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An NB-IoT Payload for Space Communications and Navigation

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Abstract

This paper presents a payload design for a Narrowband Internet of Things (NB-IoT) based communication and navigational system. The main objective of this design is to enable the integration of NB-IoT in a constellation of satellites. NB-IoT technology is attracting considerable attention in satellite communications because it has the potential to support reliable, wide-area, and low-power connectivity for critical applications such as telemetry, command and control, and safety messaging. Its versatility makes NB-IoT particularly well-suited to both conventional aviation and the expanding Unmanned Aerial Vehicle (UAV) sector. Drawing on these use cases, this paper identifies the key requirements and uses them to inform the payload design. The payload leverages Software-Defined Radio (SDR) technology for operational flexibility, addressing spectrum allocation, RF interference, and Doppler shift challenges. The design uses a phased-array antenna design of 10 by 10 circular patch elements optimised for space-based NB-IoT transmissions in the S-band frequency. This allows for electronic steering of its beam, minimising the overall payload mass and complexity while increasing its footprint and ensuring connectivity within a 40-degree half-cone angle. Navigation signal processing is achieved by leveraging the Doppler shifting of the communication signal, providing a velocity-based location. To provide a reliable communications link, the system also incorporates error correction techniques in a protocol designed and implemented to compensate for the Doppler shift in the signal. To validate the results of the design, a technology demonstrator using an SDR as well as custom Electrical Power System (EPS) and On-Board Data Handling (OBDH) boards are presented. These results demonstrate that successful connectivity and data transmission are feasible in a simulated environment, paving the way for future satellite-to-UAV communication using NB-IoT protocols. This payload system will contribute to the advancement of satellite-based NB-IoT networks, offering new possibilities for autonomous aerial operations. Future work could focus on optimising power efficiency and conducting real-world flight tests to validate system performance and reliability further.

Acronyms/Abbreviations

3GPP 3rd Generation Partnership Project

BVLOS Beyond Visual Line of Sight

EIRP Effective Isotropic Radiated Power

EPS Electrical Power System

FSPL Free Space Path Loss

LEO Low Earth Orbit

NB-IoT Narrowband Internet of Things

NTN Non-Terrestrial Network

OBDH On-Board Data Handling

PNT Positioning, Navigation, and Timing

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QAM Quadrature Amplitude Modulation

RF Radio Frequency

SDR Software-Defined Radio

UAV Unmanned Aerial Vehicle

1. Introduction

The extension of Narrowband Internet of Things (NB-IoT) to Low Earth Orbit (LEO) constellations promises to unlock global connectivity for low-power devices, with a particularly strong use case in the Unmanned Aerial Vehicle (UAV) market. However, realising this potential requires a payload specifically designed to overcome the unique challenges of the LEO environment, namely significant Doppler shifts, power limitations, and the need for reliable, wide-area coverage from a fast-moving platform.

This paper details the design of an NB-IoT payload for a LEO satellite constellation intended for communications and navigation. The design process addresses the entire communication chain, from the link budget and antenna architecture to the RF chain and protocol-level implementation. A key design driver is the requirement to support UAVs operating Beyond Visual Line of Sight (BVLOS), which necessitates robust command-and-control links. The payload design leverages a phased-array antenna for electronic beam-steering, Software-Defined Radio (SDR) for flexibility, and tailored Doppler compensation strategies to maintain link integrity. Furthermore, it incorporates a novel approach to Positioning, Navigation, and Timing (PNT) by utilising the communications signal itself, providing an integrated solution.

2. Payload Requirements and Link Budget

The payload design is founded on a set of specific requirements derived from the overall mission objectives and stakeholder needs. The primary function is to establish and maintain a 3GPP-compliant NB-IoT link.

2.1 Key Requirements

The core requirements for the payload are summarised in Table 1. A key performance metric is the required antenna gain of at least 24.4 dB, which is driven by the link budget analysis. The system must also support a data rate of 43 kbps to handle telemetry and command data, and tolerate a residual Doppler shift of up to 950 Hz per subcarrier, as specified by 3GPP standards for NTN operations [1].

Table 1: Key Payload Requirements.

Req. ID	Definition	Traceability
PAY-FUN-02	Transmit a data rate of 43 kbps	Data budget
PAY-PER-03	Gain of at least 24.4 dB	Link analysis
PAY-PER-04	Achieve required Eb/N0 of 18 dB	Link analysis
PAY-FUN-06	Steer antenna beam up to 40°	Mission analysis
PAY-FUN-18	Support Doppler shift up to 950 Hz	3GPP

2.2 Link Budget Analysis

A detailed link budget was performed to size the communication system. The analysis was based on S-band frequencies (1.98 GHz uplink, 2.17 GHz downlink) and a 180 kHz bandwidth. 16-QAM was selected as the modulation scheme for its balance of spectral efficiency and power requirements, with a required Eb/N0 of 18 dB (including a 3 dB margin) for a Bit Error Rate of 10^{-6} [2].

The analysis confirmed that the uplink from the user terminal to the satellite is the most restrictive link due to the limited power of the user device. The final link budget (summarised in Table 2) closes with a margin, validating the baseline design parameters and confirming that an antenna gain of approximately 24 dB is required.

Table 2: Link Budget Summary.

Parameter	Uplink	Downlink
Frequency (GHz)	1.98	2.17
Data Rate (kbps)	43	43
EIRP (dBm)	40	74
Required Rx Gain (dB)	24.0	7.0
Final Eb/N0 (dB)	19.84	35.07
Required Eb/N0 (dB)	18.0	18.0
Margin (dB)	**1.84**	**17.07**

3. Payload Hardware Design

3.1 Phased-Array Antenna

A trade-off analysis concluded that a phased-array antenna is superior to a parabolic dish for this mission due to its electronic steering capabilities (eliminating moving parts), multibeam potential, and lower aerodynamic drag profile [2].

The chosen design is a 10x10 array of circular patch elements. Circular patch elements were selected for their

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robust circular polarisation, which ensures consistent signal reception regardless of satellite or UAV orientation.

- **Element Design:** The circular patch element is designed for a centre frequency of 2.1 GHz on an FR4 substrate, achieving a gain of 6.07 dB per element.
- **Array Configuration:** The 100 elements are arranged in a 10x10 grid with an inter-element spacing of 0.57λ. This spacing was optimised to maximise gain while preventing the formation of grating lobes when steering the beam up to the required 40° off-boresight.
- **Performance:** The final array achieves a total gain of 26.67 dB. When steering to 40°, the scan loss is less than 2 dB (Fig. 1), ensuring the link remains robust across the coverage area.

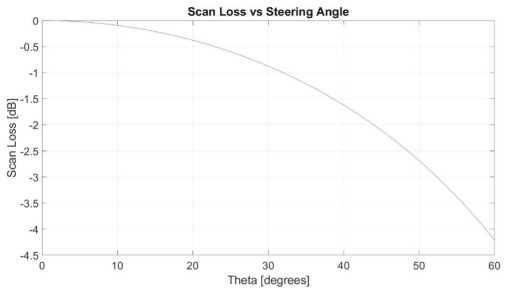


Fig. 1: Scan loss in relation to the beam steering angle.

3.2 RF Chain Architecture

The RF chain architecture is designed to support the phased-array antenna and its multibeam functionality. A hybrid beamforming architecture was chosen, integrating Software-Defined Radio (SDR) for maximum flexibility. SDR allows for in-orbit updates to waveforms and protocols, ensuring compatibility with future network standards like 6G.

Phase shifters are a critical component for electronic beam-steering. The required phase shift between consecutive elements was modelled in MATLAB, confirming the ability to steer the beam across the required field of view. The design allocates one RF chain per desired beam, providing redundancy and the flexibility to form a single high-gain beam or multiple lower-gain beams as needed.

4. Doppler Compensation and Protocol

The high relative velocity between the LEO satellite and the user terminal induces significant Doppler shifts, reaching up to 45 kHz. This far exceeds the tolerance of the NB-IoT waveform and must be actively compensated.

4.1 Doppler Shift Mitigation

The compensation strategy focuses on pre-compensating for the large, predictable Doppler shift caused by the satellite's movement. The satellite payload calculates the expected Doppler shift towards the centre of a given cell and applies an inverse frequency shift to its transmitted signal. The smaller, residual Doppler (from user motion and intra-cell variation) remains within the 950 Hz tolerance of the user terminal's receiver [1]. Fig. 2 and Fig. 3 show the distinct magnitudes of the two Doppler components (satellite movement and user's movement, respectively).

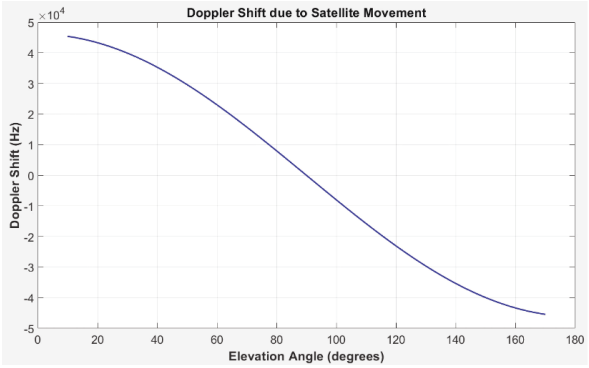


Fig. 2: Plot of the Doppler shift caused by the satellite movement

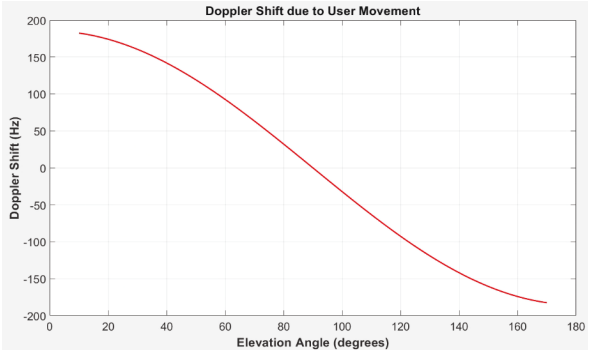


Fig. 3: Plot of the Doppler shift caused by the user's movement

4.2 Protocol Implementation and Validation

The full NB-IoT protocol stack was designed using the open-source srsLTE software suite as a baseline [3]. This allowed for rapid development and standards compliance. To enhance robustness in the satellite link, the protocol leverages signal repetition. MATLAB simulations were used to determine the necessary number of repetitions to ensure reliable communication. The results (Fig. 4) show that a minimum of 16 repetitions is required to achieve 100% throughput, ensuring all data blocks are correctly decoded despite channel impairments.

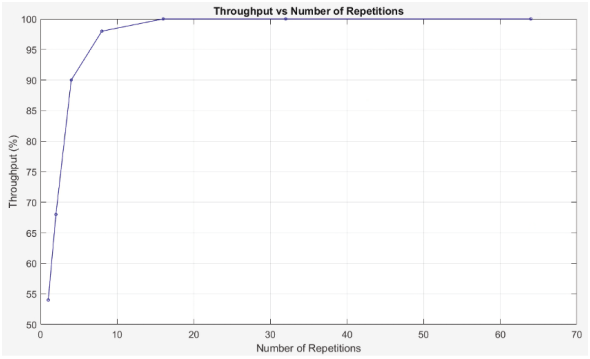


Fig. 4: Throughput vs. number of repetitions.

A hardware technology demonstrator was designed, using BladeRF SDRs and Raspberry Pis to simulate the satellite payload and the user terminal. This test bench, while not fully executed due to time constraints, provides a clear path for future validation of the complete protocol stack in a real-world hardware environment [4].

5. Conclusions

This paper has presented a design for an NB-IoT communications and navigation payload for a LEO satellite constellation. The design successfully meets the mission requirements, closing the link budget with sufficient margin and addressing the critical challenge of Doppler shift through a pre-compensation strategy. The selection of a 10x10 phased-array antenna provides the required gain of 26.67 dB and electronic beam-steering up to 40°, while the SDR-based RF chain ensures future flexibility. The protocol-level design leverages signal repetition to guarantee robust data delivery. The proposed payload provides a solid foundation for enabling critical UAV BVLOS operations and extending NB-IoT networks into space. Future work should focus on hardware prototyping to validate antenna performance and end-to-end testing of the full protocol stack using the designed test bench.

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