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A Low-Earth Orbit Narrowband Communications And Navigation Constellation Study

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Abstract

This paper presents a system-level study of a Low Earth Orbit (LEO) satellite constellation designed to provide Narrowband-IoT (NB-IoT) connectivity and complementary Positioning, Navigation, and Timing (PNT) services. NB-IoT technology is drawing significant interest in satellite communications as it has the potential to support reliable, wide-area, and low-power connectivity for applications like telemetry, command and control, and safety messaging. This makes NB-IoT particularly useful for use cases such as traditional aviation and the growing Unmanned Aerial Vehicle (UAV) sector. This paper takes these use cases to formulate requirements that drive the mission design. A trade space exploration approach is adopted to navigate the engineering trade-offs derived from stakeholder needs and user requirements. The key figures of merit (FoMs) include constellation geometry and coverage, communication performance, navigational accuracy, risk and trade-off metrics, and compliance with relevant standards (3GPP, ITU regulation, and ECSS guidelines). The resultant system architecture features a total of 2798 satellites spread across a dual-shell configuration at operational altitudes of 600 km and 610 km, arranged to ensure global coverage, including the poles. Each satellite carries an NB-IoT payload acting as a 3GPP-compliant base station, and an inter-satellite link is included to complete the space segment. Software-Defined Radio (SDR) technology is leveraged for operational flexibility, addressing spectrum allocation, RF interference, and Doppler shift challenges. The design also makes use of the communication signal for PNT purposes. The analysis confirms the robustness of this approach, and business projections indicate a suitable return on investment by servicing tens of millions of devices globally. The proposed constellation is a technology enabler that integrates space and terrestrial networks to provide ubiquitous narrowband connectivity and navigational services. Systems engineering rigour ensures the proposed design meets technical objectives and is resilient to risks in orbit and the marketplace. This work highlights that by leveraging relevant standards and careful economic planning, LEO NB-IoT constellations can be both technologically feasible and commercially viable.

Acronyms/Abbreviations

3GPP 3rd Generation Partnership Project

B2B Business-to-Business

BVLOS Beyond Visual Line of Sight

ECSS European Cooperation for Space Standardisation

FoM Figure of Merit

GDP Group Design Project

GEO Geostationary Orbit

IAC International Astronautical Congress

ISL Inter-Satellite Link

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ITU International Telecommunication Union

LEO Low Earth Orbit

NB-IoT Narrowband Internet of Things

NTN Non-Terrestrial Network

PNT Positioning, Navigation, and Timing

RPN Risk Priority Number

SDR Software-Defined Radio

UAV Unmanned Aerial Vehicle

WP Work Package

1. Introduction

The proliferation of Internet of Things (IoT) devices has created a demand for ubiquitous, low-power connectivity that terrestrial networks alone cannot satisfy. Over 80% of the Earth's surface lacks cellular coverage, creating significant gaps for applications in aviation, maritime, and logistics [1]. Narrowband-IoT (NB-IoT), a 3GPP standard, was engineered for low-power, low-bandwidth devices but was initially limited by terrestrial infrastructure [2, 3]. The introduction of Non-Terrestrial Networks (NTN) in 3GPP Release 17 enables NB-IoT protocols to operate over satellites, promising truly global IoT coverage [4].

A key early market for this technology is the Unmanned Aerial Vehicle (UAV) sector. The UAV market is projected to grow from $31.70B in 2023 to $148.19B by 2032 [5]. Safe and effective Beyond Visual Line of Sight (BVLOS) operations for UAVs require continuous, reliable command-and-control (C2) and telemetry links, which satellite-based NB-IoT is well-suited to provide. Extending NB-IoT to a Low Earth Orbit (LEO) satellite constellation offers inherent advantages such as low propagation delay and global coverage, including polar regions. This can be augmented with complementary Positioning, Navigation, and Timing (PNT) services at minimal additional cost.

This paper presents the system-level design and analysis of such a LEO constellation. It details the mission architecture derived from stakeholder requirements, the dual-shell constellation design optimised for coverage and latency, the satellite bus concept, and analyses of the system's performance, risk, and commercial viability. The work follows European Cooperation for Space Standardisation (ECSS) system engineering processes through project phases 0 to C [6].

2. System Requirements and Mission Objectives

The mission design was driven by top-level requirements formulated through stakeholder engagement (primarily with Viasat) and market analysis. The primary objective is to provide robust, global NB-IoT communications and PNT augmentation, with a focus on serving the aviation and UAV sectors.

The key top-level mission requirements are summarised below:

- **Orbit:** The constellation shall operate in LEO, within an altitude of 200 km – 1500 km.
- **Frequency:** Operations shall be in Frequency Range 1 (FR1), specifically S-band, to align with 3GPP standards and existing space applications.
- **Lifetime:** The mission shall have an operational lifetime of 6 years, with satellites to be de-orbited within 25 years of end-of-life, per IADC guidelines.
- **PNT Accuracy:** The mission shall provide a navigational accuracy of ±100 meters for latitude and longitude.
- **Coverage:** The system must provide global coverage, including polar regions, to support ubiquitous connectivity.
- **Latency:** Round-trip signal latency must be kept below 16 milliseconds to support time-sensitive applications.

A comprehensive analysis of stakeholder needs confirmed that while low-power operation and massive device capacity are key strengths of NB-IoT, limitations in throughput and latency require careful system design and mitigation strategies [7]. A trade-off study prioritised global coverage and low latency as the primary figures of merit guiding the architectural design.

3. Constellation and Satellite Architecture

To meet the requirements for global coverage, low latency, and continuous service, a dual-shell constellation architecture was designed and optimised using analytical modelling in MATLAB and simulation in Ansys STK [8].

3.1 Constellation Design

The final architecture consists of 2,798 operational satellites distributed across two distinct shells, supplemented by 510 in-orbit spares.

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- **Main Shell:** Comprises 1,188 satellites to provide zonal coverage of all major countries. It is configured with 27 orbital planes and 44 satellites per plane, at an operational altitude of 600 km with an inclination of 67.5°. This inclination was chosen to maximise coverage over key landmasses while minimising the number of satellites required.

- **Polar Shell:** Comprises 1,100 satellites to ensure continuous coverage over the polar regions. It is configured with 25 planes and 44 satellites per plane, at a slightly higher altitude of 610 km and a 90° inclination. The altitude separation mitigates collision risk between the two shells.

This dual-shell approach (visualised in Fig. 1) provides robust global coverage while optimising satellite distribution. The design also incorporates a multi-echelon sparing strategy, with spares held in a 580 km parking orbit and on the ground, allowing for rapid replenishment and high service availability. The final constellation parameters are summarised in Table 1.

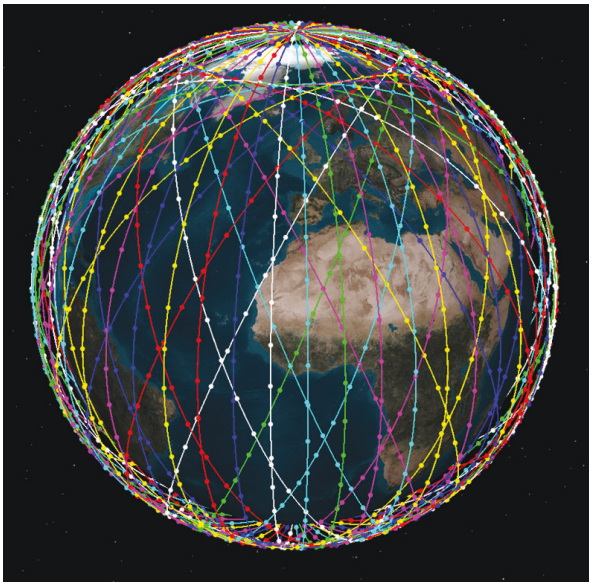


Fig. 1: 3D visualisation of the dual-shell constellation configuration.

Table 1: Final Constellation Configuration Summary.

Parameter	Main Shell	Polar Shell
Operational Altitude	600 km	610 km
Inclination	67.5 deg	90 deg
Number of Planes	27	25
Satellites per Plane	44	44
Total Satellites	1,188	1,100
Total Operational Satellites: 2,798		
In-Orbit Spares: 510		

3.2 Satellite Bus and Payload

The satellite platform is designed as a compact, lightweight spacecraft inspired by the form factor of SpaceX's Starlink satellites to allow for high-density launch configurations.

- **Structure and Mass:** Each satellite has a total wet mass of 140 kg and a dry mass of 135 kg. The flat, compact design (Fig. 2) enables up to 162 satellites to be launched on a single Falcon 9 rocket, allowing for full constellation deployment in as few as 18 launches [7].

- **Power:** The electrical power system (EPS) is designed to produce 482.74 W from a 3.62 m^2 solar panel, accommodating the high power demand of the communications payload. A Li-Ion battery system provides power during eclipse periods [9].

- **Propulsion:** A single Hall Effect Thruster is used for station-keeping and end-of-life de-orbiting, enabling the 6-year operational lifetime.

- **Payload:** The primary payload is an NB-IoT transceiver acting as a 3GPP-compliant base station. It utilises a 10x10 element phased-array antenna for electronic beam-steering and multibeam capabilities. An optical Inter-Satellite Link (ISL) provides continuous connectivity within the constellation, reducing reliance on ground stations. PNT services are derived by processing the Doppler shift of the communication signal.

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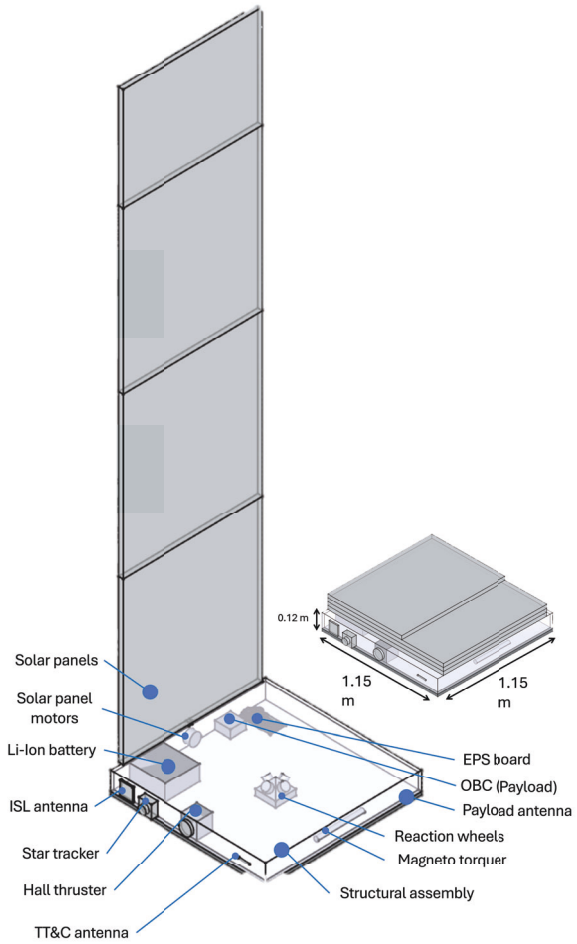


Fig. 2: CAD model of the satellite in both stowed and deployed configurations.

4. System Analysis and Feasibility

4.1 Performance Analysis

The constellation's performance was validated against key requirements.

- **Coverage:** The dual-shell design provides seamless, 100% global coverage, as confirmed by simulations in STK.
- **Latency:** The operational altitudes of 600/610 km ensure that the maximum round-trip signal latency remains below 16 ms [8].

4.2 Risk and Economic Analysis

A formal risk analysis was conducted using the Risk Priority Number (RPN) method as mandated by ECSS-M-ST-80C [10]. Key Class A risks identified included launch vehicle failure and antenna pointing inaccuracy, which require immediate design and mitigation attention (Table 2).

Table 2: Top RPN Items Identified in Risk Analysis.

Failure Mode	RPN	Class
Launch vehicle catastrophic loss	25	A
Antenna pointing inaccuracy	24	A
HPA electrical failure	24	A
Antenna gain shortfall	20	B
Propulsion system failure	16	B

An economic analysis was performed to assess commercial viability. A profit-sensitivity analysis revealed that revenue is highly sensitive to device adoption rate and subscription price, while costs are dominated by satellite manufacturing expenses rather than launch costs. A build cost below $2M per satellite and a lifetime of 6-7 years were identified as the optimal balance for profitability. A B2B subscription model was deemed most viable, leveraging large customer bases in the aviation and logistics sectors [7]. A subsequent Discounted Cash Flow (DCF) analysis confirmed these findings, identifying a feasible operating region with an Average Revenue Per User (ARPU) greater than $35/month and a satellite build cost below $0.8M.

5. Conclusions

This study has successfully demonstrated the system-level design of a viable LEO satellite constellation for global NB-IoT communication and PNT services. Through a rigorous systems engineering approach, a final architecture comprising 2798 satellites in a dual-shell configuration at 600/610 km has been defined. This design meets the primary objectives of global coverage, low latency (<16 ms), a 6-year lifetime, and ±100 m PNT accuracy. The analysis confirmed the design's robustness and its commercial viability under a B2B service model. The proposed constellation represents a feasible solution to address the growing connectivity demands of the UAV sector and the broader IoT ecosystem, integrating established standards with careful engineering and economic planning to create a technologically achievable and commercially sound system.

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