Pervasive LPWAN connectivity through LEO Satellites: trading off reliability, throughput, latency, and energy efficiency

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Chapter 1
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Abstract With the increasing success of the Internet of Things (IoT) industry and the consequent conception of new IoT applications, a significant variety of network design challenges has been unfolded. As a consequence, different Low Power Wide Area Networks (LPWAN) technologies have been developed and marketed to address each specific application need. Among them, the Narrowband IoT (NB-IoT) was developed to target reliable communications over the licensed spectrum, while the Long Range (LoRa) was conceived as a loss-tolerant means over unlicensed frequencies. Recently, satellite LPWAN appeared as a new connectivity option and an affordable solution, particularly suitable for remote and not easily accessible areas. This book chapter timely addresses the opportunities and challenges of such satellite LPWAN architecture by providing a general framework for the evaluation of its performances. The chapter also describes a methodological approach for designing the network, selecting the configuration parameters and the traffic patterns, fitting the best trade-off among reliability, latency, throughput, and energy efficiency.

1.1 Introduction

Low Power Wide Area Network (LPWAN) is becoming a revolutionary technology for the Internet of Things (IoT) due to its low power consumption, long distance coverage, and low cost of the devices [19]. Many LPWAN technologies have been

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developed over the last few years. 3GPP standardized Cat-M and Narrow Band IoT (NB-IoT) [2], two complementary technologies targeting reliable applications over the licensed spectrum. At the same time, the unlicensed spectrum was recently populated by other loss tolerant LPWAN technologies, quickly dominating the IoT landscape and market for their easy deployment. Among them, Sigfox[1] and the Long Range (LoRa) technology [3].

With the cost reduction of CubeSat Low Earth Orbit (LEO) satellites, and the low latency achievable with large LEO constellations, satellite LPWAN recently became a new solution to connect a large set of IoT devices deployed in remote and even inaccessible areas [16]. Many IoT companies and satellite operators have invested a lot in making such a solution feasible. While few real deployments already exist, many research challenges still need to be addressed to make such network architecture a reality and bring IoT connectivity everywhere [43]. Clearly, satellite communications are still unable to support the low-latency requirements demanded by some IoT applications, like mission-critical applications, tactile Internet, factory automation, and Ultra-Reliable and Low-Latency (URLLC) systems [20]. On the contrary, they can easily meet the requirements of delay-tolerant applications, such as smart agriculture, smart grid, cross-border tracking systems, and maritime Internet of Things [52] and surveillance [34].

Interestingly, both LoRa and NB-IoT are highly configurable protocols that provide the possibility to choose among multiple link layer communication schemes to tackle different reliability requirements. Higher reliability is usually achieved at the price of larger latency. Notably, this trade-off between reliability and latency is highly susceptible to the amount of offered traffic, making the network throughput an additional element to be taken into account when designing the network. As a matter of fact, reliability, latency, and throughput are the three main Key Performance Indicators (KPIs) for any communication network [48]. Remarkably, the subset of IoT networks is featured by an additional KPI, i.e., energy efficiency. Indeed, a typical IoT network includes numerous cheap smart devices equipped with batteries, whose most energy-expensive activity is related to the radio module. Hence, IoT communication protocols should be designed to prolong the battery lifetime without requiring frequent substitutions or recharges. All in all, trading-off among reliability, latency, throughput and energy efficiency results as the sole approach able to tackle the need of any application. In this book chapter, a methodological approach to evaluate the performance of a satellite LPWAN network is presented, considering the challenges introduced by satellites.

The rest of the chapter is organized as follows. Sec. 1.2 introduces and compares NB-IoT and LoRa technologies by highlighting those technological facets making them easily exploitable for ground-to-satellite low power communications. Then, Sec. 1.3 investigates how the communication KPIs are strictly dependent on a set of parameters, with some of them being unmodifiable physical properties and the others being configurable protocol settings. Sec. 1.4 describes the opportunities and

challenges inherent to the integration of LPWAN with LEO satellites. Sec. 1.5 shows how the LPWAN KPIs are impacted by the satellite features. Finally, Sec. 1.6 draws conclusions and envisages future research directions.

1.2 LPWAN Technologies: LoRa vs NB-IoT

In the IoT landscape, the Low Power Wide Area Network (LPWAN) technology emerged as the best choice for enabling very low-cost long-range connections. Many LPWAN technologies have been developed over the last years, e.g., LoRa, Sigfox, NB-IoT, and CAT-M. This chapter focuses on LoRa and NB-IoT, whose integration with LEO satellites has already been investigated in the research community and partly implemented in the context of ongoing 3GPP work items [16]. Since the approach described throughout this chapter aims at picturing the integration of any LPWAN technology on ground-to-satellite IoT links, the key features of LoRa and NB-IoT are described in parallel according to a comprehensive mindset, in order to provide useful insights for the proper choice of the most fitting communication pattern. To help the reading, a very high-level comparison is provided in Table 1.1.

Table 1.1: Comparative Matrix: NB-IoT vs LoRaWAN

Feature **Technology*	**LoRaWAN**	**NB-IoT**
Specifications	Non-3GPP	3GPP
Uplink Modulation	CSS	SC-FDMA
Downlink Modulation	CSS	OFDM
Frequency Band	ISM unlicensed band	Cellular licensed band
Bandwidth	125/250/500 kHz	180 kHz
Maximum Data Rate	50 kbps	200 kbps
Coverage Range	5-20km [42]	1-10km
Security	AES 128 bit	3GPP(128-256 bit)

In details, **LoRa** was introduced by Semtech Corporation [1] and adopts a *Chirp Spread Spectrum* (CSS) modulation scheme to enable long range communication even in noisy environments [35]. Herein, a narrowband input signal is spread over a wider bandwidth and immediately transmitted; then, it can be correctly decoded very far away, even if severely attenuated. The LoRa modulation further enables the use of several Spreading Factors (SFs) to increase the ability of the receiver to decode simultaneous signal transmissions on the same frequency channel. Each SF is associated with a specific data-rate, transmission range, and energy consumption. Such communications happen on the *unlicensed* Industrial, Scientific, and Medical (ISM) *band*, thus competing for the use of the radio resources with other interfering technologies operating in the same frequency bands. The enormous interest of

[1] Semtech: https://www.semtech.com/lora

companies on such a cutting-edge technology pushed for the creation of the LoRa Alliance with the aim of promoting LoRa and designing a Medium Access Control (MAC) layer able to manage the communication resource exploitation in LoRa Wide Area Networks (LoRaWAN). The LoRaWAN protocol was initially defined as an open specification for LPWAN IoT, and, in December 2021, it has been finally recognized as a standard by the International Telecommunication Union (ITU [2]). The transposition as an ITU-T Recommendation (ITU-T Y.4480) validates the market trend in adopting LoRaWAN as an internationally recognized standard and defines the path ahead toward even wider adoption. More interestingly, several companies have been working with Semtech to ensure a pervasive availability of IoT services through LEO satellites equipped with LoRa transceivers. Among such companies, it is worth mentioning Lacuna Space [3], Thuraya [4], ACTILITY [5], and WYLD [6].

Instead, **NB-IoT** employs a *narrow band modulation* and works into the *licensed spectrum*. It was conceived by 3GPP and proposed for the first time in Release 13 [2] to make current cellular networks ready to support IoT applications with low cost, low power consumption, and low data rates. The development of the NB-IoT standard was initially based on the existing Long-Term Evolution (LTE) functionalities. Such an approach (i.e., leveraging on existing technology) allowed minimizing the development effort and shortening the time to market. The NB-IoT specification is still evolving, and the most recent releases, i.e., Rel-17 and Rel-18, focus on IoT over Non-Terrestrial Networks (NTN) to provide broader global coverage. Their objective is to address the challenges inherent to the integration of NB-IoT over ground-to-satellite links, i.e., initial synchronization, high propagation delays, Doppler variation rate, high paging load with a considerable number of users, etc. Several companies, like Sateliot[7], Ligado [8], and GateHouse[9], have invested in designing and developing global NB-IoT satellite networks and can already offer such service.

From the **Network Architecture** point of view, LoRaWAN and NB-IoT present a similar hierarchical structure with two tiers, as depicted in Fig. 1.1. With LoRaWAN, low power End Devices (EDs) communicate through LoRa links with all the LoRaWAN Gateways (GWs) in their transmission range. The GWs are totally controlled by the LoRaWAN Network Server (LNS), and their function is to encapsulate uplink LoRa frames received by EDs within TCP/IP packets and forward them to the LNS. The GWs also forward the downlink traffic from LNS to EDs. In fact, the LoRaWAN MAC protocol is established between any ED and the LNS. In turn, the LNS can be interconnected with several application servers.

[2] LoRaWAN® Formally Recognized as ITU International Standard for Low Power Wide Area Networking: https://lora-alliance.org/lora-alliance-press-release/

[3] Lacuna Space: https://lacuna.space/

[4] Thuraya: https://thuraya.com/

[5] Actility: https://www.actility.com/

[6] Wyld networks: https://wyldnetworks.com/

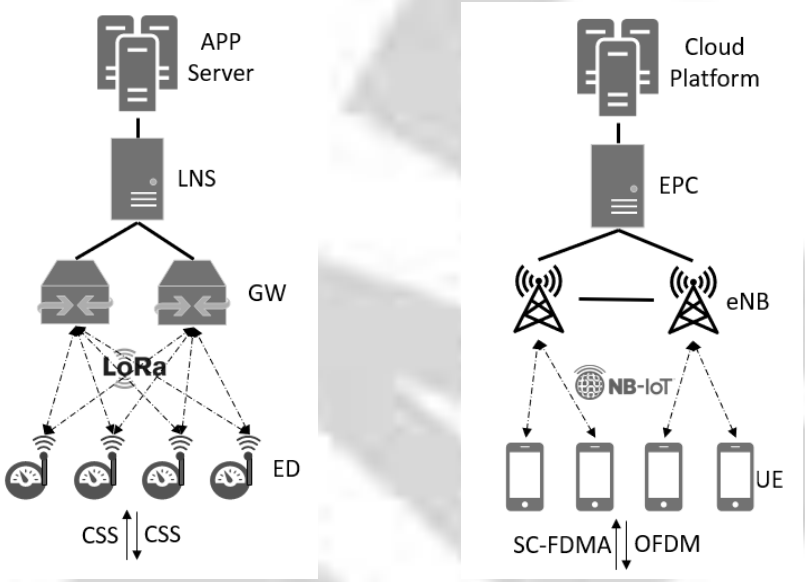
[7] Sateliot: https://sateliot.space/en/

[8] Ligado: https://ligado.com/

[9] Gatehouse: https://gatehouse.com/

Similarly, the NB-IoT network architecture can be divided into two main parts: the core network, namely the Evolved Packet Core (EPC), and the access network, namely the Evolved Universal Terrestrial Radio Access Network (E-UTRAN). EPC is responsible for transmitting the collected IoT data to the cloud platform for further processing and managing mobile devices [2].

The access network includes the User Equipment (UE) and the evolved Node B (eNB). Clearly, an NB-IoT UE plays the same network role as a LoRaWAN ED. Indeed, UEs and EDs are equipped with one or more sensors, a microcontroller, and a radio transceiver, and they are in charge of collecting and transmitting IoT data to the Internet through respectively the EPC and the LNS. Instead, the eNB (as the LGW) is the base station connecting the UE to the core network.



(a) LoRaWAN (b) NB-IoT

Fig. 1.1: Comparison between NB-IoT and LoRaWAN architectures

From the perspective of **physical layer**, LoRa achieves long range transmissions up to $\sim$ 20km thanks to the CSS modulation [42]. When an ED has some data to transmit, the signal is spread over the air using a specific bandwidth (BW) and SF. According to the LoRaWAN specification, the SF can assume integer values from 7 to 12. The SF impacts other two parameters of the LoRa PHY layer protocol, i.e., the Data Rate (DR) and the Time on the Air (ToA). The DR is the number of bytes transmitted per second on the air. The ToA is the amount of time for a message to be delivered to the GW, and its length is directly proportional to the size of the transmitted frame and inversely proportional to the DR.

The LORa DR can be calculated as

$$DR = SF \times \frac{Bandwidth}{2^{SF}} \times CR. \tag{1.1}$$

The CR is the code rate, which is a fractional number that represents the proportion of useful (non-redundant) data in the encoded data stream to the total encoded data. In fact, a higher SF allows a longer coverage range and a higher resilience against noise. However, according to the Equation 1.1, this comes at the cost of a smaller DR, that in turn implies a longer ToA and larger energy consumption. To overcome such limitations, Semtech recently designed a new LoRa PHY layer, namely Long-Range Frequency Hopping Spread Spectrum (LR-FHSS), also known as LoRa-Extended [15]. The LR-FHSS operates in the same channels as the regular LoRa PHY. But the LoRa bandwidth is divided into several smaller ones, named hops. In LR-FHSS, ED and GWs get synchronized using a pseudo random sequence, which specifies the specific hops to use for the data transmission. This sequence is exchanged using a header, with two or three replicas sent in randomly selected hops. Once the synchronization is established, then the ED starts transmitting the payload, which is divided into several small portions named *fragments*. Each fragment is sent over a different hop, following the pseudo random sequence previously exchanged. This results in a longer ToA, for transmitting the same payload, compared to the LoRa PHY (see Fig. 1.2). It must be noticed that LR-FHSS applies only to the uplink transmission. Downlink traffic still follows the regular LoRa PHY.

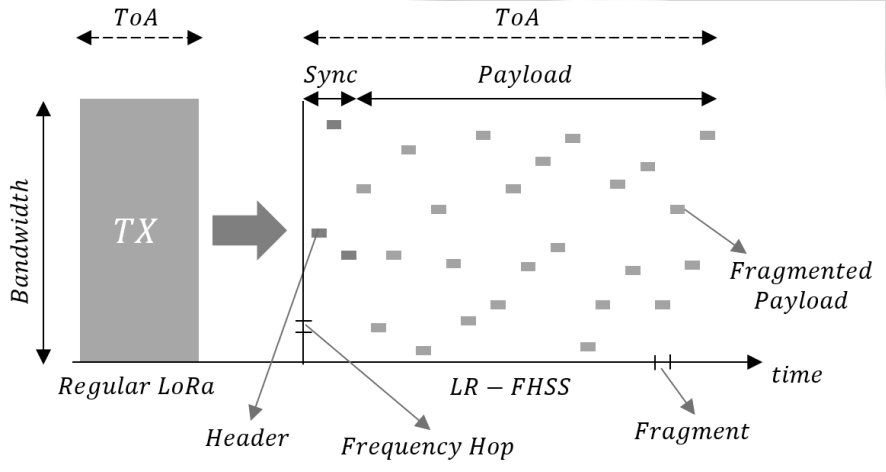


Fig. 1.2: LoRa PHY vs LR-FHSS

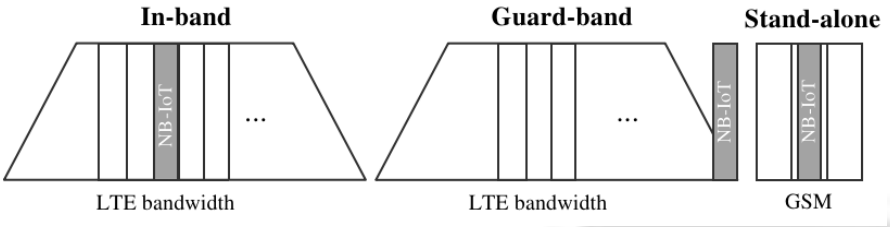


Fig. 1.3: NB-IoT deployment modes

> **Important**

However, since LoRa uses the unlicensed ISM band, the duty cycle must be configured to limit the maximum amount of data each device can upload daily, while respecting the access policies. In Europe, the European Telecommunications Standards Institute (ETSI) enforces per sub-band duty cycle policies ranging from 0.1% to 10% [26]. In the Federal Communications Commission (FCC) regions, a maximum ToA of 400ms is imposed, for the uplink transmissions, while there is no restriction on the duty cycle. Finally, concerning the bandwidth, 125 kHz can be adopted in both regions, while 250 kHz and 500 kHz are allowed in the ETSI and FCC regions, respectively.

Like LTE, and differently from LoRa, NB-IoT adopts two different modulation schemes for downlink and uplink messages, respectively Orthogonal Frequency-Division Multiple Access (OFDMA), and Single Carrier-Frequency Division Multiple Access (SC-FDMA). NB-IoT occupies the 180 kHz frequency band, corresponding to a block of resources in the LTE bandwidth. NB-IoT supports three deployment modes, illustrated in Fig. 1.3. The In-band mode occupies one of the Physical Resources Blocks (PRBs) of LTE. The Guard-band mode occupies only the protection band of LTE. In the stand-alone mode, NB-IoT can be deployed in any frequency spectrum, such as Global System for Mobile (GSM) frequency bands.

Fig. 1.4 illustrates the structure of NB-IoT radio frame. Each radio frame has a duration of 10 ms and is divided into 10 subframes. Each subframe is made up of 2 slots. One subframe consists of 12 x 14 Resource Elements (REs) with a 15 kHz subcarrier for downlink (3.75 kHz or 15 kHz for uplink). 3GPP has defined several channels and signals with distinct functions for uplink and downlink, as described hereafter.

For the downlink, as shown in Fig. 1.5, two synchronization signals, Narrowband Primary Synchronization Signal (NPSS) and Narrowband Secondary Synchronization Signal (NSSS), are transmitted in the subframes 5 and 9 to synchronize UE and eNB in time and frequency. The first subframe is Narrowband Physical Broadcast Channel (NPBCH), which is used to exchange critical system information such as deployment mode. The remaining subframes are occupied by the other two chan-

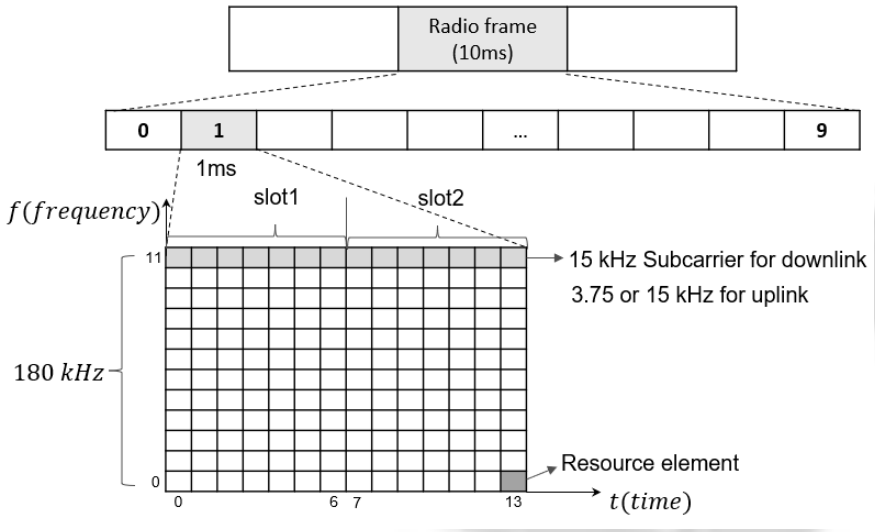


Fig. 1.4: Radio Frame of NB-IoT

nels: Narrowband Physical Downlink Control Channel (NPDCCH) and Narrowband Physical Downlink Shared Channel (NPDSCH). The control channel contains information on uplink and downlink resource scheduling, allowing the UE to know when to receive or send messages. In the shared channel, downlink data and other system messages are exchanged. Note that control and shared channels may occupy several subframes, depending on the size of the message, the number of repetitions, etc.

Two different channels are defined for uplink transmission, as also pictured in Fig. 1.5. The first connection attempt (Random access preamble) of the UE to the eNB is transmitted in Narrowband Physical Random Access Channel (NPRACH), where the collision happens. The uplink data is transmitted in Narrowband Physical Uplink Shared Channel (NPUSCH). Those resources are allocated by the upper layer avoiding a-priori any collision. Therefore, this channel is also known as a non-contention channel. Finally, NB-IoT supports two transmission modes: Multiton and Singleton. Singleton uplink messages occupy only one subcarrier, while Multiton uplink messages occupy multiple (3, 6, 12) subcarriers. So multiple UEs can occupy the same channel, allowing more users to be connected simultaneously.

Unlike NB-IoT, in a LoRaWAN network EDs do not negotiate the resource allocation with the GW, but they still need to join the network, before being able to transmit the data. To this aim, they should exchange some keys with the LNS, and ensure the secure data exchange over the end-to-end system. As shown in Fig. 1.6, two different join procedures are supported by the standard: Activation Before Personalization (ABP) and Over The Air Activation (OTAA). In the ABP, the keys are pre-stored in the ED. When there is a message to send, the keys are sent along with the data and authenticated by the LNS. Instead, in the OTAA mode, the EDs need

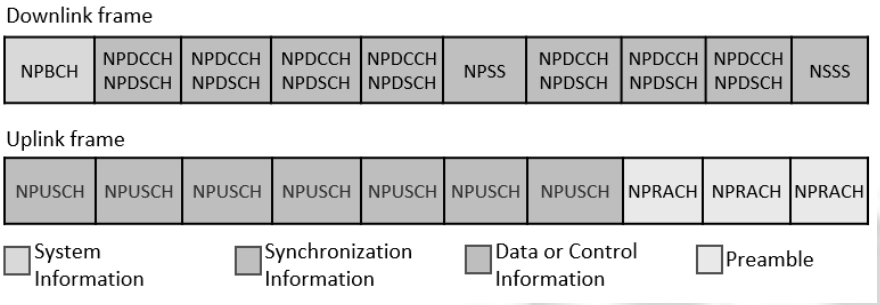


Fig. 1.5: Downlink and uplink frames of NB-IoT

to send a *join request* and receive *join accept* from the LNS, before being accepted in the network.

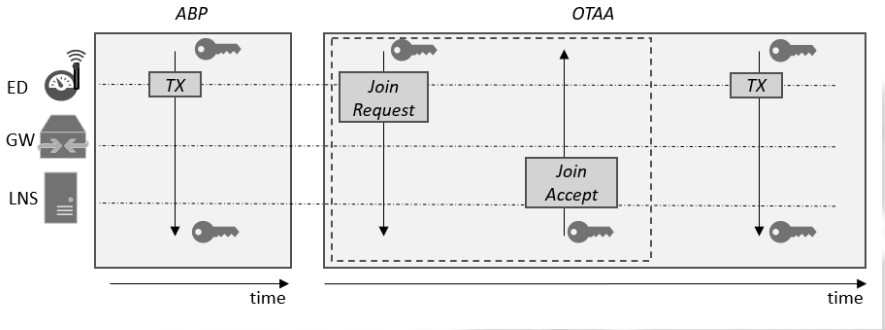


Fig. 1.6: LoRaWAN Join procedures: OTAA vs ABP.

The LoRaWAN protocol adopts an ALOHA-based random-access scheme [46] as **Medium Access Control Protocol**. EDs transmit without listening and sensing the channel before. The LoRa EDs can operate in three different communication classes, illustrated in Fig. 1.7. Class A is the simplest mode and the default class, supported by all the EDs. After each uplink transmission, two receive windows, $Rx1$ and $Rx2$, are opened, allowing the ED to receive downlink traffic from the LNS through the GW. The ED waits for $1s$ before opening the $Rx1$. If the ED cannot receive any downlink in the $Rx1$, then it opens the $Rx2$, after an additional delay of $1s$. The ED switches into sleep mode after $Rx2$, till the next uplink has started. The class C is like Class A, with the difference that the receiving windows are never closed, and they stay open till the next uplink. Thus, the class C is less energy-efficient than Class A. In Class B, the EDs use beacon messages sent from the GW to synchronize with the LNS. It allows the EDs to open additional receive windows, named ping slots,

without the need of prior uplink transmission. Since ED must be in RX mode during the ping slots, Class B implies additional energy consumption compared to Class A. It must be noticed that Class B devices still operate like Class A devices for uplink transmissions.

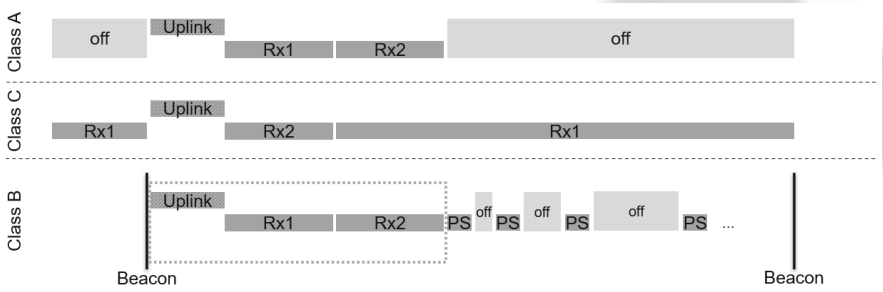


Fig. 1.7: The LoRaWAN communication mode: Classes A, B and C.

The UE of the NB-IoT must synchronize with the eNB by receiving the synchronization signals before connecting with the eNB. For LoRa, only Class B enables the synchronization between the ED and the GW using beacons.

When a UE is covered by more than one eNB simultaneously, it measures the received power and then selects the one with the best available coverage (best signal quality). In LoRa, the ED transmits to any gateways in its coverage range. It is up to the LNS to select the best gateway for sending back downlink traffic. Moreover, while in LoRaWAN, the ED receives the configuration parameters from the LNS, in an NB-IoT network, the UE itself determines the Coverage Enhancement (CE) level according to its distance from the eNB and thus, chooses the number of repetitions of a message (2-1024 times). The higher the CE level (0-2), the higher the power consumption of the data transmission [32].

When the UE has a message to send or monitors paging, it will connect to the eNB as shown in Fig. 1.8. The random-access process will begin once the UE completes the synchronization with the eNB. A random-access preamble is sent to the eNB using the random-access channel (Msg1). The UE starts a timer and waits for a random-access response (Msg2). If no response is received, the UE will send a new preamble. After a successful reception of Msg2, Msg3 is sent from the UE to the eNB, which holds control information of radio resources, data volume, reconfiguration request, etc. Msg4 is the connection setup and the contention resolution, where the eNB accepts to establish the connection with a UE. After receiving Msg4, the UE will enter the connected state from the idle state. Then the eNB and UE exchange messages for authentication and AS security configuration (Msg6-9). After that, UE sends its uplink data and receives downlink data. Finally, the eNB releases the connection if it detects inactivity from the UE (Msg10).

NB-IoT defines two optimization methods for data transmission to reduce message exchange: the User Plane (UP) and the Control Plane (CP) optimization. The CP

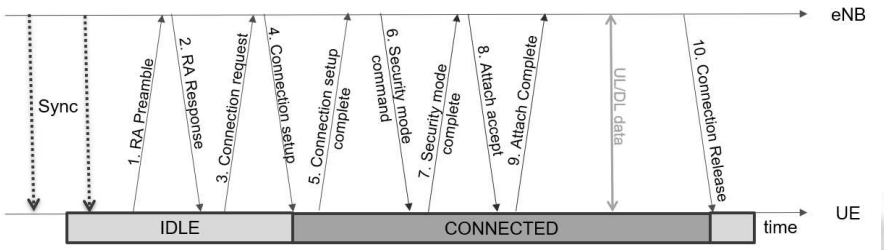


Fig. 1.8: NB-IoT Workflow

carries the signaling responsible for accessing the UE, allocating resources (e.g., messages exchanged after random access), etc.; the UP carries the user data.

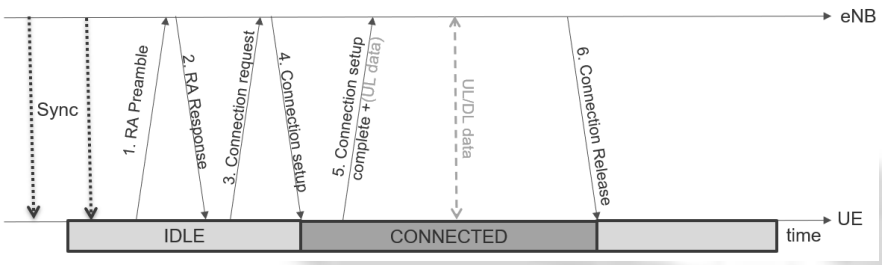


Fig. 1.9: NB-IoT CP optimization

It must be noticed that for sending and receiving a few bytes of data, the signaling overhead consumed by the UE from the idle state to the connected state is much more significant than the data load. To make data transmission more efficient, two optimization schemes have been proposed: Control Plane (CP) and User Plane (UP) optimization. With the CP optimization shown in Fig. 1.9, small packets can be added to the control message (Msg5) and bypass the security configurations to improve the speed for transferring small data. This mode is insecure compared to other modes.

The UP optimization allows idle users to transfer data quickly through the *suspend and resume* process. After establishing the first connection (see Fig. 1.10), the user's information can be stored in the eNB. No Connection Release message is transmitted. When there is new data to transfer, the UE can soon recover the connection without re-establishing the security information.

In Release 15, 3GPP defined the *Early Data Transmission* (EDT) mode to reduce UE energy consumption and message latency by reducing the number of transmissions [33]. Specified for both UP and CP optimization, the EDT can be used when the UE is in idle mode and has less than the maximum broadcast uplink data to send.

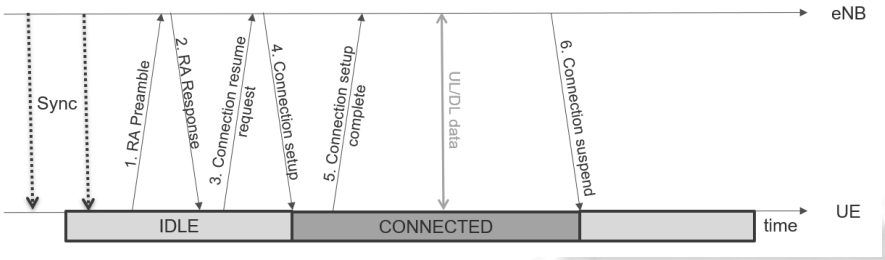


Fig. 1.10: NB-IoT UP optimization

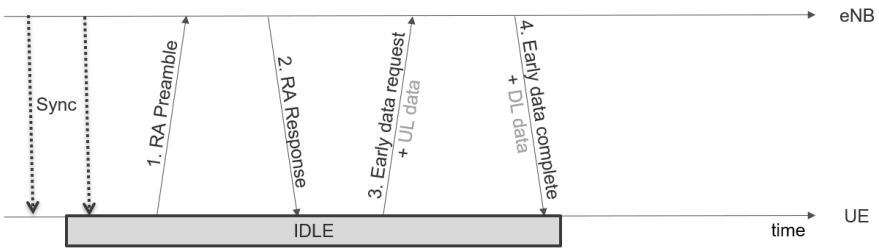


Fig. 1.11: NB-IoT Early Data Transmission

In this mode, only four messages between the eNB and the UE are required to complete the data transmission because the data is sent during the random-access procedure. As shown in Fig. 1.11, the data is included in Msg3. The method of encapsulating and transmitting uplink data is like the optimization of the CP. If the UE receives the Msg4 indicating that the procedure is terminated, it can go to the sleep state or stay in the idle state.

Thanks to more complex synchronization and resource allocation techniques, NB-IoT can offer higher reliability compared to LoRa. This is paid with (i) longer transmission delays, which can be reduced using CP, UP optimization, and EDT; and (ii) higher energy consumption for the IoT device. LoRa, while being more energy-efficient, it suffers from high collision probability due to the random-access mechanism. Both reliability and throughput can be improved using resource allocation schemes, like TDMA approaches.

In the following, an in-depth analysis of the performance achievable with the two technologies is conducted in order to identify key protocol metrics impacting the performance.

1.3 Methodological Approach for Performance Evaluation

Evaluating the performances of NB-IoT and LoRaWAN is the very first step to effectively comparing their modes of operation. Then, the best communication protocol can be selected to fit the target application's requirements expressed as a set of Key Performance Indicators (KPI). Remarkably, the typical KPIs for network performance evaluation are **Reliability**, **Latency**, and **Throughput** [48].

As already discussed in Section 1.1, IoT networks require the evaluation of another important KPI, i.e., **Energy Efficiency**. In this chapter, only these four most critical KPIs for LPWAN will be discussed and analyzed. The importance of evaluating all these aspects to choose the most fitting network technology can be intuitively understood as follows. NB-IoT is designed to be a reliable, delay-tolerant protocol on the licensed spectrum, while LoRa is a loss-tolerant protocol. Hence, they provide different link-layer solutions for different needs, making it possible to choose between reliable and delay-constrained protocols.

With the goal of deeply understanding which parameters affect the identified KPIs, this section focuses on the analysis of the LPWAN terrestrial network, while an extension to ground-to-satellite communications will be discussed in the following sections.

Table 1.2: Comparison of the models and their KPIs

KPI **Models*	**NB-IoT**	**LoRaWAN**
Reliability	[37] [11] [24]	[9] [39] [38] [12] [23] [50]
Latency	[40] [37] [7] [8]	[9] [50]
Throughput	[49] [40] [24]	[9] [12] [39]
Energy Efficiency	[40] [7] [8] [10]	[45] [41]

The most recent works on LPWAN modelling that drove the identification of the KPIs are listed in Table 1.2. Instead, Table 1.3 summarises the mathematical notation used in this section, and throughout the entire chapter.

First of all, a communication protocol is reliable if the transmitter can be notified through an acknowledgement (ACK) about the correct delivery of data frames from the receiver. 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 [31]. Such a KPI can be evaluated for LoRaWAN confirmed-based communications and for NB-IoT. When the analyzed protocol enables re-transmission of unacknowledged frames up to a maximum of M times, then the reliability R of the protocol is

$$R = 1 - PLR^M, \tag{1.2}$$

where PLR is the measured Packet Loss Ratio.

Clearly, being the PLR a positive real number lower than 1, a higher value for M translates into increased communication reliability [37]. At the same time, a higher PLR negatively impacts such a KPI. As a consequence, the communication reliability can be kept over a given threshold value by properly tuning either the maximum number of retransmissions M or the PLR. While M can be quickly configured as a parameter setting within the device firmware or via a remote MAC command, the PLR is not a directly configurable parameter since it depends on several variables, as follows:

$$PLR = f(MAC, PHY, g, d), \tag{1.3}$$

As a matter of fact, it is worth noticing that the PLR depends on both MAC and PHY layer configurations. More specifically, a collision-free MAC strategy makes the PLR only dependent on the Signal to Noise Ratio (SNR) [24]. Contrariwise, when the MAC layer is contention-based, frames are correctly delivered if they do not incur collisions. Moreover, the PHY layer configuration, such as LoRa's SF value [12, 23] and NB-IoT's CE level, will also affect the PLR. With a higher SF value or CE level, the maximum distance between EDs (UEs) and GW (eNB) increases. Therefore, the PLR also increases with distance [39]. On the other hand, a broader coverage area corresponds to a higher network load, which in turn increases the collision probability [9]. In addition, the traffic generation rate g of each device and the density of devices d also determine the network load. The collision can happen in both the join and data transmission phase in the LoRaWAN [9, 38, 50] by using the same SF at the same time in the specific channel. But for NB-IoT, the packet loss caused by collision only occurs in the random-access phase. By increasing the network load, allocating the limited network resources would be the main issue in the NB-IoT. The resource allocation time (service time) may be too long in the data transmission phase, also resulting in packet loss [11]. It has to be noticed that the number of retransmissions can also be increased by the unavailability of the network [4]. This is the case, for instance, of a satellite LoRa gateway: the device may try to deliver several times the message to a network that it is not available.

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. It can be described as

$$L = f(MAC, t_p, \tilde{m}) \tag{1.4}$$

Without considering retransmissions, the different modes of the MAC protocol, such as EDT mode for NB-IoT and Class B for LoRa, have different message exchange strategies, thus giving various network latencies. Furthermore, differences in the distance between the device and the GW (eNB) result in different propagation times t_p [41], which are usually negligible for terrestrial networks (but considerable for satellite networks). In fact, in the case of retransmissions caused by packet loss, an extra delay will be added to the network, which depends on the average number of retransmission $\tilde{m}$. PLR directly determines the expected number of retransmissions required to transmit a packet successfully, and M provides an upper limit for this number. So the average number of retransmission is

$$\tilde{m} = f(PLR, M). \tag{1.5}$$

Obviously, the parameters that affect the PLR also affect the latency, such as the number of connected devices, CE level [7, 8], SF [9, 50], low SNR [40], etc. As introduced in the previous part, when the PLR is high, a better way to keep the network reliability is to increase the maximum number of retransmissions. But as the maximum number of retransmissions increases, the network latency also increases [37], so a trade-off strategy is needed based on the specific application requirements.

The **Throughput** is the rate of successful packet delivery. The value of throughput is impacted by the traffic generated by each device, the network density, and PLR, as shown in equation 1.6. Obviously, the network with more density will have more generated traffic that also increases the PLR. Note that the ideal throughput is the generated traffic when PLR is equal to 0.

$$T = f(g, d, PLR) \tag{1.6}$$

For LoRa, several factors such as Inter-SF and Intra-SF [39] impact the throughput by generating collisions due to orthogonality issues of the SFs. These factors will reduce the throughput especially in networks with high node density, or co-existing with other networks, or with large distance between the EDs and the GW [12]. In this situation, an higher value of g will imply less throughput by increasing more ToA and collision probability. Same for NB-IoT, the model of network throughput can be built on the basis of PLR analysis [24]. The parameters such as the number of UEs and traffic generation rate [40] are also critical factors that affect the throughput. On the other hand, as the generated traffic increases, the system throughput will increase,

but the probability of collision will also increase, which has a negative impact on the system throughput [49]. Therefore, an optimum scheduling technique can reach the maximum available throughput by efficiently allocating the network resources [9].

The **Energy efficiency** describes the number of transmission bits obtained when the system consumes a unit of energy and presents the utilization efficiency of energy by the system [14]. Thus, the energy efficiency can be described as

$$EE = \frac{g_s}{E} = \frac{T}{N \times E}, \tag{1.7}$$

where g_s is the rate of successful transmissions for each device. In other words, its value is equal to the network throughput T divided by the total number of devices N in the network. Also the average energy consumption E depends on several parameters

$$E = f(PHY, MAC, \tilde{m}). \tag{1.8}$$

Like other KPIs, the number of retransmissions caused by high PLR directly impacts the energy consumption rate, which requires extra energy to transmit fewer packets per unit of time [40]. For NB-IoT, with the different CE levels based on link quality, battery lifetime can be from 3 years to 23 years [7]. In the LoRaWAN, the energy consumption is different based on the SF selection [41]. The lifetime of an ED battery will be less than two years for the transmission interval of 60 s with $SF = 7$, while it would be about 3 months for $SF = 12$ [45]. The main goal of the NB-IoT EDT mode is to simplify the transmission process, reducing energy consumption. The model proposed in [10] focused on the energy consumption of the UE, when working in EDT mode. The results show a significant improvement in the performance. In the LoRaWAN, different classes have different energy consumption behavior: Class A as the efficient, Class C as the thirsty, and Class B as the middle energy consumer. Also, other variants were proposed in literature. For instance, Class S was introduced in [17] to improved the performance of the Class B in throughput and respectively energy efficiency by wisely enlarging the slots of Class B. Based on Class S, TREMA [18] presented a scheduling technique to leverage from its energy efficiency and higher throughput.

! Attention

Clearly, the best performance cannot be achieved for all the KPIs at the same time. Therefore, a trade-off must be considered based on the needs of the specific application. When considering a satellite LPWAN, the KPIs are affected by the several challenges introduced by the LEO satellite. In what follows, the challenges and their impact on the KPIs are discussed.

1.4 Satellite LPWAN: Opportunities and Challenges

Satellite technology is emerging as a key enabler to transform IoT connectivity and allows global IoT coverage in beyond 5G systems [44, 47, 27]. By integrating satellites with long-range low power network technology, it is possible to deliver seamless connectivity, extended to air, sea [52], and other remote, difficult accessible areas. Besides extended coverage, the combination of satellites and LPWAN also gives the opportunity of increasing reliability and network capacity. In fact, satellites may be the only available communication medium when terrestrial networks are not available or not operational anymore (e.g., after a natural disaster).

Over the last years, IoT by satellite became more and more affordable, available, and accessible, thanks to the launch of several low-cost miniaturized Low Earth Orbit (LEO) satellites (CubeSats) [6]. Those LEO satellites are the most appealing ones for IoT applications due to the shorter delay that they introduce ($\simeq$ 40 ms) compared to Geostationary Earth Orbit (GEO) satellites ($\simeq$ 500 ms). However, their intrinsic orbital properties imply limited visibility time (around 2 minutes per visit). This issue can be overcome by using large constellations of LEO satellites, able to provide almost continuous coverage, and it will be further solved in future systems with relay networks from LEO to GEO satellites and inter-satellite links (ISL). The foreseen scenario is illustrated in Fig. 1.12.

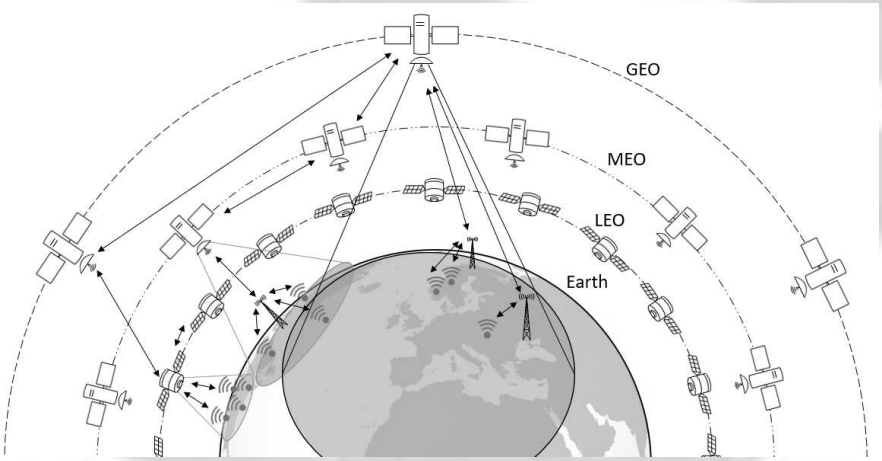


Fig. 1.12: Satellites on different orbits

Clearly, connecting IoT devices directly to LEO satellites opens many new opportunities. Besides that, there exist many challenges to overcome for allowing the smooth integration and interoperability of satellites and LPWAN terrestrial networks [30, 16]. This section overviews the challenges, while the following one will discuss their impact on the KPIs introduced in Sec. 1.3.

LEO satellites have large relative velocities to the IoT device on the ground, which results in a significant **Doppler effect**. For a LEO-600 km satellite, the maximum Doppler effect is up to ±48 kHz [22], which is much larger than the bandwidth of one NB-IoT sub-carrier, equal to only 15 kHz. Moreover, the large distance between the IoT device on the ground and the LEO satellites (500 - 2000 km) introduces a higher **propagation delay**. In NB-IoT networks, UE and eNB must be synchronized in time and frequency. To this aim, several messages are exchanged between the UE and eNB (at least four in EDT mode) before the actual data transmission. Complete the synchronization and resource allocation phase within the limited visibility time of the satellite is a big challenge for NB-IoT. Due to the Doppler effect and long propagation delay, NB-IoT could easily fail to accomplish the message transmission. While LoRa does not request synchronization between the ED and the gateway prior to the data transmission, the Doppler effect still impacts the LoRa PHY protocol since CSS signals are extremely sensitive to time and frequency offsets. In [25], the authors demonstrated that SF 12 is more immune against the Doppler effect when EDs communicate with satellite gateways at a height above 500 Km. Recently, a modification of the LoRa PHY, namely the differential CSS (DCSS) was proposed in [13]. DCSS allows demodulating the signals without the need of performing a complete frequency synchronization and by tolerating some timing synchronization errors, such as those introduced by the Doppler shift, variable in time.

Long transmission distance, significantly attenuated electromagnetic waves, and high transmission loss are among the remarkable features of satellite communication. They all together determine the **link budget**, which impacts the energy consumption of the ground equipment, as well the KPIs of the entire system. For NB-IoT, lower spectral efficiency will affect the transmission of resource allocation information. It follows that the UE cannot transmit uplink data on time, which will result in decreased throughput and increased delay [36, 22]. Link budget from LoRa ground sensor to satellite gateway has been computed empirically in literature [28], confirming the feasibility of the communication. Both LoRa PHY with SF 12 and LR-FHSS protocol allow increasing network capacity and collision robustness against link budget constraints [15].

As distance increases, ground devices must consume more power than what is needed in terrestrial systems to send or receive messages. This translates into a shorter battery lifetime for the NB-IoT UEs [36]. The same applies to LoRa EDs. In [29], the authors evaluated the performance of a satellite LoRaWAN using Iridium Satellites: they proved that EDs with a battery of 2400 mAh could operate $\sim$ 1 year, transmitting every 100 minutes. To increase the battery lifetime, the transmission rate should be decreased, which translates in reduced throughput.

A large constellation of LEO satellites with inter-satellite-links (as illustrated in Fig. 1.12) can provide full and continuous coverage to IoT devices on the heart. Such seamless connectivity comes with increased cost and complexity of the network. A more feasible solution consists of **discontinuous communication** with a small constellation of few LEO satellites [51]. In such a scenario with intermittent connectivity, to save energy the IoT devices must wake up and transmit only when the satellite is available. Following the NB-IoT specifications, the synchronization signal must

be received before the data transmission. In Rel. 17, 3GPP proposed the use of the Global Navigation Satellite System (GNSS) signal for the UE to compute the satellites and their own position. This method can pre-compensate for the Doppler effect, the frequency and time offset caused by the long distance. Those advantages come at the price of high energy consumption. Another solution proposed in literature [21] makes use of the synchronization signal transmitted in each NB-IoT downlink radio frame to inform on time the ground UEs about the arrival time of the satellite. Even though LoRa, unlike NB-IoT, does not request any synchronization prior to the data transmission, the EDs must be aware of the satellite passes to avoid wasting energy in unsuccessful transmissions. To this aim, the EDs must have access to the Two-Line Element (TLE) data of the satellite (see Fig. 1.13). The TLE provides a set of algebraic information, i.e., the satellite orbital elements, which allow predicting the satellite trajectory over time. Due to deviations from its initial orbit, the TLE data must be updated periodically. Current satellite LoRaWAN solutions available on the market make use of the TLE data [10]. Due to the considerable number of EDs that could be in the satellite coverage (i.e., within the satellite footprint), the knowledge of the satellite passes is not enough to ensure good network performance. In fact, the probability of collision, already high in LoRaWAN terrestrial networks [9], could only get worst in such a hybrid scenario. It follows the need of adopting scheduling techniques [5] to avoid collisions. In addition, *bulk data transmission* [53] could be used in combination with TDMA approaches to ensure efficient use of the limited satellite resources (2-3 times visibility per day, for approximately 2 minutes.).

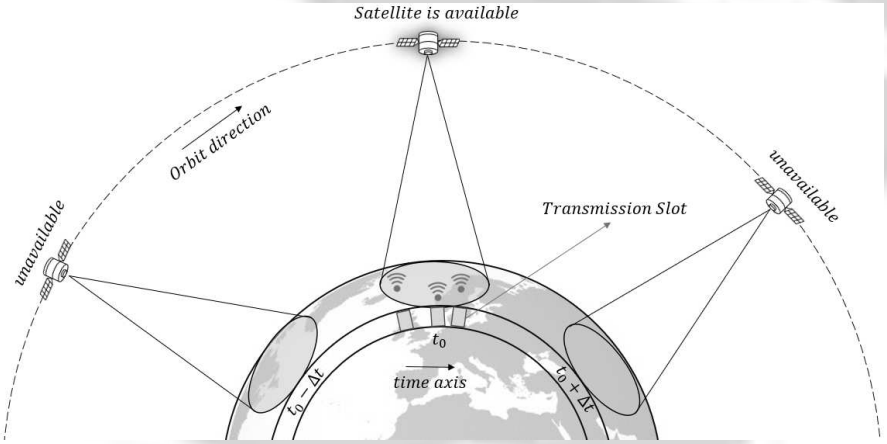


Fig. 1.13: LEO satellite coverage, while moving along its orbit. The knowledge of the satellite TLE allows the EDs to transmit when they are in the coverage range of the satellite (i.e., within the satellite footprint).

[10] Lacuna Space: https://lacuna.space/

The unavailability of the satellite does not affect only the access network. The communication between the satellite and the network server can be discontinuous too. To ensure end-to-end communication over the entire network, and avoid packet drops, the satellite gateway or satellite eNB must have the ability to store the messages and forward them when passing through the ground satellite gateway. The lack of connectivity between the satellite and the LNS can also hamper the exchange of LoRa confirmed uplink messages. Even in the case of correct reception of the packet at the LNS, in absence of ACK (not forwarded at all by the gateway because not available, either not transmitted on time, within the receiving windows), the ED would retry the transmission. This results in the wasting of resources: ED's energy, channel resources with contention, and possible collision with other concurrent transmissions. Overall, it translates to deterioration of the network performance in terms of reliability, throughput, and energy efficiency.

Tips

Discontinuous communication can also cause network authentication problems. In a NB-IoT network, the network authentication is unfeasible when the UE and the ground base station are not in the same satellite coverage at the same time. Discontinuous communication makes the handshake between the UE and the core network impossible, which poses a challenge to the reliability of the satellite IoT. Like NB-IoT, the LoRaWAN OTAA join procedure would fail when EDs and LNS are not at the same time under the coverage of the satellite gateway [4]. Moreover, stable connectivity is needed to support downlink multicast traffic. Prior to the multicast data exchange, several uplink and downlink unicast messages must be exchanged between the EDs and the LNS (multicast session set-up). Intermittent links would cause the expiration of multicast session timeouts and would thus prevent the multicast transmission.

1.5 Qualitative Performance Analysis of Satellite LPWAN

In Section 1.3, some KPIs for the performance evaluation of terrestrial LPWAN networks were analyzed. However, when integrating LPWAN with LEO satellites, the challenges presented in Section 1.4 must be taken into account to model and estimate the KPIs of the combined network. In this section, the analysis presented is referred to the availability of a single satellite equipped either with a LoRa GW or a NB-IoT eNB. This represents the worst case scenario. Instead, LEO constellations will be considered in future works to feature the scalability of such network architecture.

First, it has to be noticed that the **reliability** of the satellite LPWAN network would be highly affected by the LEO satellite and its visibility time. In fact, a major source of packet losses is caused by the frequent unavailability of the LoRa GW (eNB). Let a_S be the satellite availability. Then, the reliability of the satellite LPWAN R_s is

$$R_s = R \times a_S. \tag{1.9}$$

Clearly, R_s as R is mainly a function of the PLR. The latter can still be formulated as in equation 1.3. Thus, it is dependent by PHY and MAC parameters, traffic generation rate per node, and node density. Thanks to its large footprint, the LEO satellite can provide wide coverage, resulting in a large number of IoT devices being in the satellite visibility at the same time. The higher value of the node density increases the PLR, and thus deteriorates the reliability. When considering a constellation of LEO satellites, offering continuous coverage, it results $a_S \rightarrow 1$, and thus, $R_s \rightarrow R$.

The **Latency** of the network, as expressed in Equation 1.4, is affected by the MAC schemes, together with the propagation time, and the average number of retransmissions. More in details, the Latency is the combination of different delays, due to the initial synchronization, the following data processing and propagation, and finally the data delivery to the application sever over the satellite backhaul. In a simplified manner, the Latency L_s can be formulated as:

$$L_s = t_{sync} + m \times (t_{pr} + t_p) + t_{sb} \tag{1.10}$$

with m representing the total number of packet exchanged, including retransmissions. A device takes t_{pr} to generate a packet, which will propagate for t_p to be received by the gateway. Ground-to-satellite links are featured by a larger propagation delay t_p than that of terrestrial networks. Besides, such a delay is not fixed and its duration varies according to satellite movements. Meanwhile, the packet takes t_{sb} to be delivered from the satellite gateway till the remote sever. In case of a LEO satellite constellation, t_{sb} includes the ISL link delay. The network latency increases according to growing numbers of ISL.

For LoRa unconfirmed messages, the Equation 1.10 is simplified, with $m = 1$ and $t_{sync} = 0$. For NB-IoT, the synchronization delay is a relevant component of the satellite network latency. Moreover, m varies according to the different NB-IoT optimization modes (UP, CP, EDT). In case of higher PLR, the value of m will increase, resulting in higher latency. Being the confirmed messages acknowledged directly by the eNB, no additional delay is introduced by the satellite backhaul.

As the reliability, also the **Throughput** is affected by the satellite availability time and large coverage range. So it can be described by equation 1.11. Unavailability of the satellite causes more packet losses and therefore less throughput. Similarly, having many devices (with higher density d) in the coverage range of the satellite translates in higher PLR, due to data packet collision in LoRa, and congestion during NB-IoT synchronization. As consequence of increased PLR, the throughput of the satellite LPWAN decreases.

$$T_s = T \times a_S \tag{1.11}$$

The communication with a satellite gateway strongly impacts the energy consumption of the IoT device on the ground. The long distance between the device and the satellite asks for more power consumption, both in transmission and E_{TX}, and

reception mode E_{RX}. Instead, the energy required for processing the message, E_{pr} remains the same as in fully terrestrial networks. Thus, the energy consumption can be described as

$$E_{total} = E_{sync} + m_1 \times (E_{pr} + E_{TX}) + m_2 \times (E_{pr} + E_{RX}), \tag{1.12}$$

where m_1 and m_2 represent the number of uplink and downlink packets, respectively.

For unconfirmed LoRa message, the equation 1.12 is simplified, by considering $m_1 = 1$, $m_2 = 0$ and $E_{sync} = 0$. In case of LoRa confirmed messages, then $m_1 = m_2$ and m_1 represent the number of retransmissions, $m - 1$. In a NB-IoT network, the value of m_1 and m_2 change based on the different optimization method adopted. Moreover, the energy spent during the synchronization phase E_{sync} represents a relevant component of the whole energy consumption of the IoT device.

As mentioned in the previous section, one LEO satellite suffers from long unavailability times during a specific time period. Such behaviour makes satellite LPWAN not fit the applications that require higher reliability (like mission-critical, Tactile Internet, etc.) . Since the satellite has a broader coverage area, more devices will try to connect to the satellite at the same time, and the probability of collision will be greatly increased. As a result, applications requiring high throughput cannot be satisfied. Therefore, the network size (i.e., the number of served devices) should be reduced, to increase the network throughput. Finally, satellites impose the network to have longer delays and thus longer latency comparing to the terrestrial networks. This makes them not a good fit for ultra low latency applications. While the goal of any network is to support higher scalability, then increasing the number of LEO satellites and providing a full coverage will help supporting the applications that need higher reliability and throughput.

1.6 Conclusion and Future work

NB-IoT and LoRaWAN are among the LPWAN technologies that have fostered a widespread deployment of IoT networks, thanks to their low power, low cost and long distance communications. These features have recently been explored for ground-to-satellite communications, enabling a truly pervasive and ubiquitous IoT availability. Such a network architecture is clearly expected to trigger the growth of novel IoT applications unimaginable before. Indeed, the success of the future satellite IoT will come from its ability to meet the needs of specific use cases. Timely, this chapter pictures a methodological approach finalized to the correct choice of the LPWAN technology and the best communication pattern fitting the needs of *any* satellite IoT application. To do that, reliability, latency, throughput, and energy efficiency have been identified as KPIs to be used for comparing different protocols. Importantly, their inner dependency on configurable setting, e.g., the maximum number of retransmissions in contention-based medium access schemes, has also been properly investigated. Such an analysis will be leveraged in future research

works to design both novel medium access schemes, and efficient algorithms able to autonomously adapt the communication protocol to time-varying traffic conditions and to grant a sufficient level of quality of service. In addition, such an analysis will be extended to tackle the availability of LEO satellite constellations, thus targeting highly available and scalable LPWANs backhauled by LEO satellites.

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Table 1.3: Symbol definitions

Symbol	Definition
g	Traffic generation rate per single node
g_r	Traffic successful transmission rate per single node
PHY	PHY layer configurations
MAC	MAC layer configurations
t_p	Propagation time between the device and the gateway
t_{pr}	Message Processing time
t_{sb}	Delivery Time over the Satellite backhaul, from the satellite to the server
t_{sync}	Synchronization Time between the UE and eNB
E	Device energy consumption
EE	Energy Efficiency of the network
E_{sync}	Energy spent for the synchronization
E_{TX}	Energy consumption in TX mode
E_{RX}	Energy consumption in RX mode
E_{pr}	Energy consumption for processing the data
E_{total}	Total energy required to deliver the message to the satellite
a_S	Satellite availability rate during a specific period
DR	Message Data Rate
d	Density of devices operating in the network
N	Number of devices operating in the network
M	Maximum number of retransmissions
$\tilde{m}$	Average number of retransmission
r_t	Number of retransmissions
L	e2e LPWAN network latency
L_s	e2e satellite LPWAN network latency
T	e2e LPWAN network throughput
T_s	e2e satellite LPWAN network throughput
R	e2e LPWAN network reliability
R_s	e2e satellite LPWAN network reliability

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