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Ubiquitous IoT Through Space Communications

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Abstract—Low-Power Wide-Area Networks (LPWANs) provide a low-cost solution for connecting low-power devices over long distances. Among LPWAN technologies, Narrowband IoT (NB-IoT) has gained prominence because of its wide coverage and high reliability. Recently, as the demand for IoT connectivity in remote and underserved regions continues to grow, integrating NB-IoT with Low-Earth Orbit (LEO) satellite networks has gained increasing attention. Due to satellite communication’s dynamic nature, this integration poses significant challenges, including synchronization issues and managing high-density User Equipment (UE) during the random access procedure. This digest paper summarizes key contributions from a doctoral thesis that addresses these challenges. A systematic framework based on key performance indicators (KPIs) is proposed to evaluate and optimize satellite IoT communication, addressing reliability, latency, throughput, and energy efficiency trade-offs. A lightweight downlink synchronization method is proposed, which reduces device complexity in LEO satellite environments. In addition, a GNSS-free wake-up strategy is developed to improve energy efficiency, particularly in scenarios with intermittent satellite coverage. To address the challenge of random access in high-density environments, an early detection method is introduced. This method reduces collisions during the random access procedure and improves the network capacity to support many UEs. These contributions provide a comprehensive set of solutions to address the limitations of current NB-IoT and LEO satellite integration strategies, paving the way for efficient and scalable IoT networks in challenging environments.

Index Terms—IoT, LPWAN, Satellite

I. INTRODUCTION

In recent years, Low-Power Wide-Area Networks (LPWANs) have emerged as an essential technology in the Internet of Things (IoT) [1]. Many LPWAN technologies have been developed. The unlicensed spectrum was populated by loss-tolerant LPWAN technologies, quickly dominating the IoT landscape and market due to their easy deployment. Among them, Sigfox [2] and the Long Range (LoRa) technology [3]. At the same time, the Narrowband IoT (NB-IoT) technology is gaining widespread attention because its synchronization and resource allocation strategy make it exceptionally effective in applications requiring high reliability and connection quality [4]. Designed by the Third Generation Partnership Project (3GPP) since Release 13, NB-IoT works on the licensed spectrum. It inherits and simplifies most of the features of Long Term Evolution (LTE), thus being compatible with

existing infrastructure and significantly reducing deployment complexity [5].

However, there are significant limitations with respect to geographic coverage in traditional ground networks such as mountains and marine areas. Moreover, in natural disasters, wars, and other critical situations, the gateway on the ground or the connection between the gateway and the server can easily be disrupted. Thereby, backhauling IoT devices with satellite networks has emerged as a significant advancement towards the objective of global connectivity [6]. In this context, the Direct-to-Satellite (DtS) architecture stands out. Due to their proximity to Earth, Low-Earth Orbit (LEO) satellites are particularly suitable for DtS IoT. They offer lower propagation delays and stronger signals for efficient communication with low-power devices. Recent advances in CubeSat technology have also significantly reduced the cost of LEO satellites [7]. However, battery-operated LPWAN devices also pose significant challenges as they communicate directly with satellites. The high maneuverability of LEO satellites causes significant variations in Doppler effects and propagation delays, making synchronization of NB-IoT networks challenging. Limited satellite availability increases energy consumption, as devices often wait for transmission opportunities. The standard solution [8], which relies on Global Navigation Satellite Systems (GNSS) for real-time positioning and precompensation, increases energy consumption, as GNSS modules must operate frequently. Furthermore, the larger satellite coverage area results in congestion and high collision rates during the random access phase of NB-IoT. To address these challenges, based on the dissertation [9], this digest details several key contributions to improving the efficiency and reliability of NB-IoT networks integrated with LEO satellites.

- **Performance Evaluation Framework [10]:** A systematic framework is proposed based on key performance indicators (KPIs) such as reliability, latency, throughput, and energy efficiency. This framework provides a structured approach to evaluating and optimizing the performance of satellite-based IoT (LPWAN) communication systems. It balances trade-offs among various metrics to meet application requirements.
- **GNSS-Free Synchronization Method [11]:** A novel method for downlink synchronization is introduced, eliminating the need for GNSS modules. This approach significantly reduces device complexity by leveraging Doppler prediction while maintaining synchronization accuracy in

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the dynamic LEO satellite environment.

- **GNSS-Free Wake-Up Strategy [12]:** A GNSS-free wake-up strategy is designed to further improve energy efficiency. This strategy optimizes the management of active and sleep states for User Equipment (UE). It allows devices to preserve power during intermittent satellite coverage and extend battery life without compromising communication reliability.
- **Early Collisions Detection Method [9]:** An early collision detection method in high-density scenarios mitigates congestion and reduces collisions during the random access phase. This approach enhances the network’s capacity to handle many UEs, ensuring reliable connections efficiently.

The remainder of the paper is organized as follows. Sec. II briefly reviews related works, while Sec. III pictures the core ideas of the dissertation in detail. Finally, Sec. IV concludes and envisages future works.

II. RELATED WORKS

Integrating LTE technologies with LEO satellites has become a popular research direction. [13] explores satellite-enabled LTE systems within LEO constellations. [14], [15] assume that each UE is equipped with a GNSS receiver and uses the captured positioning together with the Two-Line Element set (TLE) to determine the relative position of the LEO satellite and use this information to predict the frequency and time offset. Furthermore, 3GPP standards [8] base the correct functioning of NB-IoT on the availability of GNSS in UEs. The specification recognizes that GNSS is energy-intensive, so the evaluation of energy consumption related to some implementations is also detailed. Calculating and pre-compensating frequency shifts and delays through GNSS and TLE data is undoubtedly an accurate solution. However, from a practical point of view, GNSS draws more current than needed, adds complexity to circuit design, and eventually increases the cost of low-power devices. Furthermore, from a technical perspective, linking NB-IoT for LEO DtS communications to the availability of GNSS makes such an architecture neither resilient to outages nor viable in GNSS-denied environments.

In fact, the need for GNSS-free DtS solutions has been recognized in the scientific literature. [16] proposes a Doppler precompensation of NB-IoT beacon signals that does not require any change on the configuration of UEs: they do not need either to be equipped with GNSS or to listen to a broader spectrum to cope with Doppler effect. This strategy is energy-efficient for UEs but requires significant changes in the hardware and software of the eNB-equipped satellite. Alternatively, [17] proposed to modify the physical layer of NB-IoT about the structure of the preamble and the synchronization procedure to achieve uplink synchronization. In addition, there is no precompensation, thus requiring the UE to keep receiving the synchronization signals until the first uplink signal is sent. Both solutions require significant changes to either the NB-IoT protocol or the hardware. Regarding Doppler compensation without GNSS, a commonly used approach is

“Fast-tracking,” where a terminal on the ground should keep receiving downlink beacon signals to calculate the real-time Doppler offset [18]–[21]. However, these approaches require high processing units and constant communication capabilities, which do not match the desired behavior of low-power duty-cycled IoT devices. Instead, the “predictive tracking” strategy estimates the Doppler curve during the satellite’s passage from the Doppler-shifted frequency of several consecutive downlink synchronization signals. Once the Doppler curve is understood, the expected trajectory is also known, so the frequency shift does not need to be further estimated. [22] uses the received signal combined with TLE satellite position information to plot a Doppler curve, allowing prediction of the Doppler shift at each moment throughout the process. Using a mathematical model, the authors of [23] proposed a method to calculate the Doppler curve using two downlink signals. However, neither of these papers considered the impact of the downlink signal measurement error on the Doppler curve drawing. Building on these works, this digest introduces a method (Sec. III-B) that avoids hardware-level modifications for satellite and ground devices while accounting for downlink signal measurement errors in Doppler curve prediction.

Regarding the availability problem, similar to the synchronization issue, GNSS is used by devices to determine their location on the Earth. Combined with satellite constellation information, this allows the calculation of the next satellite pass, allowing devices to wake up at the appropriate time. After collecting the satellite orbital data transmitted by an eNB-equipped LEO satellite through downlink messages, a UE can calculate the trajectory of that satellite using algorithms like the Simplified General Perturbations Model 4 (SGP4) [24]. In fact, given TLE sets, the SGP4 algorithm can calculate the position of a satellite at a specific time. Its high efficiency and accuracy make it a suitable choice for IoT devices. For the UE’s position, some methods for locating IoT devices, including terrestrial-based LPWAN techniques, novel GNSS solutions, and innovative positioning techniques leveraging LEO satellite constellations, have been summarized and compared in [25]. Two methods are commonly proposed for LEO satellites: uplink signals collected by satellites or downlink signals collected by ground UEs. Both methods rely on Doppler frequency shift measurements. The first method requires ground stations to integrate uplink signals from multiple satellites, increasing complexity and preventing devices from determining their location. Both methods also depend on multiple satellites being simultaneously available, which is impractical in scenarios with a single or limited number of satellites.

Alternatively, predicting the next satellite pass can be done using the SGP4 algorithm, which calculates the satellite’s future position relative to the UE. Although accurate, this approach demands significant computational resources, which poses challenges for resource-constrained IoT devices. In [26], the authors proposed a novel method to calculate the revisit time of LEO satellites and applied it to the optimal design of remote sensing satellites. Yet, this method focuses on

repeated ground track orbits [27], thus resulting applicable only to a particular subset of LEO orbits. To provide a more general solution, [28] proposed a semi-analytical method to calculate revisit times for the Walker constellation [29] with discontinuous coverage. However, only the maximum and average revisit times are discussed. To face these challenges, this digest discusses a strategy (Sec. III-C) that avoids the need for positioning equipment and complex calculations to predict the next satellite pass.

However, even with efficient wake-up strategies, the random access procedure poses another critical challenge, particularly in high-density scenarios where multiple devices attempt to connect simultaneously, leading to collisions. Studies on early collision detection mainly follow two approaches: modifying only the eNB or redesigning the preamble structure. For the first approach, [30] proposes a GNSS-free NB-IoT random access scheme using a two-stage change point detection technique with an auto-encoder, while [31] employs a CNN-based method for collision detection in LTE networks without protocol changes. Both methods place high computational demands on satellites, making them unsuitable for low-cost LEO systems. For the second approach, [32] introduces Single Root Preamble Sequences (SRPS) to improve collision detection and preamble accuracy by enabling early detection, preventing Msg2 transmission during collisions. However, while all existing studies focus on detecting collisions, they do not reduce the probability of collisions. So, In Sec. III-B, two methods are introduced for addressing random access collisions, aiming to reduce collision rates and improve the success of the random access procedure through enhanced detection and optimized design.

III. PROPOSED APPROACHES

A. KPIs for *DtS IoT*

Before resolving the challenges, it is worth designing a basic framework to evaluate the performance of LPWANs (NB-IoT and LoRaWAN), which is the first step to effectively compare their modes of operation. This section discusses only these four most critical KPIs (reliability, latency, throughput, and energy-efficiency) for LPWAN [10]. The importance of evaluating all these aspects in choosing the most suitable network technology can be intuitively understood. At the same time, an extension to ground-to-satellite communications will also be discussed.

First, a communication protocol is reliable if the transmitter can be notified by an acknowledgment (ACK) that the correct delivery of data frames from the receiver has occurred. The lack of any ACK mechanism makes the communication protocol unreliable. This is the case of unconfirmed Class A LoRaWAN frame transmissions. Instead, the portion of acknowledged transmissions provides a measure of the **reliability** of the communication protocol. This KPI can be evaluated for LoRaWAN confirmed-based communications and NB-IoT. For satellite LPWANs, reliability is significantly influenced by the visibility of LEO satellites. Packet losses often occur due to the intermittent availability of the LoRa gateway (eNB). Although

LEO satellites provide wide coverage, the high density of nodes in their footprint increases packet loss rates (PLR), reducing reliability. However, with a constellation of LEO satellites that ensures continuous coverage, reliability can be equivalent to that of terrestrial systems.

Then, the time elapsed from the generation of the data frame to its correct delivery (through a variable number of retransmissions) is the **latency** of the network, which is affected by the MAC schemes, together with the propagation time and the average number of retransmissions. Due to satellite movement, the propagation delay in satellite networks is significantly longer and more variable than in terrestrial networks. Additionally, intersatellite links (ISLs) contribute to latency for LEO constellations, with more ISLs leading to higher delays. For NB-IoT, synchronization delays are a significant factor and latency varies depending on the optimization mode. Higher PLR increases the number of retransmissions, resulting in higher latency. However, for confirmed messages, acknowledgments are handled directly by the eNB, avoiding additional satellite backhaul delays.

The **throughput** is the rate of successful packet delivery. The traffic generated by each device, the density of nodes and the PLR impact the throughput value. The network with more density will generate more traffic, increasing the PLR. Note that the ideal throughput is the traffic generated when *PLR* equals 0. As in the case of reliability, the throughput is also affected by the satellite availability time and the wide coverage range. The unavailability of the satellite causes more packet losses and, therefore, less throughput. Similarly, having many devices (with higher density) in the satellite's coverage range translates into higher PLR due to data packet collisions in LoRa and congestion during NB-IoT synchronization. As a consequence of increased PLR, the throughput of the satellite LPWAN decreases.

Finally, the network **energy efficiency** measures the number of successfully transmitted bits per unit of energy consumed, reflecting how effectively the system consumes energy. It is influenced by network throughput and energy consumption, which depend on factors such as PHY and MAC parameters and the number of transmissions. In satellite networks, the distance between IoT devices and satellites significantly increases energy consumption for transmission and reception. In contrast, the energy required for processing messages remains similar to that in terrestrial networks. The energy consumed for the synchronization process also becomes a significant component, especially in NB-IoT systems, where energy consumption varies depending on the adopted optimization method and the number of uplink and downlink packets. Clearly, the best performance cannot be achieved for all KPIs at the same time. Therefore, a trade-off must be considered based on the specific application needs.

B. *Energy-efficient synchronization for DtS NB-IoT*

The first and foremost challenge in effectively integrating NB-IoT with satellite communication is the synchronization issue. However, using NB-IoT for ground-to-satellite com-

munications is not cheap and energy efficient because some technical barriers hinder its worldwide adoption. Due to the high-speed motion of LEO satellites, communications are affected by the Doppler effect, with a measured frequency offset of ± 40 kHz for satellites elevated 600 km above the ground [19]. As a result, the signal can be significantly degraded, and link layer frames can be lost. In this sense, as introduced before, starting from Release 17 [8], 3GPP has been specifying how NB-IoT/eMTC (enhanced Machine Type Communication) can support non-terrestrial networking and the case scenario pictured above: each UE must be equipped with a GNSS receiver and must be configured with the ephemeris of the satellite using the TLE to pre-compensate the Doppler shift and propagation delay. However, the need for a GNSS receiver implies extra power consumption and an increased cost of UEs. In this context, a new approach is proposed to predict the Doppler effect by estimating the trajectory of the satellite through the sky without GNSS capabilities [11]. This is done through the observation of NB-IoT downlink signals. The computed prediction is used to precompensate the Doppler shift.

When a UE wakes up (or is bootstrapped), the first step is to perform a cell search to obtain key information about the network. This is done by waiting for a Narrowband Primary Synchronization Signal (NPSS) received from an eNB in the scope. The NPSS is a 1ms-long signal periodically broadcast by any eNB every 10 ms. The UE uses such a signal for the initial time and frequency synchronization.

With the method presented in [11], the UE constructs a Doppler curve from multiple NPSS signals to precompensate frequency shifts during satellite visibility. The Doppler effect represents the frequency shift caused by the relative motion between a satellite and a UE. In LEO satellite communications, this shift depends on parameters such as the satellite’s altitude and elevation angle. Errors affect the measured Doppler shift, which is modeled as Additive White Gaussian Noise (AWGN) with zero mean and adjustable variance. The measured shift combines the actual Doppler shift and the measurement error. The Doppler curve parameters, including the satellite’s trajectory and maximum elevation angle, are estimated using the least-squares method. The method uses the measured Doppler shifts from multiple NPSS signals and aligns them with the modeled Doppler curve based on the satellite’s motion. The residuals between the measured and predicted shifts are calculated and the Gauss-Newton algorithm iteratively minimizes these residuals.

Fig. 1 shows how to interpret the simulation results. The figure compares the original Doppler curve and the estimated one calculated through the mathematical model. Here, the standard deviation of the simulated AWGN-like source of errors is set to 20 Hz, and the UE needs to receive 10 NPSS beacons to estimate the Doppler curve. Zooming in on the evaluated time interval (see Fig. 1), it can be seen that each signal is affected by a random error, and the final fitting result is very close to the original Doppler curve, which shows that the mathematical model is feasible. The simulation

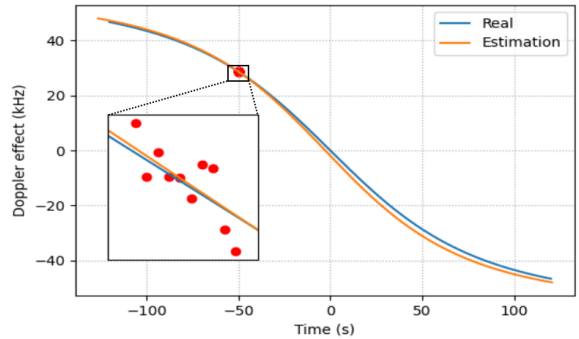


Fig. 1. Example of a sample simulation result [11].

results show that a UE needs to listen to about **10** beacon signals in **1** second to accurately and robustly predict the Doppler curve, thus enabling a lightweight (and eventually truly energy-efficient) implementation of NB-IoT over ground-to-satellite links.

C. A wake-up strategy for GNSS-free *DtS* NB-IoT

So far, to be able to get synchronized with a LEO satellite, it has been assumed that the satellite is within the range of a UE. Another challenge arises: ensuring that ground devices wake up only when a satellite is within range and remain in sleep mode without relying on GNSS. To address the challenge of discontinuous coverage, the 3GPP standards base the correct functioning of NB-IoT on the availability of GNSS in UEs. The specification recognizes that GNSS is energy expensive, so the evaluation of energy consumption related to some implementations is also detailed. Calculating and precompensating frequency shifts and delays through GNSS and TLE data is undoubtedly an accurate solution. Still, as [12] shows, GNSS-enabled devices are not the best choice for IoT applications.

In [12], a wake-up strategy is proposed, and it can be summarized as a “poll, learn, go” process. The “**poll**” part is represented by a Network Search phase. When an NB-IoT UE needs to send or receive data through the Internet, it first needs to get synchronized with an eNB in its vicinity. Ground UEs intermittently wake up and poll the radio for beacon signals, i.e., NPSS NB-IoT signals. To save energy, the UE uses an intermittent listening strategy, waking up regularly and listening for NPSS signals for 11 ms before returning to sleep. Through simulations, the optimal interval was found to be approximately 150 seconds, roughly matching the satellite pass window.

Once an NPSS signal is detected, the wake-up strategy enters its “**learn**” part. During this phase, the UE tries to predict when a LEO satellite will be within its range and builds up a list of next satellite passes. The UE wakes up at each expected satellite pass to check whether the prediction was correct and to continuously update the list. In detail, after receiving the first NPSS signal, the UE estimates the satellite’s maximum elevation angle with the method proposed

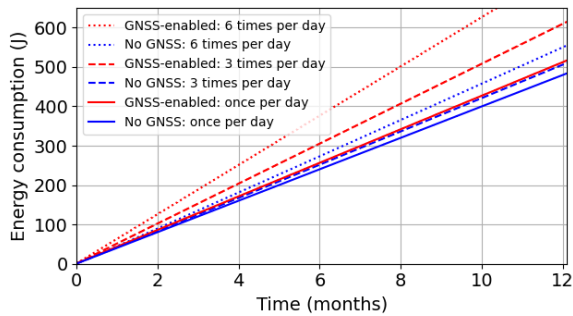


Fig. 2. Comparison of energy consumption during one year [12].

in the previous section and calculates two possible locations for its position using Doppler shift measurements and orbital information provided by the satellite. Then, the UE predicts the next satellite passes based on its estimated position and the satellite’s trajectory. Using these predictions, the UE can enter sleep mode and wake up just before the predicted satellite passes. The wake-up timing is adjusted to account for uncertainties in revisit times and visibility windows. If no NPSS signal is received during the predicted pass, the UE will adjust its predictions and repeat the process for the next satellite pass in the list. Finally, an algorithm is proposed to refine the position of the UE over multiple satellite passes.

Once the UE verifies that its prediction is converging to stability, the wake-up strategy enters into the “go” part of the strategy. As shown in 2, which compares the GNSS-free wake-up strategy introduced in [9] (red) with the GNSS-based solution of 3GPP (blue), showing that the energy consumption of the GNSS-free strategy is lower than that of the GNSS-based solution. Moreover, as daily transmissions increase, the energy savings with the GNSS-free strategy become increasingly significant.

D. Early detection in random access for DTS NB-IoT

The methods introduced, including lightweight synchronization through Doppler effect prediction and energy-efficient wake-up techniques, ensure that NB-IoT UEs maintain reliable communication links with LEO satellites even in scenarios where the GNSS is unavailable. These methods focus just on energy consumption among the KPIs introduced in Sec. III-A. The analysis that was conducted focused on the behavior of a single UE since the number of UEs does not affect these methods because only downlink system messages and synchronization signals are used. Satellites have a much larger coverage area than traditional terrestrial networks, accommodating a significantly higher number of UEs, thus increasing the likelihood of congestion during the random access phase. The random access procedure in LTE (NB-IoT) consists of Msg1, where UEs transmit a random access preamble, followed by Msg2, where the eNB responds with timing alignment and uplink resource allocation. In Msg3, UEs send identification messages using the assigned resources, and finally, Msg4, which eNB sends, resolves the contention by confirming the successful access

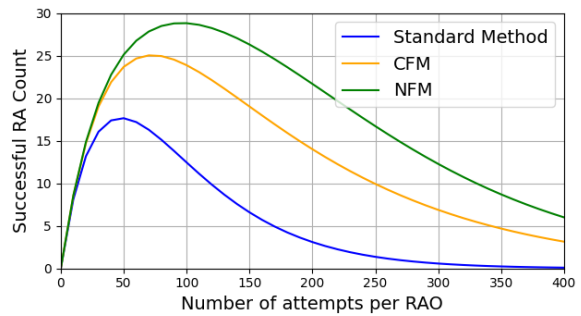


Fig. 3. Comparison of simulations with theoretical models.

for one UE. As introduced before, related work in this domain has focused on utilizing various techniques to detect when an eNB receives Msg1 from different UEs on the same subcarrier, allowing it to avoid sending Msg2. These methods can prevent UEs from proceeding to Msg3 by preventing the transmission of Msg2, reducing unnecessary energy consumption. However, the problem with these approaches is that when multiple Msg1 signals are received simultaneously on the same subcarrier, a collision inevitably occurs, making it impossible to identify which UEs can transmit Msg3. As a result, even though the energy costs associated with Msg3 are avoided, the probability of a successful connection remains low, as only a few UEs can ultimately connect to the eNB.

To address the limitations of current collision detection methods, dissertation [9] introduces two novel methods, the Closest First Method (CFM) and the Non-collided First Method (NFM). CFM uses the Timing Advance (TA) value returned in Msg2 to allow UEs to determine whether their Msg1 transmission was successful. By dividing the satellite’s coverage area into regions corresponding to specific TA values, UEs can match their location with the region associated with the received TA value. Only UEs with a matching region send Msg3, effectively detecting potential collisions early. Additionally, CFM does not require hardware modifications in UEs or satellites, while NFM is based on advanced techniques that enable the satellite to distinguish between preambles from different UEs [32]. After adjusting the delay precompensation, the satellite can find the time slot containing only a single preamble and return the corresponding TA value, ensuring that Msg3 transmissions are free of collisions.

As shown in Fig. 3, some simulation results validated the theoretical models and demonstrated that both methods significantly improve the random access success rates compared to the standard approach, with NFM consistently outperforming CFM. The impact of position estimation errors was also analyzed, showing that higher errors reduce success rates, particularly as the number of time slots increases. For severe position errors, fewer time slots may yield better results by minimizing the chances of misjudging areas.

IV. CONCLUSION

This dissertation comprehensively explores the integration of NB-IoT with LEO satellites, addressing critical challenges, and proposing innovative solutions to enhance performance in satellite-based IoT networks. To effectively evaluate and optimize satellite IoT communications, a mathematical framework based on four key performance indicators (reliability, latency, throughput, and energy efficiency) is proposed. To address the synchronization challenges posed by LEO satellites, a GNSS-free downlink synchronization method is introduced, leveraging Doppler curve estimation to reduce energy consumption and system costs. Furthermore, an intermittent wake-up strategy for GNSS-free UEs is proposed, enhancing energy efficiency while ensuring reliable communication, even in scenarios with intermittent satellite coverage. To address the issue of random access collisions in high-density environments, two innovative methods (CFM and NFM) are presented, enabling more effective collision resolution and significantly improving system throughput. These contributions collectively provide practical and efficient solutions to enhance NB-IoT integration with LEO satellite systems.

Future works will focus on hardware implementation, detailed latency and reliability evaluation, and optimization of resource allocation strategies. The hardware implementation will validate the feasibility of the proposed methods, addressing complexities in Doppler curve estimation, wake-up strategies, and random access performance. Evaluating latency and reliability will help us understand the effects of satellite dynamics and interference on communication, enabling protocol improvements. Another critical area for future work is the optimization of resource allocation strategies. Although this dissertation focused on increasing the number of devices that can successfully perform random access, the challenge of efficiently allocating resources during the data transmission phase remains. Efficient resource management is essential to handle the high density of devices and the dynamic nature of satellite communications. Research should explore advanced algorithms and techniques for dynamic resource allocation, considering factors such as traffic patterns, device mobility, and varying network loads. This helps maximize resource use and enhance overall network performance.

REFERENCES

- [1] R. S. Sinha, Y. Wei, and S.-H. Hwang, "A survey on lpwa technology: Lora and nb-iot," *ICT Express*, vol. 3, no. 1, 2017.
- [2] Sigfox, "Sigfox, Available online: <https://www.sigfox.com/en>," 2010, accessed on 1 May 2022.
- [3] Semtech, "LoRa Alliance, LoRaWAN Specifications, Available online: <https://lora-alliance.org/>," 2009, accessed on 1 September 2021.
- [4] E. M. Migabo, K. D. Djouani, and A. M. Kurien, "The narrowband internet of things (nb-iot) resources management performance state of art, challenges, and opportunities," *IEEE Access*, vol. 8, 2020.
- [5] 3GPP, "3GPP Specifications, Available online: <https://3gpp.org/>," 2015.
- [6] M. R. Palattella and N. Accettura, "Enabling Internet of Everything Everywhere: LPWAN with Satellite Backhaul," in *Global Information Infrastructure and Networking Symposium (GIIS)*, 2018.
- [7] A. H. Poghosyan and A. Golkar, "Cubesat evolution: Analyzing cubesat capabilities for conducting science missions," *Progress in Aerospace Sciences*, vol. 88, 2017.
- [8] 3GPP, "Tr 36.763, study on narrow-band internet of things (nb-iot) / enhanced machine type communication (emtc) support for non-terrestrial networks (ntn) (release 17, v17.0.0)," 3GPP, Tech. Rep., June 2021.
- [9] Z. Zhou, "Ubiquitous IoT through space communications," Theses, UPS Toulouse, Oct. 2024. [Online]. Available: <https://laas.hal.science/tel-04822405>
- [10] Z. Zhou, M. Afhamisis, M. R. Palattella, N. Accettura, and P. Berthou, "Pervasive LPWAN connectivity through LEO Satellites: trading off reliability, throughput, latency, and energy efficiency," in *Low-Power Wide-Area Networks: Opportunities, Challenges, Risks and Threats*, I. Butun and I. F. Akyildiz, Eds. Springer, 2022.
- [11] Z. Zhou, N. Accettura, R. Prévost, and P. Berthou, "Lightweight synchronization to nb-iot enabled leo satellites through doppler prediction," in *Proc. of WiMob*, 2023, pp. 218–223.
- [12] Z. Zhou, N. Accettura, and P. Berthou, "A wake-up strategy enabling gnss-free nb-iot links to sparse leo satellite constellations," *IEEE Internet of Things Journal*, pp. 1–1, 2025.
- [13] A. Guidotti, A. Vanelli-Coralli, M. Caus, J. Bas, G. Colavolpe, T. Foggi, S. Cioni, A. Modenini, and D. Tarchi, "Satellite-enabled lte systems in leo constellations," in *2017 IEEE ICC Workshops*, 2017.
- [14] M. Conti, S. Andrenacci, N. Maturo, S. Chatzinotas, and A. Vanelli-Coralli, "Doppler impact analysis for nb-iot and satellite systems integration," in *ICC*, 2020.
- [15] O. Liberg, S. E. Löwenmark, S. Euler, B. Hofström, T. Khan, X. Lin, and J. Sedin, "Narrowband internet of things for non-terrestrial networks," *IEEE Communications Standards Magazine*, vol. 4, no. 4, 2020.
- [16] O. Kodheli, S. Andrenacci, N. Maturo, S. Chatzinotas, and F. Zimmer, "Resource allocation approach for differential doppler reduction in nb-iot over leo satellite," in *ASMS/SPSC*, 2018.
- [17] H. Chougrani, S. Kisseleff, W. A. Martins, and S. Chatzinotas, "Nb-iot random access for nonterrestrial networks: Preamble detection and uplink synchronization," *IEEE IoT Journal*, vol. 9, no. 16, 2022.
- [18] J. Li, Y. Zhang, Y. Zhang, W. Xiong, Y. Huang, and Z. Wang, "Fast tracking doppler compensation for ofdm-based leo satellite data transmission," in *IEEE ICC*, 2016.
- [19] W. Wang, Y. Tong, L. Li, A.-A. Lu, L. You, and X. Gao, "Near optimal timing and frequency offset estimation for 5g integrated leo satellite communication system," *IEEE Access*, vol. 7, 2019.
- [20] Z. Huang, "A pilot-aided method of doppler offset estimation and compensation," in *ICCCS*, 2021.
- [21] C. An and H.-G. Ryu, "Compensation systems and performance comparison of the very high doppler frequency," in *IEEE ComNet*, 2020.
- [22] H. Rouzegar and M. Ghanbarisabagh, "Estimation of doppler curve for leo satellites," *Wireless Personal Communications*, 2019.
- [23] I. Ali, N. Al-Dhahir, and J. E. Hershey, "Doppler characterization for leo satellites," *IEEE Trans. Commun.*, vol. 46, 1998.
- [24] J. Morales, J. J. Khalife, U. S. Cruz, and Z. Kassas, "Orbit modeling for simultaneous tracking and navigation using leo satellite signals," *Proc. of the 32nd Int. Tech. Meeting of the Sat. Division of The Inst. of Navig. (ION GNSS+ 2019)*, 2019.
- [25] T. Janssen, A. Koppert, R. Berkvens, and M. Weyn, "A survey on iot positioning leveraging lpwan, gnss, and leo-pnt," *IEEE Internet of Things Journal*, vol. 10, no. 13, 2023.
- [26] X. Luo, M. Wang, G. Dai, and X. Chen, "A novel technique to compute the revisit time of satellites and its application in remote sensing satellite optimization design," *Int. J. of Aerospace Engineering*, 2017.
- [27] M. Jafari-Nadoushan and N. Assadian, "Repeat ground track orbit design with desired revisit time and optimal tilt," *Aerospace Science and Technology*, vol. 40, 2015.
- [28] N. H. Crisp, S. Livadiotti, and P. C. E. Roberts, "A semi-analytical method for calculating revisit time for satellite constellations with discontinuous coverage," *ArXiv*, vol. abs/1807.02021, 2018.
- [29] C.-J. Wang, "Structural properties of a low earth orbit satellite constellation - the walker delta network," in *Proceedings of MILCOM '93 - IEEE Military Communications Conference*, vol. 3, 1993.
- [30] Y. Xu, J. Jiang, D. He, and W. Zhang, "A nb-iot random access scheme based on change point detection in ntns," *IEEE Open Journal of the Communications Society*, vol. 4, 2023.
- [31] Y. Yin, D. Zhao, X. Li, and S. Zeng, "Learning based preamble collision detection of cellular random access by physical layer features," in *NaNA*, 2023.
- [32] L. Zhen, Y. Zhang, K. Yu, N. Kumar, A. Barnawi, and Y. Xie, "Early collision detection for massive random access in satellite-based internet of things," *IEEE TVT*, vol. 70, no. 5, pp. 5184–5189, 2021.