term satellite availability and reliability analysis.
- Performance evaluation platform measuring latency, packet delivery ratio (PDR), and link stability under satellite propagation conditions.
- Geometric optimization algorithm implementation (Graham scan) for node distribution and coverage improvement.
- Hybrid analytical–experimental evaluation methodology integrating stochastic modeling and field experimentation.
- Scientific publications and conference contributions derived from the developed models and experimental results.

10. Conclusions

This doctoral thesis demonstrates that satellite aging is a structural Quality of Service (QoS) driver in collaborative hybrid satellite–LoRaWAN IoT systems, framed under 3C technologies (communication, coordination, cooperation). Using an SPN-based stochastic model with Erlang degradation, combined with geometric and communication-theoretic analysis, it is established that satellite availability governs cross-layer dependencies within a cooperative context. The integration of Graham-based convex optimization (policy G) improves spatial conditioning over NG, stabilizing PDOP and mitigating degradation propagation.

In adittion, by unifying stochastic reliability modeling, geometric precision analysis, communication performance, and collaborative adaptation into a single analytical structure, this thesis provides a predictive, aging-aware framework for resilient constellation management and sustainable hybrid satellite-terrestrial deployment, establishing a paradigm where collaborative systems transform satellite aging into an optimizable dimension for next-generation IoT infrastructures.

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