Discover Internet of Things

Review

A systematic and comprehensive review on low power wide area network: characteristics, architecture, applications and research challenges

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Abstract

The Internet of Things (IoT) has become a rapidly growing research field. This is due to the advancement of digital technologies, miniaturization, and the reduction of the cost of IoT devices and wireless connectivity, among others. Despite the plethora of technologies used for the Internet of Things, the trade-off between long data transmission range and low power consumption was not found until the advent of Low Power Wide Area Network (LPWAN) technologies. This paper reviews the main aspects of LPWANs and their technologies based on an exhaustive search in several online scientific databases, such as Springer, IEEE Xplore, the ACM digital library, and Google Scholar. This research methodology enabled us to gather recent work on LPWANs, which forms the basis of this article. It is informative and knowledge-updating support in the LPWANs' environment that broadly covers LPWANs. This research work has developed the characteristics of LPWANs and the techniques used to achieve long-range energy efficiency, high scalability, and low cost. In addition, it presents the application areas of LPWAN technologies with use-case network architectures for each area, addresses spectrum and energy optimization, and discusses open research challenges that need to be focused to provide guidelines for further contributions.

Article Highlights

The article highlights the nuances of the various LPWAN solutions and presents several highlights:

- An overview and general architecture of LPWANs, including detailed descriptions of LoRa, Sigfox, and NB-IoT technologies, as well as standards proposed by international organizations, such as IEEE, ETSI, and 3GPP, in order to enhance understanding of LPWANs and their specifics.
- A presentation of applications based on LPWAN technologies and a network architecture illustrating a use case for each industry sector, facilitating their integration into different fields.
- A discussion on the open research challenges in the field of LPWANs with causes and possible solutions to encourage exploration and further contributions.

Keywords IoT · LPWAN · Standardization · Architecture · Applications · Research challenges

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1 Introduction

Because of its importance in helping to solve several of the problems of the twenty-first century, such as deforestation, terrorism, pandemics, etc., the Internet of Things (IoT) has become the point of convergence of many researchers, practitioners, and industrialists [1]. The basic foundation of the Internet of Things is providing everyday objects with the possibility of being identified in a network and exchanging information without human intervention. IoT technologies can be used in almost all domains of life. One of its underlying communications technologies, notably the LPWAN (Low Power Wide Area Network) technologies, is involved in several projects in different sectors, including health [2–4], agriculture [5–7], logistics [8–11], transport [12–14], environmental monitoring [15–17], smart buildings [18–20], etc. In recent years, they have received considerable attention from the research community, resulting in several scientific publications. Thus, Fig. 1 presents the statistics of studies, particularly computer science and engineering articles on the LPWAN and its underlying technologies published in two major online libraries, notably IEEE Xplore [21] and Springer [22], over the last 6 years.

The Internet of Things is not a single technology but a collection of technologies with characteristics such as the transmission range, the amount of information transmitted, the frequency band used, etc. [23]. Thus, a collection of technologies with a long transmission range, low energy consumption, and moderate costs is grouped in the LPWAN concept.

The networks deployed in the context of the Internet of Things are categorized into two main families, namely short-range low power networks and long-range low-power networks [24]. Thus, Wi-Fi [25], Z-Wave [26], ZigBee [27], Bluetooth Low Energy [28], RFID [29], IPv6 low-power wireless personal area networks (6LoWPAN) [30], and Near-field communication (NFC) [31] are short-range networks with low throughput and high energy consumption. These networks are unsuitable for applications where a long transmission range is a non-negotiable requirement. The solution could be cellular networks, but their energy consumption and data rates are very high. LPWAN has emerged to meet certain applications with long transmission ranges and low power consumption. These networks are formed by proprietary technologies like Sigfox [32], Ingenu [33], and open technologies such as LoRa [34], Weightless [35], DASH7 [36], NB-FI [37].

Table 1 provides a summary of the main recent Survey articles on LPWANs. A review of these articles has revealed certain weaknesses in existing studies. In response to these findings, this research work proposes a comprehensive and detailed study of the main aspects of LPWANs, accessible to a wide audience.

This paper reviews the state of the art of LPWANs and their underlying technologies by broadly examining the literature. Thus, it first develops their characteristics and the techniques used to achieve long-range energy efficiency, high scalability, and low costs. Next, it proposes an interesting discussion for identifying open research challenges. So, the main contributions of this paper are the following:

- Proposal of an in-depth study on the state of the art of LPWANs by detailing characteristics of and presenting the different standards proposed by international organizations.
- Presentation of global architecture of LPWAN.
- Identification of similarities and differences and a detailed description of LPWAN technologies, in particular LoRa, Sigfox, and NB-IoT.
- Presentation of relevant applications that are based on LPWAN technologies.
- Identification of potential limits of LPWAN technologies.
- An interesting and detailed study of the optimization mechanisms of LPWANs.
- An insight discussion and presentation of the challenging open research issues that need to be addressed for providing guidelines for further contributions.

The remainder of this paper is organized as follows: Sect. 2 describes the paper research methodology. Section 3 presents the outlines of LPWANs by detailing their characteristics, discusses the various standards proposed by international organizations, and presents the architecture. Section 4 focuses on LoRa, Sigfox, and NB-IoT technologies with similarities and differences, which are considered the leaders in this field. Section 5 describes some relevant applications based on LPWAN technologies, while Sect. 6 discusses the possible limits of LPWANs. Section 7 presents the network optimization mechanisms. Section 8 proposes an insightful discussion on the different LPWANs and identifies the challenging open research issues that need to be focused on for eventual new. Finally, Sect. 9 concludes the paper and proposes the potential prospects for future works.

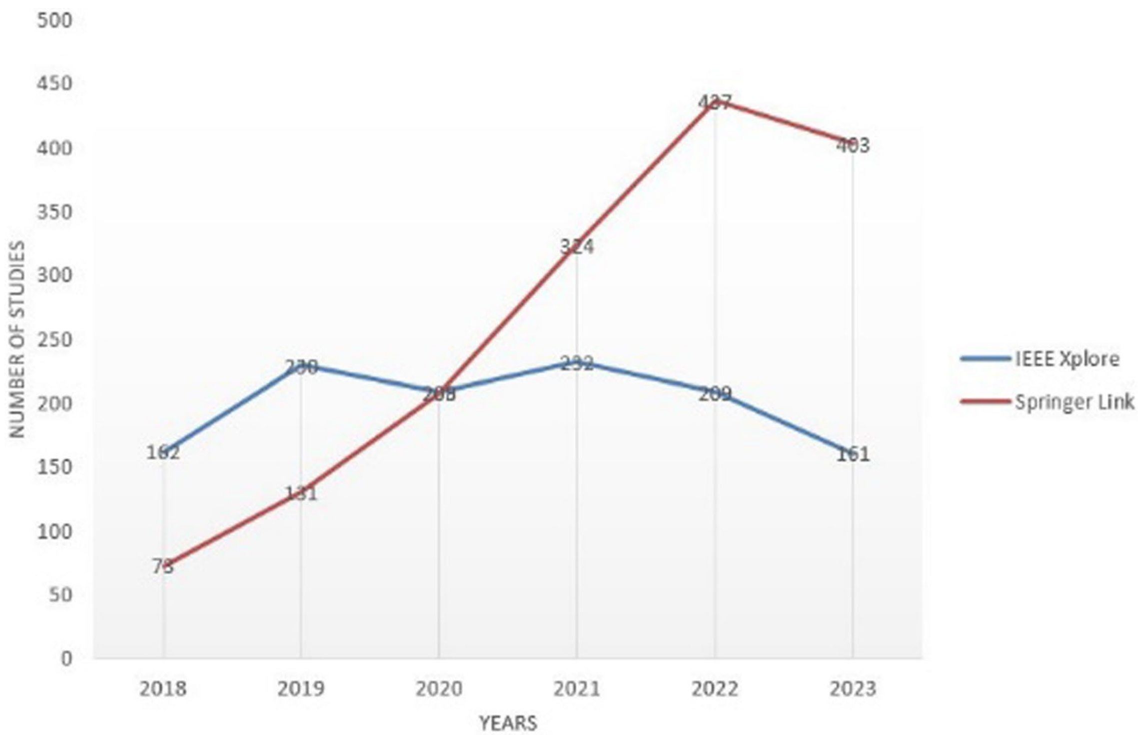


Fig. 1 number of studies in IEEE Xplore and SPRINGER on LPWAN over the last six years

2 Research methodology

To carry out this research work, we used the systematic literature review (SLR), a rigorous research method [38]. The SLR is used to evaluate, synthesize, and summarize relevant literature on a specific topic. To realize a SLR, a certain number of predefined key steps must be followed [39]. The various stages of our methodology are outlined in the following subsections.

2.1 Research questions

The formulation of research questions precedes the search and selection of articles. These questions guide and define the subsequent steps in the methodology, such as inclusion and exclusion criteria and data extraction. Our research questions in relation to our field of study are as follows:

- What is the current level of development of LPWANs?
- What are the main applications of LPWAN technologies?
- What are the optimization mechanisms for LPWANs?
- What are the research challenges associated with LPWAN technologies?

2.2 Search strategy

Developing a search strategy is a crucial step in the SLR process. It enables us to identify relevant databases in order to find related articles on the subject. An exhaustive search is carried out in several databases. The majority of the articles selected come from highly reputed computer libraries, such as Springer (https://link.springer.com), IEEE Xplore (https://ieeexplore.ieee.org/Xplore/home.jsp), and the ACM digital library (https://dl.acm.org). Advanced searches in English were carried out on these platforms using adapted Boolean operators and keywords from our search questions. An example of an advanced search query is: ("LPWAN or LoRa or Sigfox or NB-IoT) and (transport or traffic management

Table 1 Summary of the main LPWAN surveys

References	Years	Titles	Description	Limits
[7]	2020	A Survey of LPWAN Technology in Agricultural Field	The document provides a comparison of different LPWAN technologies for intelligent agriculture	The document does not open up any directions for research to improve these technologies
[43]	2018	A Comparative Survey of LPWA Networking	The paper provides a definition of LPWAN technologies and presents a systematic approach to defining appropriate use cases and a comparison	No LPWAN architecture is proposed in the paper
[50]	2019	A comparative Survey Study on LPWA IoT Technologies: Design, considerations, challenges and solutions	The article analyzes existing standards NB-IoT, LORA, Wi-Fi HaLow (802.11ah) in terms of energy efficiency, quality of service, cost and coverage distance	The applicability of the technology in different sectors is not discussed in the paper
[52]	2017	A Comparative Survey Study on LPWA Networks: LoRa and NB-IoT	The paper provides an overview and comparative study of two LPWAN technologies, LoRa and NB-IoT	The article does not mention application areas, and remains too specific to cover all LPWANs
[62]	2019	Survey on 3GPP Low Power Wide Area Technologies and its Application	The article describes the main LPWAN technologies in terms of coverage, capacity, power consumption and module cost	The article does not offer any perspectives for future work
[74]	2017	A survey on LPWA technology: LoRa and NB-IoT	The article presents a study on LoRa and NB-IoT technologies and compares these two technologies in terms of battery life, network capacity and device cost.	The article does not present any discussion or research challenges concerning LPWAN technologies
[126]	2022	A Survey on LPWAN-5G Integration: Main Challenges and Potential Solutions	This article presents an overview of LPWAN-5G integration, focusing on the main integration challenges and potential solutions	The document does not cover the behavior of the LPWAN network integrated with 5G in different areas

or road congestion") source: "Springer" or source: "IEEE Xplore" or source: "ACM digital library". In addition, other articles were identified thanks to their references in previously selected articles or on other platforms.

2.3 Inclusion and exclusion criteria

Inclusion and exclusion criteria are of crucial importance in ensuring the relevance and quality of the studies reviewed. Studies are evaluated for inclusion or exclusion in two stages. In the first phase, the title, keywords, and abstract are analyzed to assess the relevance of the article to our search. The second phase consists of a complete reading of the article to decide on its inclusion or exclusion according to the following criteria:

1) We include studies that are either conference papers, journal articles, white papers provided by standards bodies, or documents from companies promoting LPWAN-related technologies.
2) We include articles directly answering the research questions in sub-Sect. 2.1.
3) We include articles that present LPWANs or the underlying technologies.
4) We exclude articles that are not published in peer-reviewed journals.
5) We exclude articles that are not written in English.
6) We include recent articles, i.e., published between 2013 and 2024.
7) We include case studies on the use of LPWAN technology in different sectors.

2.4 Data extraction

Data extraction enables us to synthesize relevant information from the selected studies. Based on our research questions, we gather the following information from the selected articles:

1) The description of the LPWAN network architecture in a use case.
2) The characteristics of the LPWAN technology addressed in the article.
3) The optimization mechanisms addressed in the article.
4) The main research challenges presented in the article.

3 Characteristics of LPWAN

3.1 Definition

LPWANs are a new communication paradigm in the world of the Internet of Things. They are, supported by technologies that allow to benefit from a long communication range (10–15 km in rural areas and 2–5 km in urban areas), low energy consumption of the nodes, high scalability, and low investment cost. In terms of range, LPWANs and mesh networks can be compared, but LPWANs do not fall within the scope of mesh networks, and vice versa. In fact, there are several differences between the two types of network (LPWAN and mesh networks), the most obvious being the star topology, which is the norm in LPWANs but not in mesh networks. A comparison of LPWANS with other networks, in terms of range, data rate and power consumption, is illustrated in Fig. 2 below.

These characteristics promote the rapid and lightning development of LPWAN technologies to the point where common reference frameworks, i.e., standards, are needed to make LPWAN technologies interoperable, establish reusable designs, and provide industry best practices. The standardization actors of LPWANs are either organizations specialized in standardization (IEEE, ETSI, 3GPP) or industry consortia (WEIGHTLESS-SIG, LoRa™ Alliance, DASH7 Alliance) [40]. The architectures of LPWANs are all quite similar. They are generally composed of four elements: end nodes, gateways, network servers, and application servers [24]. In the rest of this section, the standard characteristics, standards of international organizations and the specific architecture of LPWANs are discussed.

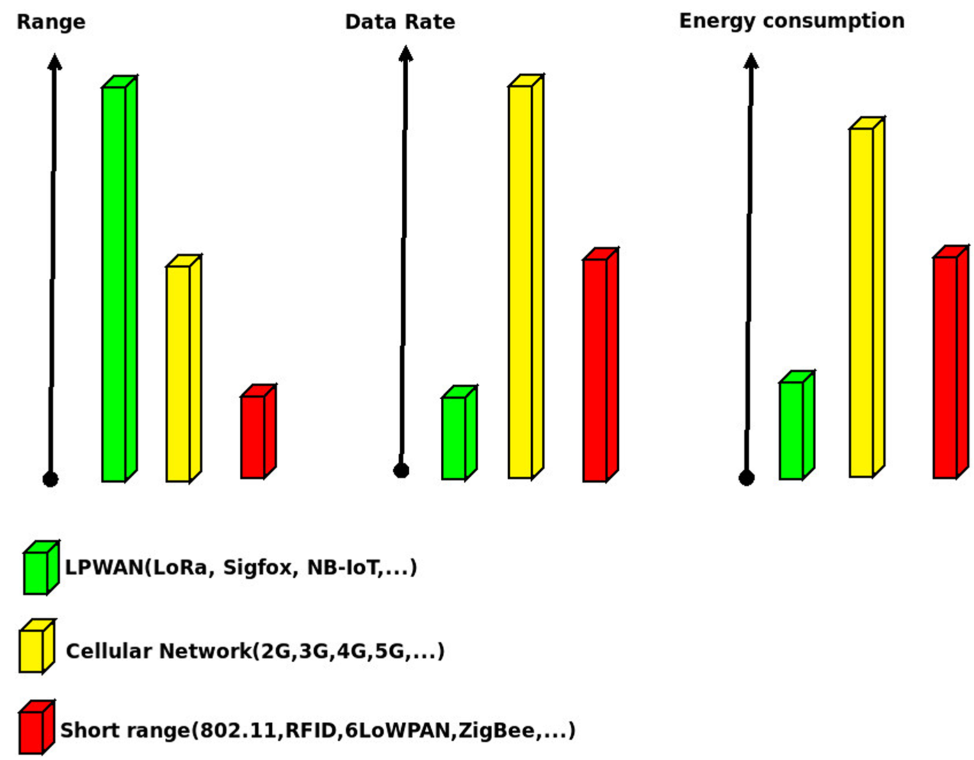


Fig. 2 Comparison of LPWANS with other networks in terms of range, data rate and power consumption

3.2 LPWAN standard characteristics of LPWAN

LPWANs are characterized by good signal propagation that can reach tens of kilometers[41], low power consumption of devices[42, 43], a gateway or relay antenna serving a large number of devices[44, 45], and low cost of devices[46]. These characteristics are summarized in Table 2 and expanded upon below.

3.2.1 Long transmission range

Optimal signal propagation is one of the most essential features of LPWAN technologies. This is its main difference from basic IoT technologies such as Z-wave, ZigBee, BLE (Bluetooth Low Energy), RFID (Radio frequency identification), IEEE 802.11, etc. The sub-1GHZ ISM band and adapted modulation schemes offer a transmission range of 10–15 km

Table 2 Standard characteristics of LPWAN

Standard characteristics	Influential factors
Long transmission range	- Use of the Sub-1 GHz band (except RPMA and NB-IoT) - Types of modulation (narrow band modulation and spread spectrum modulation)
Low energy consumption	- Star topologies - Duty cycles - Use of simple protocol access channel (e.g. ALOHA for LoRa and sigfox)
Scalability	- Use of multi-channel communication - Deployment of multiple base stations (gateways) - Data rate adaptation mechanisms
Low cost	- Simple LPWAN transceivers - One base station serves tens of thousands of devices - Unlicensed and licensed frequency band usage

in rural areas and 2–5 km in urban areas. LPWAN technologies such as NB-IoT, which operate using a cellular infrastructure, inherit the latter's long range.

The characteristics of the Sub-1 GHz frequency band are suitable for many IoT applications as it has a high penetration capacity, and the signals suffer less attenuation and multipath fading [47]. The LPWAN technologies discussed in this research work operate in the ISM band, with the exception of RPMA (Random Phase Multiple Access) and cellular LPWANs. Fewer technologies operate in this band compared to the 2.4 GHz band, thus bypassing the interference problems of the 2.4 GHz band and helping to provide a long communication range. LoRaWAN, IEEE 802.11ah, IEEE 802.15.4 g, SigFox, Weightless-N, Weightless-P, and DASH7 all operate in the sub-GHz frequency band [48]. RPMA (Random Phase Multiple Access) operates in the 2.4 GHz band.

The modulation type dramatically influences the transmission of the signal and, therefore, its range. In LPWANs, two modulation schemes are generally used. These are narrowband modulation and spread spectrum modulation [49]. Narrowband modulation techniques encode the signal in a small bandwidth, typically less than 25 kHz. The noise level within the bands is low, and the overall spectrum is shared between several links, resulting in a transmission range of up to several kilometers. It is in this context that Ultra Narrowband (UNB) was born. In UNB (spectrum < 1 kHz), the signal is modulated with the help of phase shift keying. SigFox and Telensa are technologies based on UNB.

In contrast to narrowband modulation, spread spectrum modulation allows a narrowband signal to be spread over a wider frequency band, hence the name. The signal is more resistant to interference and jamming attacks. The spread spectrum technique can be classified into several categories, such as DSSS (Direct-Sequence Spread Spectrum), FHSS (Frequency Hopping Spread Spectrum), and CSS (Chirp Spread Spectrum). LoRa and Ingenu's RPMA use this modulation technique.

3.2.2 Low energy consumption

In a network of objects, the energy consumption of the nodes is mainly related to the network topology, the periods of operation of the nodes, and the type of protocols used. Batteries often power these nodes and are usually deployed in thousands in a network, which allows scalability. It is, therefore, essential to preserve the life of the batteries over the years to control the cost of network maintenance [50].

A star topology is emphasized in LPWANs over the mesh topology often used in sensor networks. With a multi-hop topology, some nodes in the network work harder than others and deplete their energy much faster. So, to avoid this problem, LPWANs adopt a star topology where nodes are directly connected to gateways (a one-hop topology), thus reducing the energy consumption of these end nodes.

The service cycle consists of periodic operations of the terminals. In other words, there are intervals of time when the nodes are in idle mode, which may occur following a transmission. LPWAN technologies such as LoRa, Sigfox and NB-IoT are adopting the duty cycle, this can drastically reduce the energy consumption of network devices [51]. Nodes agree with gateways on downlink transmission times. Some LPWAN technologies, such as LoRa, do not require this mechanism, especially with LoRa Class C. Although the duty cycle saves terminal power, it can be a brake on many applications, and in some regions of the world it cannot be dispensed with because it is imposed by legislation (regulations on the use of spectrum in the ISM band).

Using a simplified medium access protocol helps save the energy of nodes in LPWANs. Several LPWAN technologies, such as SigFox and LoRaWAN, use ALOHA [52], a random access MAC protocol in which terminals transmit without carrier sensing, making their transceivers simple. NB-IoT does not use the ALOHA protocol. So if a terminal needs to send data, it initiates a random access procedure by sending its first preamble via the Narrowband physical random access channel (NPRACH) to acquire an uplink resource for data transmission.

3.2.3 Scalability

Scalability is a crucial requirement for LPWANs. Many use cases of them require the support of multiple devices of the order of a hundred thousand [53]. It is the ability of networks to interconnect a massive number of devices without compromising the quality and provision of services. A large number of devices operating together naturally gives rise to interference problems and can negatively affect network performance. Several techniques are considered to achieve scalability, including multi-channel communication, deployment of multiple base stations (gateways), and data rate adaptation mechanisms.

3.2.4 Low cost

The rush to LPWAN technologies is almost due to the low cost of the devices. For example, a LoRa or Sigfox device costs around $3–5 [41]. Several ways are used to reduce capital expenditure on LPWANs. Indeed, the transceivers have to handle less complex waveforms to allow devices to reduce transceiver footprint, peak data rates, and memory size. This minimizes hardware complexity and cost. A base station can connect tens of thousands of end devices distributed over several kilometers, significantly reducing costs for network operators. LPWAN technologies use unlicensed including the industrial, scientific and medical (ISM) band or television white spaces, or operator-owned licensed bands which avoids additional license costs.

3.3 LPWAN standards of international organizations

LPWANs have become the focus of several organizations in recent years. These organizations are working on standards that meet the device requirements for utilization. Among them can be listed the Institute of Electrical and Electronics Engineers (IEEE), the European Telecommunications Standards Institute (ETSI), and the 3rd Generation Partnership Project (3GPP) [40]. IEEE has introduced the IEE 802.15.4 k and IEEE 802.11ah standards, while ETSI has published the standard for low-throughput networks, and 3GPP has developed the EC-GSM-IoT, NB-IoT, and LTE-M standards, as shown in Fig. 3.

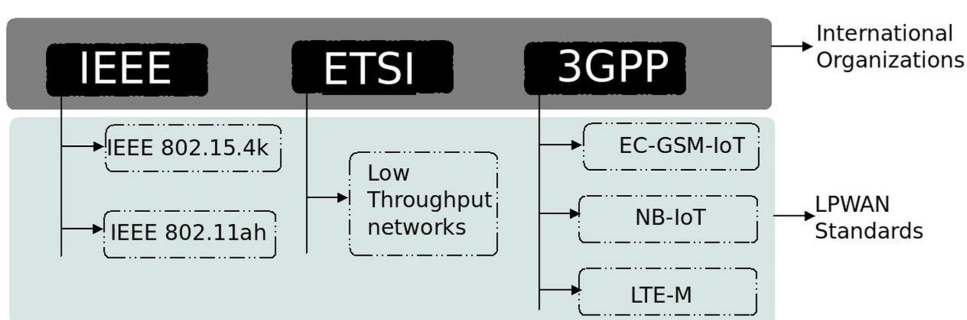
3.3.1 IEEE

Aware of the breakthrough in LPWAN applications, the IEEE evolved the IEEE 802.15.4 standard by circumventing these limitations, including a communication distance of hundreds of meters and a complex topology affecting power consumption [54]. The new standard obtained is called IEEE 802.15.4 k [55]. This standard proposes a star network topology consisting of two devices (end terminals and base stations) with a transmission range of up to 20 km. IEEE 802.15.4 k recommends Direct Sequence Spread Spectrum (DSSS) or Frequency Shift Keying (FSK) modulation on the physical layer. Similarly, the IEEE 802.11 standard, known commercially as Wi-Fi and intended to connect a limited number of devices with short-distance transmissions and high data rates, is the basis for the IEEE 802.11ah standard [56]. The IEEE 802.11ah or Wi-Fi Halow standard is a physical and MAC layer communication protocol designed for long-range communication compared to IEEE 802.11 and operating in the sub-1 GHz frequency band [57]. A single access point can cover many terminals with optimal energy efficiency. In addition, the IEEE has proposed two standards, IEEE 802.15.4 k and IEEE 802.11ah, to align with the LPWAN application market.

3.3.2 ETSI

The European standards group, ETSI, has published a set of specifications for low throughput networks (LTNs), which are divided into three areas: use cases, network functional architecture, and protocols and interfaces [58]. LTN technology is intended for applications requiring the transmission of a small amount of information (e.g., 12 bytes) over a significant distance (e.g., 10 km) with low energy consumption [59]. It is, therefore, designed to meet the requirements of LPWANs. The different areas in which LTNs can be used are metering, smart city, industrial, logistic etc. for more information on the areas of use, you can consult the Use Cases for Low Throughput Networks [60]. In LTN, the architecture is composed of the object (LEP for LTN End Point) with an LTN module, the base station (LAP for LTN Access Point) for relaying packets transmitted by LEP, an LTN server for storing and transmitting application data and managing the network, the CRA

Fig. 3 Standards for LPWAN



(Central Registration Authority) server for LEP and LAP identification codes and the last element of the architecture is the application server which manages user messages.

There is a radio interface between the LEP and the LAP, which is used for UNB (Ultra Narrow Band) or OSS (Orthogonal Sequence Spread Spectrum) communication. Depending on the type of communication used by the LEP (UNB or OSSS), LEP identification varies. For UNB communication, a unique 32-bit identifier (NID for UNB Node Identifier) is assigned to each LEP by the CRA, so each packet sent by the LEP is marked with the NID. In addition to the NID, LEPs have a 128-bit secret key (SEK) to authenticate packets. For OSSS communication, LEPs are allocated two identifiers: a 64-bit long identifier assigned during production and a 32-bit short identifier (short ID) that depends on the network. An activation key, a network session key and an application session key, all 128 bits long, are also used by the LEP. Communication between the LAP and the LTN server can be carried out using any standard Internet WAN protocol. The exchange between the LTN server and the application servers is based on the REST (REpresentational State Transfer) principle.

3.3.3 3GPP

To position itself in the IoT market, particularly the LPWANs application market, and guarantee interoperability between suppliers and telephone operators, the 3rd Generation Partnership Project (3GPP) is adapting cellular network infrastructures and exploiting the availability of licensed spectrum. Thus, we are witnessing the birth of standards such as Extended Coverage GSM for Internet of Things (EC-GSM-IoT), Long Term Evolution Machine Type Communications Category M1 (LTE MTC Cat M1, also referred to as LTE-M), and Narrowband IoT (NB-IoT) [61]. EC-GSM-IoT and LTE-M are cellular network optimizations to meet IoT application requirements, while NB-IoT is an LPWAN technology based on cellular networks [62]. NB-IoT will be discussed in the section on LPWAN technologies. EC-GSM-IoT is a standard defined in 3GPP Release 13, based on the Enhanced General Packet Radio Service (eGPRS). This standard allows wide coverage as it uses the resources of 2G, which is deployed worldwide. In addition, we note the low power consumption of the terminal devices and the ability of the base station to support a significant number of terminals (about 50,000) [42]. Two modulation techniques are used in EC-GSM-IoT to improve the capacity of the eGPRS network: Gaussian Minimum Shift Keying (GMSK) with a maximum data rate of 70 kbps and 8 State Phase Shift Keying (8PSK) with a maximum data rate of 240 kbps. LTE-M is one of the standards promoted by 3GPP. And several technology categories (Cat.1, Cat.2, Cat.4, and Cat.m1) have been developed with different performances [62]. According to [61], Cat.1 is already used in several M2M/IoT deployments. It offers 5 Mbps uplink and 10 Mbps downlink throughput. Like previous standards, LTE-M is based on the LTE.

3.4 Specific architecture of a LPWAN

The functional architecture in terms of layers is similar for LPWANs. The difference is often related to the names (terminologies) of the entities that form the architecture and the MAC and PHY layers, hence the challenges of seeking interoperability. This section describes the functions performed by each entity in the architecture. An end-to-end LPWAN system typically consists of end devices, relay nodes, a network server, and an application server, as shown in Fig. 4 below. The way in which these entities communicate, i.e. the protocols used, varies from one technology to another. The end devices, also called end nodes or UEs (User Equipment), are the most minor complex entities in the network. They can transmit data from or act on their environment. They are often sensors or actuators [63]. The collected data is sent to the relay nodes via a wireless radio link. Depending on the technology, the number of messages transmitted per day is limited, as in the case of Sigfox, or unlimited in LoRa and NB-IoT, in accordance with the duty cycle. From one LPWAN technology to another, the term relay node may be replaced by gateway, base station, or access point, but the functionalities remain

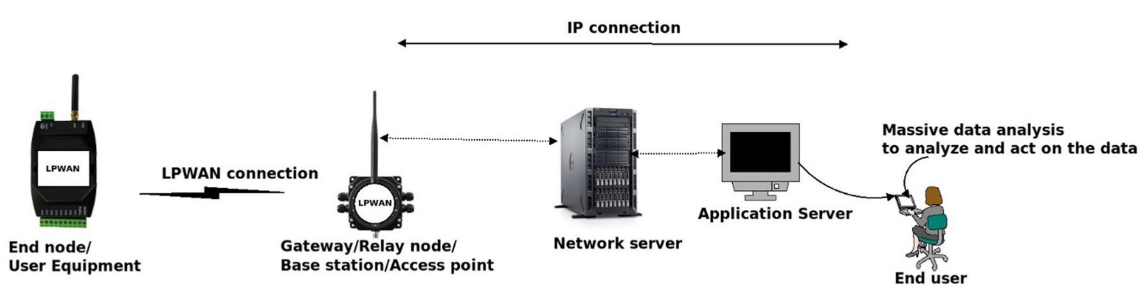


Fig. 4 LPWAN architecture

unchanged. Relay nodes usually have multiple communication interfaces because they exchange with end devices, not IP addresses except for LPWANs such as NB-IoT, whose end devices can send IP packets, and communicate via IP with the network server. For LoRa, the gateway with the highest RSSI takes care of the downlink, while for Sigfox, the gateway closest to the end device takes care of it, and for NB-IoT the device belongs to a cell managed by an enhanced base station. The relay nodes receive commands from the network servers and pass them on to the receiving end device in the case of bidirectional technologies. The other essential element of the LPWAN system is the network server or cloud server. It is the most intelligent entity in the network. It monitors the relay nodes and takes care of data aggregation. For technologies adopting the rate adaptation mechanism, the network server adjusts the parameters of the end devices to increase the overall network capacity and optimize the energy consumption of the nodes. The last element of the LPWAN architecture is the application server. It allows the data collected by the end nodes to be used by offering valuable services to the end user. It can use massive data analysis to analyze and act on the data [53].

4 Some LPWAN technologies

Given the diversity of IoT applications with different requirements, several technologies have emerged, in particular LPWAN technologies. These technologies have similarities and differences, which are discussed below. It is important to note that not all the similarities and differences are listed, but we discuss those that we feel are important for understanding how these technologies work.

All LPWAN technologies except Sigfox, discussed in this section, make use of the acknowledgement-based message retransmission method to minimize packet loss in the network. Sigfox allows a packet to be transmitted on three different channels (i.e. 3 identical packets) to maximize the probability of receiving the packet.

LPWAN technologies are all bidirectional. That is, the end nodes send data to the base station (uplink) and similarly the base station can transmit messages, often configuration or acknowledgement messages, to the end nodes (downlink). LPWAN technologies use the downlink differently. LoRa and NB-FI define three modes of operation (continuous RX (CRX), no RX and discontinuous RX (DRX) for NB-FI and class A, class B and class C for LoRa) to allow downlink communication and define the timing of transmission. Weightless uses time slots for the downlink, in particular with the Time Division Multiple Access (TDMA) method, whereas RPMA opts for the TDD (Time Division Duplex) approach and uses the downlink to know the channel conditions before the end nodes transmit. The uplink and downlink occur on the same channel in weightless, whereas in NB-IoT a physical channel (NPDCCH) is dedicated to the downlink. The extremity device initiates the downlink transmission via a request to the server in a Sigfox network. The DASH7 protocol requires terminals to periodically check the channel for downlink transmissions.

Communication security is very crucial in the IoT, so each LPWAN technology has a mechanism for protecting the message against various attacks such as signal jamming, packet forgery and replay attacks. Technologies such as LoRa, Weightless-P and RPMA ingenu use the 128-bit AES (Advanced Encryption Standard) encryption algorithm to encrypt or protect the integrity of the message. Whereas in NB-FI, the payload is protected by Magma symmetric key block encryption. By default, massages are transmitted without encryption in Sigfox, leaving customers free to choose their own encryption solution or to use the encryption provided by the Sigfox protocol. As for NB-IoT, the technology is supported by a cellular infrastructure and therefore the security standards of the technologies are reused. The encryption keys are managed by the NAS (Non-Access Stratum) protocol.

In the rest of this section, we develop LPWAN technologies with a focus on LoRa [64], SigFox [65], and NB-IoT [66]. These three technologies are overwhelmingly approved in the IoT domain [67]. However, we will briefly discuss other technologies such as Weightless, RPMA, NB-FI, and Dash 7 Alliance Protocol. Some of these characteristics (Standard, Frequency band, Max Data Rate, Range, Modulation, and Payload) are summarized in Table 3.

4.1 LoRa network

The minimized architecture of a LoRa network consists of end nodes, gateways, and a network server (Fig. 5). A LoRa (Long Range) network consists of the LoRa physical layer and a definable MAC protocol and the recommended MAC protocol is LoRaWAN maintained by the LoRa Alliance [68]. LoRa is the physical layer developed by CYCLEO which is a French company and acquired by SEMTECH. LoRa is based on CSS (Chirp Spread Spectrum) modulation which uses the Chirp technique (a signal in which the frequency increases (up-chirp) or decreases (down-chirp) with time). The modulated signals have a constant amplitude with a variable frequency [69]. In LoRa, the signals are modulated in the unlicensed

Table 3 Some features of LPWAN technologies

Technology	Standardization	Frequency band	Max data rate	Range	Modulation	Payload
LoRa	LoRa Alliance	Unlicensed ISM bands	50 kbps	5 km (urban), 20 km (rural)	CSS	243 bytes
SigFox	SigFox	Unlicensed ISM bands	100 bps	10 km (urban), 40 km (rural)	D-BPSK	12 bytes (UL), 8 bytes (DL)
NB-IoT	3GPP	LTE frequency bands licensed	200 kbps	1 km (urban), 10 km (rural)	QPSK	1600 bytes
Weghtless-P	Weightless-SIG	Unlicensed ISM bands	100 kbps	5 km (urban), 25 km (rural)	GMSK or QPSK	65,530 Bytes
NB-FI	WaveIoT	Unlicensed ISM bands	5120 bps	16 km (urban), 50 km (rural)	DBPSK	8 bytes
RPMA	INGENU	2.4 GHz band	624 kbps UL and 156 kbps DL	1 km (urban), 10 km (rural)	DSSS	16 bytes
DASH7	DASH7 Alliance	UnLicensed ISM band	200 kbps	2 km	GFSK	0–249 bytes

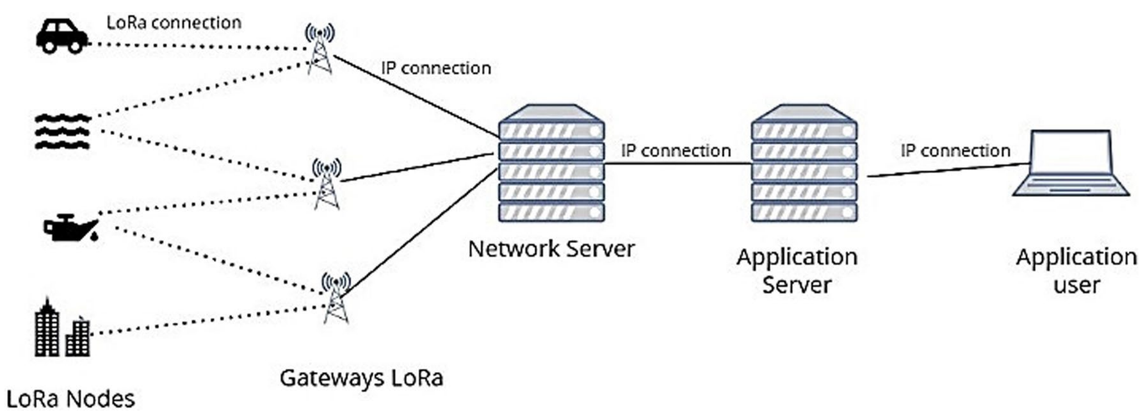


Fig. 5 LoRa Architecture

ISM (Industrial, Scientific and Medical) frequency band and this band varies according to region (e.g. 868 MHz in Europe, 915 MHz in North America) [70]. LoRaWAN (Long Range Wide Area Network) is a proposed open protocol designed to connect LoRa-equipped, battery-powered objects to the Internet. We distinguish two types of link: an uplink that occurs when a node transmits a message to the network server and a downlink when the reverse occurs. The LoRaWAN specification defines three modes of operation for end nodes suitable for various IDO applications [71]. Each mode of operation is commonly referred to as a class. After each transmission from the end nodes (uplink), the end nodes open receive windows (downlink activation). If two reception windows are available then class A is activated, if more than two are programmed then class B is implemented on the terminal. Class C, on the other hand, is constantly listening to the channel to receive messages from the network server. The activation of the terminal nodes is done in two different ways: Over the Air Activation (OTAA) and Activation by Personalization. Adaptive data rate is the mechanism that LoRa uses. The ADR (adaptive data rate) mechanism aims to increase the network's overall capacity and optimize the nodes' energy consumption [72].

4.2 Sigfox

Sigfox uses Differentials Binary Phase-Shift Keying (D-BPSK) modulation where the message has a fixed bandwidth of 100 Hz. This type of modulation is called ultra-narrow-band UNB. UNB modulation requires low power consumption, a transmission range of up to tens of kilometers, and a low data rate. Sigfox, as a company, offers a software-based communication solution, where all the network and computing complexity is managed in the Cloud rather than on devices [65]. The Sigfox architecture consists of nodes and base stations that act as gateways [73] (see Fig. 6). The end nodes of the network communicate with proprietary base stations, allowing them to dynamically adapt the data rate of each link by playing on the parameters defined in the physical layer deployed by the Sigfox network operator. In the early days, communication was only possible in one direction from the nodes to the base stations (uplink). The maximum number

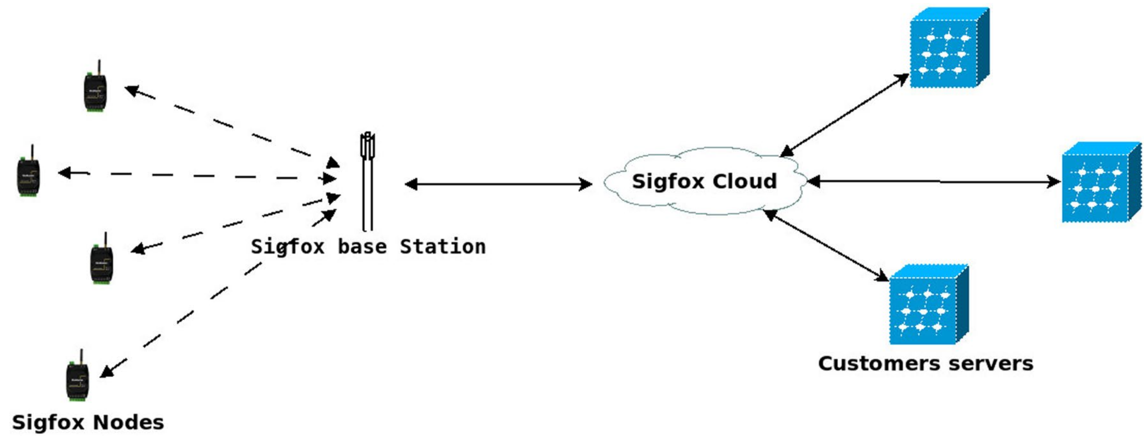


Fig. 6 SigFox Architecture [73]

of messages for the uplink is 140 messages per day. 04 messages per day are allowed on the downlink, i.e., from the base stations to the Sigfox nodes. This shows that an acknowledgment is not required following an uplink transmission in a Sigfox network. The end devices duplicate the message in three (default number) to ensure reliable communications before transmitting them on different channels [65].

4.3 NB-IoT

NB-IoT is one of the technologies dedicated to IoT, as defined by 3GPP. The architecture of an NB-IoT network includes User Equipment (UE), Enhanced Base Stations (eNodeBS), Mobility Management Entity (MME), Packet Data Network Gateway (PGW), Service Gateway (SGW) and Service Capacity Exposure Function (SCEF) [75] as shown in Fig. 7. NB-IoT is improved compared to other cellular technologies. Indeed, the use of narrowband transmission and repetition of transmission allows to reach so-called hard-to-reach areas, power-saving mechanisms are exploited to extend battery life, and simplification of network procedures reduces terminal complexity. NB-IoT technology can work with the GSM (Global system for mobile communication) network or with the LTE (Long Term Evolution) network. NB-IoT occupies a bandwidth of 180 kHz and uses Quadrature phase-shift keying (QPSK) modulation. The maximum data rate is 200 and 20 kbps on the downlink and uplink, respectively, with 1600 bytes of payload in each message.

4.4 Other technologies

Weightless [35] is a set of LPWAN technologies designed specifically for IoT applications by the Weightless-SIG group, whose principal members are Accenture, ARM, M2COMM, Sony-Europe, and Telensa. Weightless-W, Weightless-N, and Weightless-P are the three standards defined by Weightless-SIG. Each of these standards has its properties. In Weightless-N, only uplink is possible; Weightless-W is developed to operate in the TV white space, and Weightless-P uses either an unlicensed or licensed ISM frequency band. Of these three standards, Weightless-P is the closest in characteristics to other LPWAN technologies such as LoRa SigFox. Indeed, Weightless-P is bi-directional, high-performance [75] and narrowband.

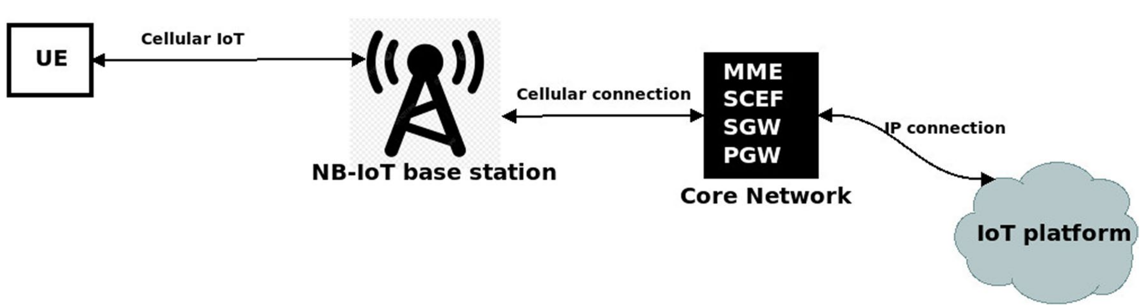


Fig. 7 NB-IoT Network architecture

Weightless-P can support a theoretical range of 2 km in urban areas, all traffic is encrypted using AES-128/256, and the data rate is 100Kbps.

RPMA (Random Phase Multiple Access) [33] is an LPWA technology developed by Ingenu. RPMA uses the universal unlicensed frequency band of 2.4 GHz with bandwidths of 80 MHz and 40 channels available in the network. RPMA can offer a data rate of 19,000 bps/MHz [76] and uses the Direct Sequence Spread Spectrum (DSSS) modulation technique. Communication in RPMA is bidirectional. With the optimization of all protocol layers, battery life can be as long as 20 years [33]

NB-FI, developed by Wave-IoT [77], is a communication protocol and a module that allows for long-distance transmission of up to 10 km and a battery life of up to 10 years [37]. DBPSK phase modulation is used in NB-FI and operates in the ISM band without a license. Regarding scalability, the NB-Fi standard supports up to 4.3 billion devices in a single network with a 32-bit ID for each device. The uplink data rate is 5120 bps, and the packet size is 8 bytes.

Dash 7 Alliance Protocol (D7AP) or DASH7, a technology derived from ISO 18000-7 [36], is developed for long-range communication operating in the ISM band. It is an extension of active Radio Frequency Identification (RFID) technology in that the communication range can be up to 2 km. DASH7 uses GFSK (Gaussian frequency-shift keying) modulation. DASH7 is one of the few LPWAN technologies that supports node mobility with a data rate of up to 200 kbps.

5 Applications of LPWAN technologies

The emergence of LPWAN technologies creates new applications in several fields, including transport, logistics, smart metering, environmental monitoring, agriculture, healthcare, etc. as illustrated in Fig. 8. The low consumption and the long communication range significantly promote the use of LPWAN technologies in many IoT projects. However, the low data rate, the limited number of messages per day for some technologies, and a high latency constitute obstacles to the enrolment of LPWAN technologies in some IoT applications, such as emergency alerts or real-time monitoring applications. Nevertheless, the sectors where LPWAN technologies are requested are numerous and diversified. This section presents an overview of the implementation of LPWAN-based IoT projects in some industries. LoRa has a good

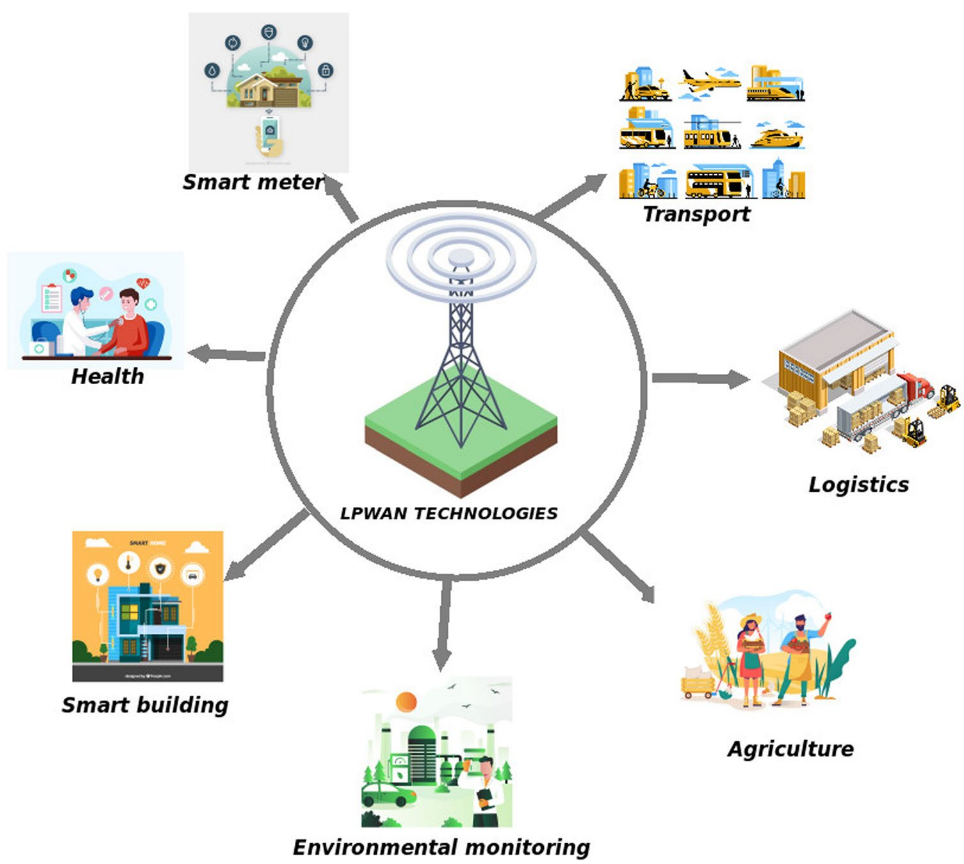


Fig. 8 LPWAN technologies application areas

market share in IoT projects based on LPWANs technologies, NB-IoT is often used in the healthcare field, and Cloud is used in IoT projects providing a public service for treatment.

5.1 Transport

LPWAN technologies can be used in transport for traffic management and intelligent parking. Indeed, most large cities face problems of traffic jams and road congestion. LPWAN technologies help solve this problem by using sensors to count vehicles at intersections or traffic lights and monitoring occupied parking spaces to guide cars to find available spaces [78, 79].

In Fig. 9, we present the architecture of a LoRa network to provide information about traffic intensity on a road. This is a use case for LPWAN technology in the transport sector. In the architecture, the cloud groups together the network server and the application server, and after analyzing the data collected by the sensors, a user will be able to access this information and find out where there is a traffic jam in order to avoid it.

In [80], an architecture based on edge computing, fog computing, and Cloud computing for road traffic monitoring is proposed. It comprises sensors, intelligent edge devices, a LoRa gateway with fog computing, cloud-based services, and end users. So, the architecture consists of five layers. The proposed architecture extends the classical LPWAN architectures, taking advantage of Cloud and fog computing. Instead of the end devices communicating directly with the gateway, the data passes through an edge computing device before arriving at the gateway.

The paper [12] proposes a system for collecting requests from older people to transport managers. LPWANs use single-hop communication, but multi-hop communication is noted in the request collection system described in this work. The request transmission devices transmit information such as the user, the desired date and time, and the destination to repeaters. The latter are connected to a gateway. The notion of gateway in this context differs from gateways in the generalized LPWAN architecture. Indeed, the gateway is composed of a small PC (NUC) that performs the processing, a screen for visualization, a LoRa module, and a microcomputer to control the module.

Also, in the work of [81], a real-time bus positioning system based on LoRa technology is presented. This system allows users to know the real-time location and expected arrival time of buses. The technologies are used in other practical cases in the field of intelligent transport [13, 14, 82].

5.2 Logistics

Logistics companies or companies that use logistics in their production processes need to determine the location and status of goods. Two important requirements for logistics are to be taken into account when choosing the technology to track the supply chain. These are the cost and battery life of the devices [67]. These requirements promote the use of LPWAN technologies.

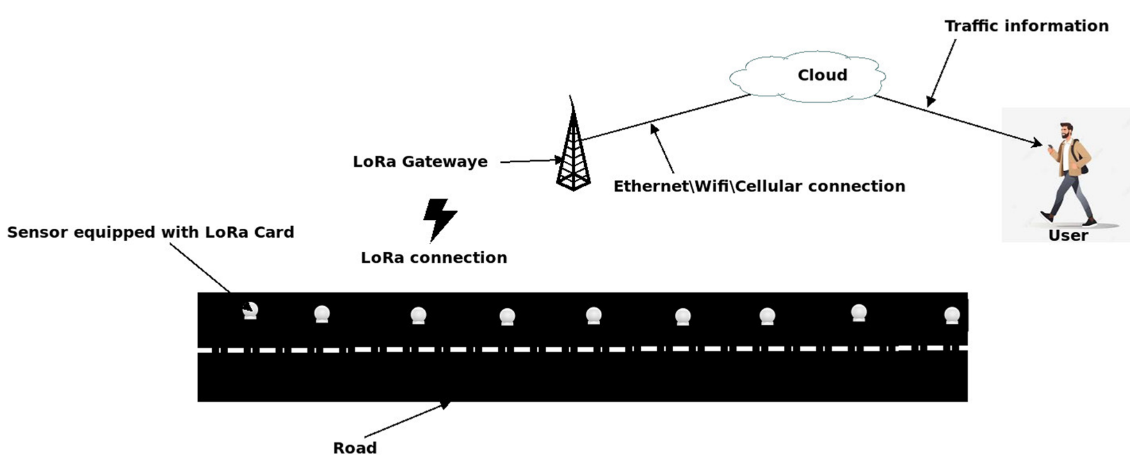


Fig. 9 Road traffic monitoring via LoRa

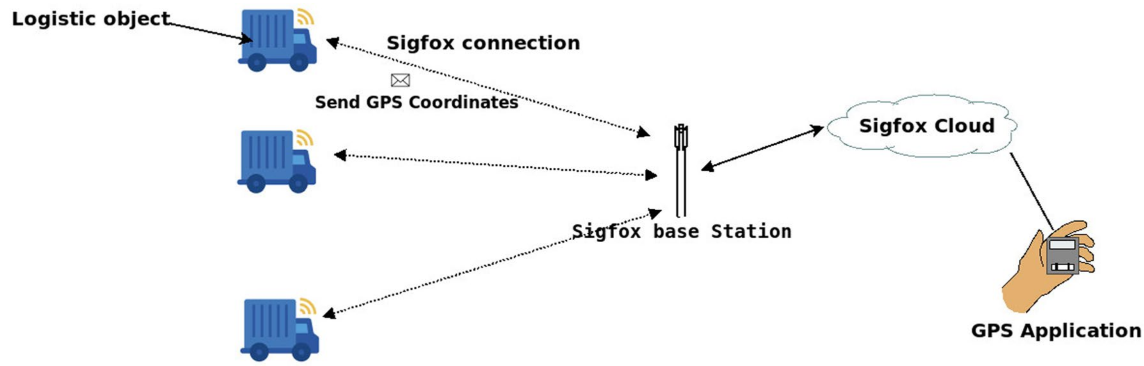


Fig. 10 Logistics object location system with Sigfox

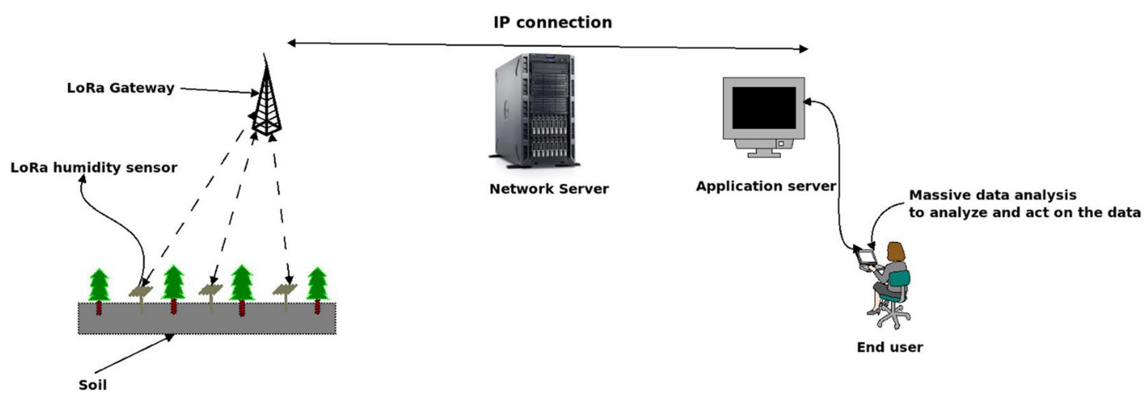


Fig. 11 Soil humidity monitoring system with LoRa

An example of the use of LPWAN technologies, more specifically with Sigfox, in logistics is the localization of logistics objects through their GPS coordinates collected thanks to the Sigfox network, as illustrated in Fig. 10. Logistics object location system with Sigfox.

In [8], Sigfox technology is used to locate logistics objects using GPS coordinates collected by the Sigfox module. This information is sent to the Sigfox Cloud for storage and processing and then visualized or exported to an XML file via web applications.

In [83], the authors proposed a smart express box system (a new delivery mode) based on NB-IoT technology. The smart express box consists of a 32-bit STM32 microcontroller, an NB-IoT module, and a key module. The STM32 module enables the smart lock to be set up and controls the information transmitted by the users. The NB-IoT module takes care of the connection between the Cloud and the STM32 module.

5.3 Agriculture

Agriculture is a sector that needs to modernize to keep pace with global population growth. Smart farming, also known as precision farming, is a set of practices that use technology to improve crop yields and reduce environmental impact. To achieve smart farming, low-rate data on soil moisture, plant health, etc. is collected and transmitted for long-distance analysis. Rural areas where agriculture takes place are often served by something other than cellular networks. Given this, LPWAN technologies are suitable for many applications in this sector due to their ability to provide connectivity to devices in rural areas [7].

A concrete application of LPWAN technologies in agriculture is shown in Fig. 11. Humidity sensors equipped with LoRa cards send the measured data to a LoRa gateway, which then activates an irrigation system.

In this paper [84], an intelligent watering system is developed that minimizes human intervention. It is composed of the IoT subsystem, the cloud-based processing subsystem, and the watering subsystem. The IoT segment consists of ATMOS 41 micro weather station to collect data such as air temperature, humidity, wind speed, solar radiation, etc., and a gateway responsible for transmitting the data from the micro station to the Cloud. The micro-station communicates with the gateway via LoRa technology, and 4G communication is used between the processing platform and the LoRa gateway. The watering system is triggered or interrupted according to the results of the processing done on the Cloud with the help of machine learning. Most of the application of LPWAN technologies in agriculture is similar to the operation described in Fig. 11. First, sensors are used to obtain data in the field, and then LPWAN modules allow the transmission of this data to a gateway that transfers it to the Cloud for analysis, processing, and decision making [5, 85–87].

5.4 Environmental monitoring

Environmental monitoring is essential to preserve the environment. It is defined in [88] as detecting indicators of ecosystem health in water, air, and soil. Monitoring can cover air quality, water quality, noise, etc. In general, monitoring areas cover large geographical areas. Therefore, good coverage of the area and long-range transmissions are essential, hence the birth of environmental monitoring projects based on LPWA network technologies.

NB-IoT technology could be used to monitor air quality via a CO2 sensor capable of communicating with an NB-IoT base station as shown in Fig. 12

The works of [52, 54, 89–93], have proposed a system based on LPWAN technology to monitor air quality. For example, in [93], the authors proposed an air pollution monitoring system. It is an IoT project based on smart sensors that return data using NB-IoT technology. The system consists of smart sensors, a LinkIT Smart 7688 microcontroller, and an NB-IoT network using LTE technology. And the data can be viewed through a smartphone.

The authors of paper [94] conducted a feasibility study of a project featuring LoRa sensor nodes distributed in a forest and a UAV supporting a LoRa gateway flying over the area to collect data from the nodes. The system's architecture is a LoRa network with these four elements (nodes, gateway, network server, and application server). A river water quality monitoring system for Citarum was developed in [95]. This system uses LoRa nodes and a LoRa gateway to communicate monitoring data (river water temperature, pH level, metal concentration (Pb and Fe), and river water turbidity) to a server for storage. In a LoRa network, the classical topology is a star. Still, in the above-mentioned study, a mesh topology is used, and they concluded that the maximum distance between two nodes on the water surface is 500 m. LPWA technologies are often involved in environmental monitoring projects.

5.5 Smart building

Today, we are increasingly witnessing building management automation with the support of innovative projects supported by sensors and actuators. The objective of intelligent buildings is to provide a high level of comfort and reduce environmental impact. Data such as temperature, CO_2 concentration, energy consumption in the building's rooms, data related to the heating system, etc., are collected for analysis and decision-making. Much of this data requires a low data rate, and the information signals must be robust enough to penetrate the buildings. Therefore, LPWA technologies are suitable for several smart building applications.

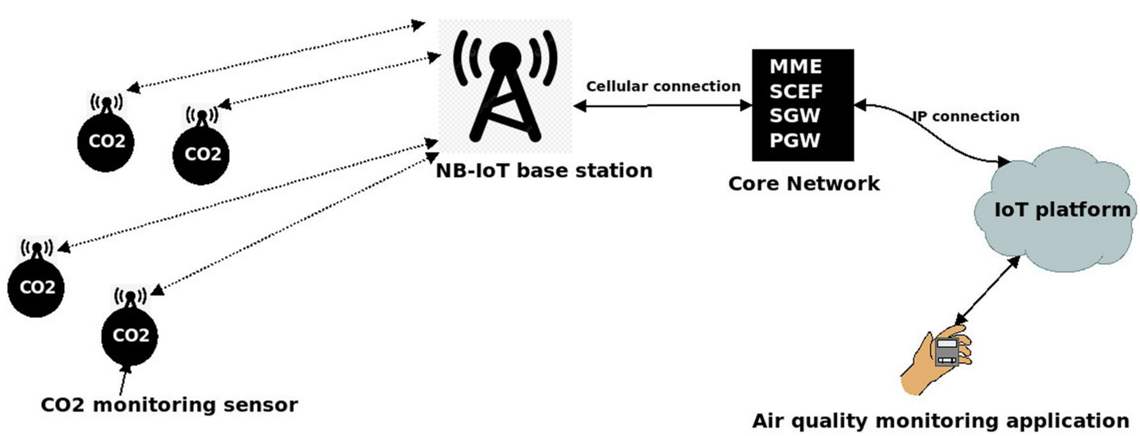


Fig. 12 Air monitoring system via NB-IOT

A use case for LoRa technology in intelligent building management is shown in Fig. 13. Temperature sensors are placed in the building and send the measured data to an application server via a LoRa gateway over a LoRa network. After analyzing the data, the application server can regulate the heating system via an actuator.

The authors in [20] have favored LoRa and Wi-Fi technologies to implement a fire detection and prevention system in an intelligent building. We highlight the use of LoRa technology as a backup network for data transmission in case of failure of the Wi-Fi network. This is made possible by the Heltec Wi-Fi LoRa 32 card, which embeds both a Wi-Fi and LoRa component. A project for monitoring temperature in indoor environments such as buildings was developed in [96]. It is based on NB-IoT technology and the OneNET cloud platform. The International Mobile Device Identification (IMEI) is used to characterize NB-IoT terminals. The Constraint application protocol (CoAP) [97] and the light-weight Machine to Machine (LwM2M) [98] application layer protocol enable the communication between NB-IoT terminals and the Cloud platform.

5.6 Health

IoT applications based on LPWA technologies have emerged in the medical field [2, 99–104]. The applications most often involve the monitoring of vital signs. The data from this monitoring needs to be transmitted urgently or periodically. If the latter is the case, then LPWANs can provide long-range communication at a moderate cost.

NB-IoT technology can be used to care for the elderly, as shown in Fig. 14. Heart rate sensors worn by elderly people send heart rate data to a NB-IoT base station. AND an IoT platform enables a control center to monitor the heart rate of these elderly people.

In [105], the possible use of LoRa technology to monitor the well-being of elderly patients is discussed. The suitability of NB-IoT technology for the healthcare sector is detailed in this article [106]. Indeed, according to the authors, NB-IoT technology consumes little energy, the bandwidth required is low, and harmful radiation to the human body is not significant in NB-IoT. In [107], a wearable system using LoRa technology is used to monitor the health status of soldiers on the battlefield and to locate them. Indeed, GPS, temperature, heart rate, and Spo2 sensors for blood oxygen level are used to have information to transmit with the LoRa network. Through the Thing Speak platform, the control unit (the base camp) uses the data transmitted to the Cloud through the gateway to provide medical assistance in case of emergency.

5.7 Smart meter

Companies with a large distribution network for water, electricity, and gas, … need smart meters to optimize their human resources by dispensing with manual reading and monitoring the network to anticipate possible failures. Smart meters usually send information at time intervals and are usually spread over a large area.

LPWAN technologies can also help to deploy smart meters, as illustrated in Fig. 15 with Sigfox technology. Homes are equipped with smart water or electricity meters capable of communicating with a Sigfox base station. Through the Sigfox Cloud, customers and the company have access to readings from these smart meters.

LPWAN technologies are used in smart metering applications [108–111]. A case of a 1000 smart meter deployment based on LoRa in Indonesia is presented in [112]. An Advanced Metering Infrastructure (AMI) for managing the water and electricity distribution network is proposed in [110]. The smart meters in the AMI include home display units (HDUs),

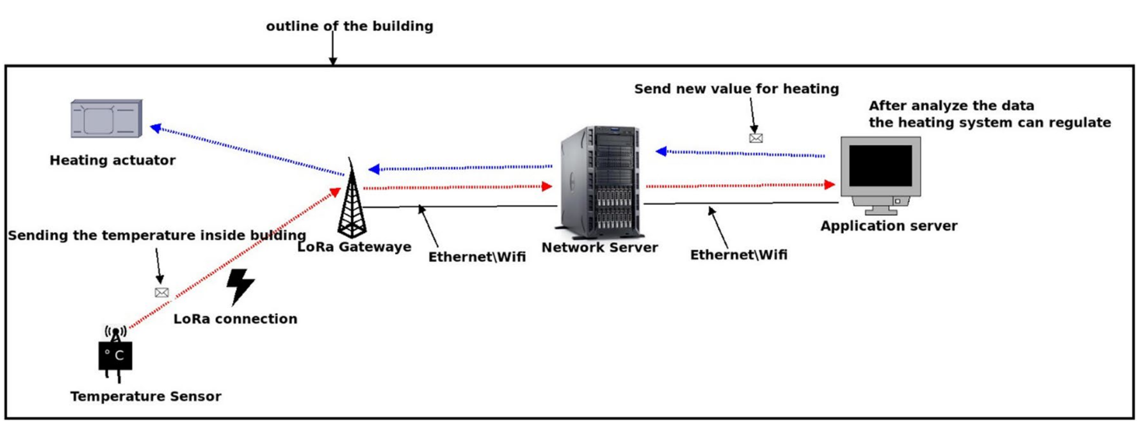


Fig. 13 Building heating control system via LoRa

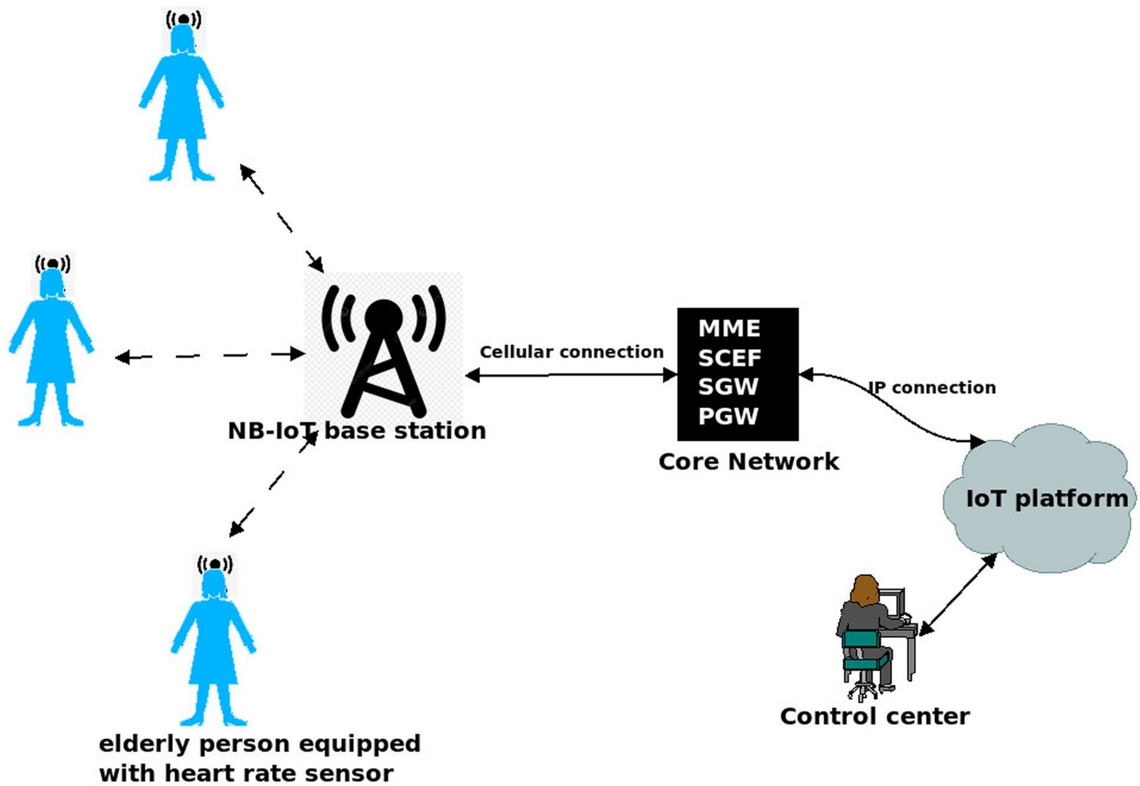


Fig. 14 Remote cardiac rhythm monitoring for the elderly via NB-IoT

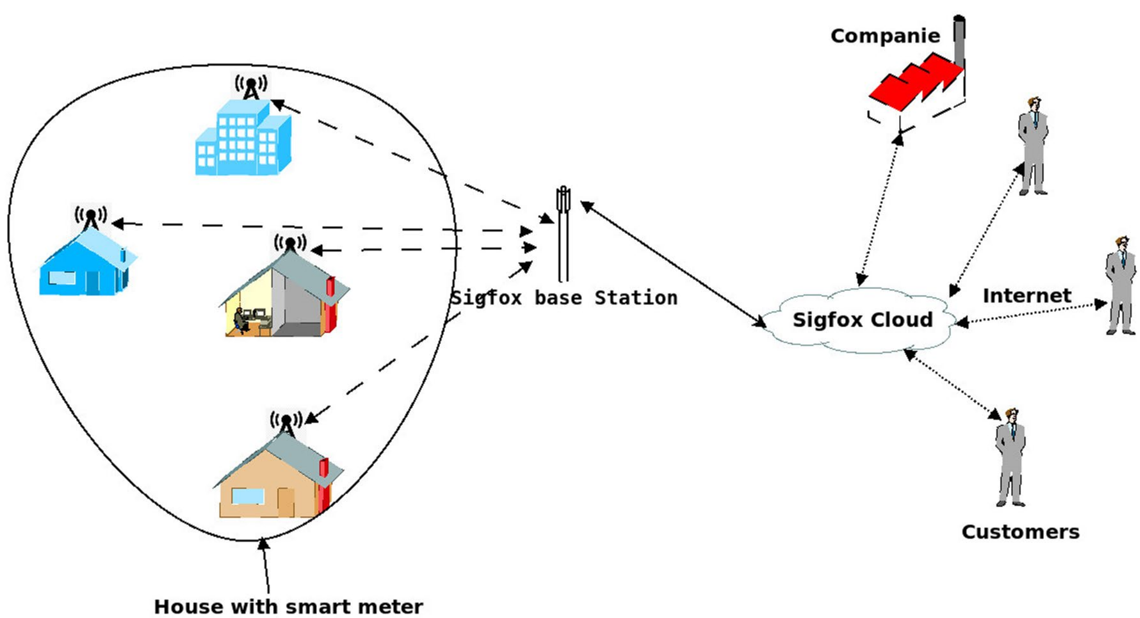


Fig. 15 Using Sigfox to deploy smart meters

home networks, and sensors. The Sigfox network provides two-way communication between the meters and the gateways. Data is transmitted to the platform for storage and reporting to consumers.

6 Potential limits of LPWAN technologies

Wireless Area Networks (WANs) have attracted a great deal of interest in recent years, and rightly so, given the many applications in which they can be used. LPWAN technologies offer huge advantages in terms of transmission range, network cost, etc., but there are a number of limitations, listed in Table 4, that need to be noted if these technologies are to be properly considered.

The first weak point of LPWAN technologies is linked to the use of the sub-GHz frequency band, in particular regulations on the maximum duration of 1% during which devices are authorized to transmit on this band (duty cycle). The sub-GHz band is used by most LPWAN technologies (LoRa, Sigfox, NB-FI) except those supported by a cellular infrastructure (3G, 4G, etc.). So the duty cycle prevents these technologies from benefiting from the acknowledgement mechanism for all messages, and the feasibility of software updates via the downlink is affected by the duty cycle. The data rate must be calculated according to the duration during which the device is authorized to occupy the frequency band.

The ALOHA channel access protocol is the mechanism most commonly used in LPWANs. With this mechanism, terminals can transmit frames at any time while respecting the duty cycle. So scalability, one of the characteristics of these networks, becomes a limit when traffic is intense. The denser the network, the higher the probability of devices transmitting at the same time, leading to numerous collisions due to the access mechanism, and consequent packet losses.

LPWAN technologies use an open frequency band, so they compete with other communication technologies for the use of the transmission medium. LPWANs face sources of interference from other devices using the band, and the unpredictability of this source of interference makes it difficult to predict its impact on the network.

7 LPWAN optimization mechanisms

The objective of optimization often guides the design of a network. Even with the advantageous characteristics of LPWANs in IoT projects, works on optimizing these networks have been widely published. Different techniques to improve LPWANs according to the requirements of applications have been developed. The objective of the deployment can be spectral efficiency, high throughput, low latency, low power consumption of the devices, or a combination of these. This work has identified two areas where LPWAN optimization can be focused: spectrum and energy consumption of the nodes.

7.1 Spectrum

Most LPWAN technologies operate in the unlicensed frequency band, where many technologies are deployed nearby. Thus, spectrum congestion affects spectral efficiency, quality of service, throughput, and latency [113]. As a result, a range of techniques has been developed to optimize the spectrum and thereby manage interference. Cognitive radio is one such approach to spectrum optimization. It is defined by the Federal Communications Commission (FCC) as: "A radio or

Table 4 Potential Limits of LPWAN

Limits	Reasons
Sub-GHz frequency band	- Regulations on the maximum duration of 1% (duty cycle) - No acknowledgement mechanism for all messages - Unfeasibility of downlink software updates
ALOHA channel access protocol	- High traffic intensity - Increased collision -Threat to scalability
Open frequency band	- Interference from other sources - Difficult to predict the impact of interference

system that senses its electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters for system operation, e.g., to maximize throughput, mitigate interference, facilitate interoperability, access secondary markets" [114]. Integrating cognitive radio into LPWANs (CR-LPWAN) allows devices to sense the spectrum through sensing technology to determine unused frequencies [115]. Cognitive radio facilitates scalability in LPWANs. Adaptive control of the transmit power of terminal devices is a means of mitigating interference and ensuring spectral efficiency. The transmit power is adjusted according to the information received by the receiver. In [116], two types of transmit power are allocated to devices to improve network performance. Spectrum optimization can also be achieved through gateways. Indeed, the deployment of several base stations increases the success rate of transmissions, which would make interference harmless. The authors of [117] have proven by simulations that using multiple gateways in LPWANs is significantly more efficient than using directional antennas for network optimization. In [118], algorithms for optimizing gateway placement are presented. By simulation, the authors claim that the delivery rate is higher with gateway placement by their algorithms than with naive gateway placement. Other techniques, such as using smart antennas or spectrum analyzers, can optimize the spectrum.

7.2 Energy efficiency

The end devices of LPWANs are usually powered by batteries [42]. Therefore, optimizing energy consumption as much as possible is crucial. The battery life of the network's terminal nodes, the energy required to transmit one bit of data or the energy consumption of the network, i.e. of all terminal nodes, can be used to measure energy efficiency. As terminals are deployed on a large scale, the maintenance operation of exchanging or recharging the batteries is costly, so it should be rare in time. For this reason, studies have been conducted to optimize energy consumption in LPWANs [42, 66, 119, 120]. Some propose a comparative evaluation of the energy efficiency of LPWAN technologies, and others present strategies to improve energy efficiency. The energy consumption of LoRa and Sigfox are discussed in [121]. Under the same test conditions, the authors concluded that Sigfox shows better energy efficiency than LoRa. NB-IoT terminals consume more energy than LoRa and Sigfox terminals [122]. In [123], an energy-efficient solution is proposed. Indeed, the authors designed an energy-sensitive system model for LPWANs IoT devices. A solar panel with a lithium-ion hybrid supercapacitor allows LPWAN devices to operate autonomously (without a battery). Physical and MAC layer parameters have an impact on the energy performance of LPWANs, which is shown in [119]. Analytical models characterizing the power consumption, lifetime, and energy cost of transmission of LoRaWAN end devices were discussed. In [120], different parameter configurations, such as spreading factor, bandwidth, and transmission power, are experimented with in a LoRa network to evaluate their energy consumption. In NB-IoT, power saving mode (PSM) and extended discontinuous reception (eDRX) are the two mechanisms for energy efficiency. The former allows devices to enter a deep sleep mode where they are not reachable but remain registered in the network. The eDRX mode makes the devices inactive for a specific time. In [66], an analytical and simulation model is proposed to evaluate the two energy-saving modes (PSM and eDRX).

8 Discussion and research challenges

We are witnessing the popularization of LPWA technologies, thanks to the convergence of several IoT researchers and the countless services they provide. This dazzling development logically raises a number of challenges that need to be overcome if LPWA technologies are to be further integrated into IoT projects. While each technology has its own inherent challenges, there are points of intersection between them. In this section, research challenges related to LPWA technologies are grouped by theme, and an in-depth analysis is carried out with the aim of proposing avenues of reflection to open research questions.

Comparative study: Throughout the previous sections, it is noted the plethora of LPWAN technologies with technical characteristics such as maximum throughput, range, modulation type, or payload, some of which are different and others similar. In every type of IoT project involving LPWAN technologies, one technology may be more suited to the project requirements than another. So comparative studies of LPWAN technologies in different environments with different performance indicators and different applications need to be carried out, either by deploying LPWAN technologies in the field or through test beds.

Scalability: Scalability, developed in 3.2.3, is one of the features put forward by players to promote LPWAN technologies. LPWAN are likely to be involved in city- or country-wide deployments. Millions of terminals are therefore expected. Sometimes, one area may concentrate more terminals than another. This can lead to one base station having more tasks than others or to the problem of insufficient spectrum resources. Not to mention the crucial problem of interference between terminals, reflected in packet collisions in the network. As a result, most studies on scalability analyze the overall capacity of LPWAN rather than circumventing or mitigating the impact of these problems. So, to overcome these problems, we need to think about optimal deployment strategies for both terminal nodes and base stations, improve access protocols to existing mediums, study the influence of physical parameters on the probability of successful terminal transmission, and think about transmission scheduling strategies to avoid simultaneous transmission of as many terminals as possible.

Machine learning and LPWA technologies: In LPWANs, the entity that manages the devices is often deployed in the cloud, where artificial intelligence algorithms can be executed, systematically sending all the data collected by the IoT terminals. This implies high energy consumption for transmission, latency, security, and confidentiality issues. The integration of artificial intelligence aims to transform IoT devices, limited in computing resources such as LPWAN terminals, into intelligent entities. The trend is to couple the new machine learning paradigm [124] called Tiny Machine Learning (TinyML) [125] with LPWANs. TinyML is a machine-learning solution for devices with limited computing resources. TinyML's machine learning integration will enable LPWA devices to become intelligent enough to be autonomous and make wise decisions, but this will only be achieved with problems. Indeed, IoT devices currently have efficient microcontrollers. Still, these microcontrollers could be more powerful, so they will need more time to perform complex tasks for new services and intelligent applications to take full advantage of machine learning. So, the challenge is to design devices with powerful processors without sacrificing one of the characteristics of LPWANs: low cost.

Interoperability: The diversity of LPWA technologies is linked to the operation of the physical and MAC layers, including frequency band, modulation, payload size, and how communication is secured. The requirements of IoT applications are diverse and varied. An IoT application may deliver several services with different LPWA technologies, each responding to an additional demand. Instead of each service having its own network, we can think of a hybrid network. In this network, multi-connectivity base stations must communicate with end nodes of different LPWA technologies. A hybrid network could optimize the costs of a complex IoT application. By deduction, data from different sources and formats needs to be processed. So, middleware development or an additional protocol layer common to all technologies to ensure communication between applications is a solution for data integration.

5G and LPWAN: Despite their long transmission range, low energy consumption, and low device cost, LPWA technologies have low data rates, which limits their scope of application, and remote areas of cities often need to be served by a 5G network. To overcome these shortcomings, research focuses on integrating LPWA technologies with the 5G network [126–128]. 5G is a flexible, scalable, and programmable communications network [129]. Integrating cellular LPWA technologies with 5G should pose no problems, as they already work with cellular infrastructure and on the licensed band. A network composed of non-cellular LPWA and 5G with the same unified management entity raises challenges related to architecture, security, and mobility. LPWANs have their own security mechanism, taking into account message length and the limited number of messages per day, whereas 5G uses authentication protocols that work with several large messages. As a result, LPWAN security mechanisms need to be revisited, rethinking the authentication of devices in the network, the provision of secure identifiers, data confidentiality, etc., to enable LPWA devices to operate in the 5G network. In terms of architecture, LPWANs have simple architectures, which is not the case for the more complex 5G networks. So, an ideal LPWAN-5G architecture is one where 5G provides connectivity between the gateway or base station and the network server. Integration can be achieved with techniques such as Software Defined Network (SDN), where a network-based management platform enables LPWAN devices to be controlled, and Network Function Virtualization (NFV), where hardware compatibility issues can be resolved by virtualizing certain services. As for mobility, 5G could bring much smoother mobility to LPWAN devices. To achieve this, the LPWAN and 5G data management entities need to communicate via a common interface. The interface will enable the exchange of encryption and subscription key information.

9 Conclusion and future works

This work provides an overview of LPWANs. By conducting an exhaustive search on renowned scientific databases such as Springer, IEEE Xplore, ACM Digital Library, and Google Scholar, this article has offered an in-depth and interesting literature review on LPWAN technologies. LPWANs have a long transmission range, energy efficiency, scalability, and low device and subscription costs. The techniques used to achieve these characteristics were discussed. LPWANs have similar architectures, so a generalized LPWAN architecture has been presented in this review. The growing potential of

LPWAN technologies has led some international organizations to take an interest in them by proposing standards. These standards, as well as existing LPWAN technologies, have been developed. Despite the research efforts made to create LPWAN technologies, reflected in their integration in several domains such as health, agriculture, smart cities, transport, etc., challenges have to be addressed for the sustainability and popularization of the technologies. These application areas, potential limitations, and challenges are discussed in this research work. The future work will be intended to study and propose a multi-server architecture for LoRaWAN to better support scalability.

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Declarations

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