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Long-range, low-power for IoT devices: The LoRa Network a review

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Abstract— **The Internet of Things (IoT) changes our ability to connect and interact with the physical world by integrating different objects into the internet. By all the many Low Power Wide Area network (LPWAN) technologies, LoRa (Long-Range Radio) stands out for its long-range capabilities, low power consumption, and robustness that's why it becomes a crucial component in cost-effective IoT applications such as smart cities, smart homes, smart factories, and smart farming. The purpose of this article is to present an overview of the LPWAN technology especially the LoRa by covering the characteristics, the challenges, and existing strategies.**

Keywords—IoT,LPWAN,Lora technology.

I. INTRODUCTION

The Internet of Things (IoT) encompasses the connectivity and data exchange among various devices and sensors. As projected by the Statista Group, the number of connected devices worldwide is expected to reach nearly 29 billion by 2030, tripling the count from 2022 [1].

The Internet of Things (IoT) plays a vital role in facilitating interconnectedness and enhancing various aspects of our life, including business activities, remote operations, and social interactions. The influence of IoT technologies is particularly prominent in urban areas. These technologies enable cities to become more efficient and sustainable by integrating data-driven systems to manage resources, enhance infrastructure, and improve the overall quality of life. In the realm of manufacturing, IoT empowers businesses with real-time monitoring, predictive maintenance, and streamlined production processes. Wearable devices connected to IoT networks allow individuals to track and manage their health, while smart homes enable automation and remote control of various household functions. Additionally, IoT is a crucial enabler for the development and deployment of autonomous vehicles, revolutionizing transportation, and mobility [2].

Due to the growing number of IoT connectivity and diverse application requirements, the task of implementing smart, efficient, flexible, and affordable IoT systems within the massive-IoT framework has become more complex therefore connectivity emerges as the principal aspect of IoT networks.

In smart city application scenarios, there is a significant presence of devices that need to communicate over long distances with minimal energy usage. In this context, LPWAN technologies come into play. Among various connectivity options, Low-Power Wide-Area Network (LPWAN) has emerged as the perfect choice for IoT networks, due to its extensive communication range, minimal energy consumption, and cost-effectiveness. LPWAN protocols excel in offering connectivity for numerous low-power, battery-operated devices, catering to delay-tolerant applications with constrained throughput per device [3]. In fact, the paper is organized as follows: First, a description of the different LPWAN technologies is given. Then, a comprehensive overview of LoRa technologies is presented, followed by an explanation of the architecture of LoRaWAN. Later, the current challenges of LoRa transmission is outlined. Finally, the benefits of integrating Lora technologies in smart cities and the future research are discussed.

II. LPWAN TECHNOLOGIES

Low Power Wide Area Network (LPWAN) introduce a fresh communication approach that complements existing cellular and short-range wireless technologies, effectively addressing the varied needs of IoT applications.

These innovative technologies provide distinctive features, such as broad coverage for low-power and low-data rate devices, which are not offered by conventional wireless technologies.

The combination of wide area coverage, low power consumption, and affordable wireless connectivity in LPWAN technologies creates a compelling business case for IoT/M2M applications with low throughput requirements that don't necessitate ultra-low latency. The increasing market for Low Power Wide Area (LPWA) networks has indeed led to intense competition among network operators, resulting in the development and adoption of more cost-effective technologies. One of the essential prerequisites for LPWAN technologies is the ability to accommodate many devices transmitting small amounts of data. With a single LPWAN base station, tens of thousands of end devices spread across several kilometers can be connected, resulting in significant cost reductions for network operators [4].

In order to understand the comparison with LPWAN technologies, it is important to highlight the main features and characteristics of these technologies. By doing so, we can gain a clearer understanding of how they differ and how they might complement each other.

A. SigFox

Sigfox is a wireless long-range technology which offers a wide range of coverage, positioning itself between Wi-Fi and cellular networks in terms of range capabilities. It operates within the license-free ISM bands, such as 868MHz in Europe, 915MHz in North America, and 433MHz in Africa. Sigfox is particularly suitable for applications that run on small, battery-powered devices with low data transfer requirements. This is because WIFI's range is often limited, while cellular networks can be expensive and power intensive. An access point in a Sigfox network can manage up to one million end-devices. Each end-device has the capability to send around 140 messages per day, with a data rate of 100 bps. Remarkably, the battery life of Sigfox devices can last up to 10 years.

Nevertheless, Sigfox challenges with its suitability for fast-moving devices in IoT applications. Experiments have shown that Sigfox can be unreliable at low latencies, making it less feasible for use in scenarios where real-time, time-sensitive data communication is required [5].

B. NBIOT

NB-IoT (Narrowband Internet of things) is a wireless communication technology specifically designed for low-power, wide-area IoT (Internet of Things) applications. It is standardized by the 3rd Generation Partnership Project (3GPP) and operates in licensed spectrum bands. NB-IoT operates alongside existing cellular networks, using a portion of the LTE (Long-Term Evolution) spectrum. It benefits from the infrastructure and security features of cellular networks while providing connectivity for a wide range of IoT devices and applications It employs QPSK modulation, Frequency Division Multiple Access [5].

Specially designed devices and sensors are also used as basic components in NB-IoT systems. These devices collect information from their surroundings and transmit it to NB-IoT base stations or transmission nodes. Individual base stations are connected to an IoT gateway and IoT cloud application servers for centralized monitoring and data analysis [6].

One of the main objectives of NB-IoT is to enhance the coverage beyond what current cellular technologies provide. To achieve this, NB-IoT incorporates transmission repetitions and diverse configurations for bandwidth allocation in the uplink transmission. These features enable NB-IoT to support a wide range of applications with varying coverage requirements and help extend the coverage of the network. [6]

C. LoRa

LoRa is a narrowband communication technology patented by Semtech. With its ability to provide adaptable radio coverage, LoRa is well-suited for large-scale IoT deployments that necessitate long-term, reliable communication and extended device lifespan. Due to its Typical low cost and flexible deployment options Lora may be the most suitable LPWAN solution to maintain dependable wireless connectivity in vast IoT networks. Table I presents a brief comparison between the above-mentioned LPWAN technologies; the next paragraph aims to discuss the characteristics of this technology [7]

Table 1 LPWAN technologies distinction [5]

Aspect	SIFOX	NB-IOT	LORA
Data Rate	100 bps 50 kbps	20 kbps 250 kbps	290 bps 50kbps
Battery Lifetime	10 years	10 years	10 years
Urban Range	10Km	1Km	2 to 5 Km
Rural Range	40Km	10Km	20Km
Modulation	BPSK	QPSK	CSS
Security	No	Yes	Yes
Cost	Low	High	Low

III. Background of LoRa

LoRa, is the underlying technology used in LoRaWAN, a wireless communication protocol. It offers several key features as shown in Fig 1, including efficient power consumption that enables devices to operate on a single battery for approximately 10 years. The data rate provided by LoRa depends on the spreading factor and channel width selected, offering options such as 27 kbps with a spreading factor of 7 and a 500 kHz channel, or 50 kbps using FSK modulation. One of the most significant advantages of LoRa is its long communication range, allowing for reliable connection over distances of 2-5 km in urban areas and up to 15 km in suburban areas. This technology was originally developed by Cycleo, a French company that has since been acquired by Semtech, a leading semiconductor manufacturer [8].

In literature, many works have been done to examine the performance of LoRaWAN. In fact, the authors in [9] offered a general introduction to LPWAN technologies, and perform a comparison between Sigfox, NBIoT and LoRaWAN in term of modulation schemes, coverage, bandwidth, and the energy consumption. Besides, in [10], a review of the LoRaWAN architecture is given by describing its main components such as EDs, GWs, network, and applications. In [16] the LoRa technology has been explored by discussing variety of perspectives and challenges. In this paper, a review of the LPWAN technologies especially the LoRaWAN is provided by analyzing the effect of the Spreading Factor (SF) on the bandwidth.

The LoRa network is built upon two essential elements: LoRa and LoRaWAN. LoRa serves as the physical layer modulation, while LoRaWAN functions as the MAC layer protocol (Figure2). By combining these two components, a wide-area network is formed that is both low-power and cost-effective.

For the Physical Layer LoRa adopts the Chirp Spread Spectrum (CSS) modulation mechanism, which provides anti-interference and long-range communication capability. The base symbol in LoRa physical layer protocol (PHY) is a chirp

with frequency linearly increasing with time. When the frequency increases with time, we name it up-chirp and otherwise down-chirp as shown in Figure 3 [11].
For the MAC Layer the LoRaWAN network is designed with a star-of-stars topology, consisting of three main components: Network Servers (NS), Gateways (GW), and End Devices (ED).

Fig1 Various use cases for IoT with LoRa [4]

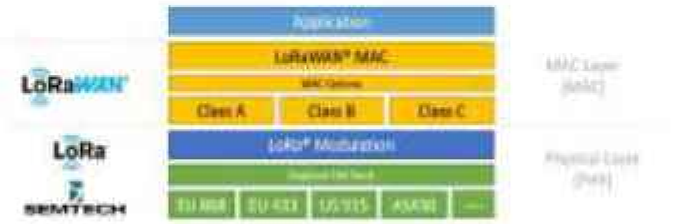

Fig2 LoRaWAN technology stack [6]

The LoRaWAN network operates with a centralized architecture where the central network server manages the communication between gateways and end devices. Gateways act as connectors, forwarding data between end devices and the network server. End devices transmit data to the nearest gateway, and the network server coordinates communication and manages the network's overall operation. This architecture allows efficient and scalable wide-area IoT deployments with long-range, low-power communication capabilities [12].
The LoRaWAN defines three ED classes: Class A, Class B, and Class C. This ED are equipped with a LoRa node printed circuit board, a radio module and printed antennas for wireless signal communication with the LoRa gateway they are also equipped with sensor microprocessors to detect and process signals and specific changes and actions These three classes exhibit variations in the rate at which they maintain open receive window time slots, a factor that directly influences the power consumption and longevity of the device's battery.

- Class A: This is the default class that allows ED to transmit an uplink at any time, followed by two short downlink receive windows. The node transmits to the gateway when needed. After transmission the node opens a receive window to obtain queued messages from the gateway
- Class B: ED with scheduled receive slots: The node behaves like a Class A node with additional receive windows at scheduled times. This allows lower downlink latency at the cost of higher power consumption.
- Class C: end-devices with maximal receive slots: these nodes are continuous listening which makes them unsuitable for battery powered operations.[13]

IV. CARECRERISTIQUES

A. Energy consumption rate

IoT devices are projected to have extended lifetimes. To address this, mesh layouts have been adopted in various industries, offering shorter communication paths compared to other network architectures. However, mesh architecture has its drawbacks, including significant implementation costs. Moreover, the need for data to traverse multiple nodes in a mesh network can lead to certain nodes depleting their batteries quickly, thereby reducing the overall lifespan of the network. Consequently, it is recommended that low-power wireless network solutions opt for the star network architecture, which allows for low power consumption while enabling long-distance communication or broad coverage [14]. LoRa appears to be a modern technology that uses star network, so it consumes very little energy.

B. Frequency

Based on reference [15], LoRaWAN works in an unlicensed frequency range to avoid interferences and get the optimal spectrum characteristics, providing an open and globally accessible spectrum for low-power, long-range communication in IoT applications. Its use of unlicensed bands eliminates regulatory hurdles and lowers barriers to entry. LoRa's operation in shared spectrum allows for cost-effective and rapid deployment without the need for specific licenses, encouraging collaboration and community-driven development. The flexibility of unlicensed bands supports the global adoption of LoRa, making it an attractive choice for businesses and developers seeking low-cost, long-range connectivity for IoT and M2M applications.

C. Modulation

The LoRa physical layer uses Chirp Spread Spectrum (CSS) modulation, a spread spectrum technique where the signal is modulated by chirp pulses (frequency varying sinusoidal pulses).
The modulation process is borrowed from RADAR technology, and consists of developing, during the transmission time of each symbol, a sinusoidal wave Su(t) presenting, around a carrier frequency fc, a linear frequency variation.
A distinction is made between Upchirps, for which the frequency increases linearly over time, Downchirps for which the frequency decreases linearly [16].
A single chirp waveform can be defined as:

$$c(t) = \begin{cases} \exp(j\varphi(t)), & \frac{-T}{2} \leq t \leq \frac{T}{2} \\ 0 \ otherwise \end{cases} \quad (1)$$

where φ(t) is the phase of chirp waveform. This sine wave whose frequency varies linearly with time is called CHIRP (Compressed High Intensity Radar Pulse) examples of this sines are shown in Fig3:

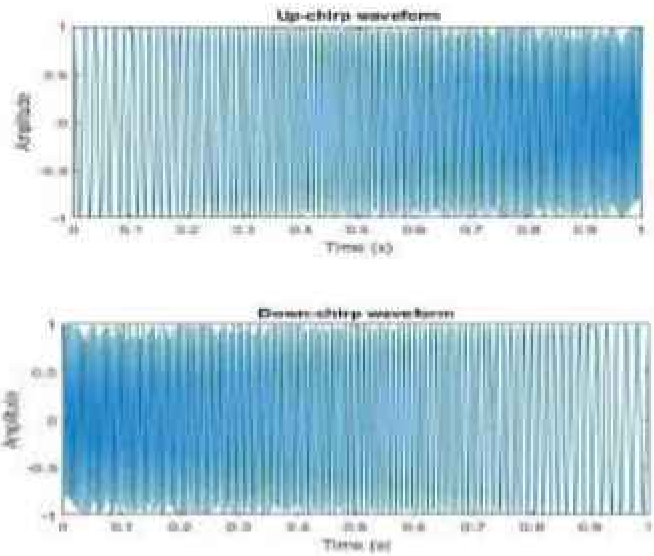

Fig3 Up-shirp and down-shirp waveform

LoRa radios and interfaces typically adhere to certain specifications which are :

-Frequency band

In Europe, the LoRa radio interface uses the ISM (Industrial, Scientific and Medical) called Sub-GHz 868 MHz (while in the United States the 915 MHz band is used). LoRaWAN, like any other ISM frequency standard, is required to adhere to the regulations established in the specific region where the network is deployed [15]. Moreover, the operator of a LoRa network has the flexibility to designate the channels through which devices communicate, and these can belong to any accessible sub band. Simultaneously, multiple signals can be transmitted on the same channel, as the spread factors are minimally orthogonal, ensuring adequacy for various Low Power Wide Area (LPWA) usage scenarios.

-Bandwidth BW

The length of a communication channel is described as bandwidth or throughput. A higher bandwidth leads to improved connection speed but reduced sensitivity (due to increased susceptibility to noise). Conversely, with reduced bandwidth, sensitivity is enhanced, but the transmission flow is diminished.
The frequency variation of a chirp (Fmax-Fmin), which we have denoted 2ΔF, noted BW for Bandwidth.

The standard provides 3 possible BW values: 125 kHz, 250 kHz and 500 kHz. In Europe, only 125 kHz and 250 kHz bandwidths are used [17].

-Spreading factor SF or number of bits per symbol

The manufacturer defines a quantity denoted SF for Spreading Factor where Ts designates the duration of transmission of a symbol.
According to the standard, the spreading factor SF can take the 6 distinct integer values 7 to 12.
The spreading factor SF also corresponds to the number of bits transmitted during the duration Ts. A higher spreading factor in LoRa improves the robustness of communication at the cost of reduced data transmission speed. The choice of spreading factor depends on the specific requirements of the application, considering factors such as data rate, range, and power consumption.

$$Ts = \frac{2^{SF}}{Bw} \quad (2)$$

-Code rate CR of the data to be transmitted

The constructor adds to the message m(t) to be transmitted additional bits which will be analyzed in reception in order to detect and correct any errors (conventional technique known as FEC for (Forward Error Correction). The number and the frequency of introduction of these bits are characterized by the coding rate CR.
The higher the value of CR is, the more the communication is considered as robust.

- Binary transmission rate

The value of the binary transmission rate, noted Rb (bit Rate) expressed in bits/s, is given by the expression:

$$R_b = SF \cdot \frac{Bw}{2^{SF}} C_R \quad (3)$$

- Speed (or rapidity) of modulation Rs

Since the spreading factor SF is equal to the number of bits per symbol, we can deduct from the previous relation, the value of the modulation speed denoted Rs (symbol Rate) and expressed in Bauds:

$$R_s = \frac{Bw}{2^{SF}} C_R \quad (4)$$

The (CSS) modulation used by the physical layer of the LoRa is instrumental in achieving extended communication distances while exhibiting resilience to interference. Although Frequency Shift Keying (FSK) modulation is also an option, it falls short of matching LoRa CSS's remarkable communication range.
CSS involves modulating the information-carrying signal using a series of chirp pulses, which are then subjected to Forward Error Correction (FEC) before transmission. This modulation technique, with its unique chirp-based approach, contributes to LoRa's robust and long-range communication capabilities.[18]

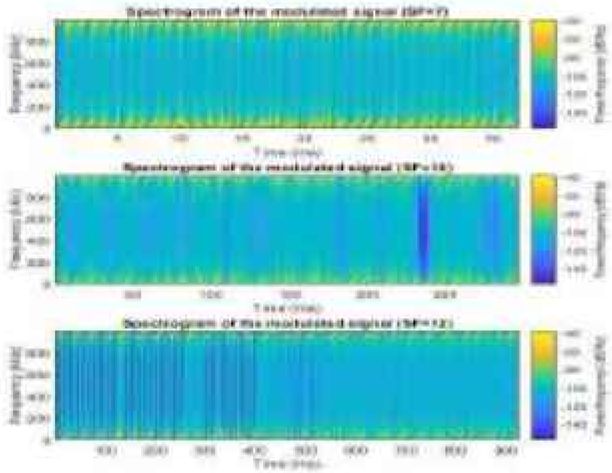

Fig4 Spectogram of the modulated signal with SF=7;10;12

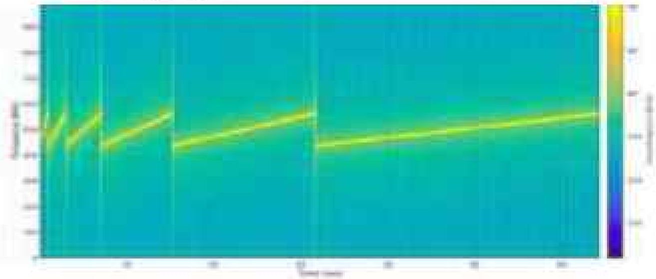

Fig5 Comparaison of the spreading factors

The simulation illustrated in figure 4 and 5 represent LoRa modulation for different spreading factors (SF). The effect of Spreading Factor (SF) on Bandwidth: Signals modulated with higher SF have greater symbol duration, which results in greater transmission duration. This can lead to greater bandwidth occupancy.
The Influence on Receiver Sensitivity: Higher SFs can provide better receiver sensitivity, meaning the signal can be detected even in noisy or low signal power conditions.
In general, higher SF achieves greater transmission range, but at the expense of data rate.
The simulated model uses SF7, SF10 and SF12 from the lowest to highest SFs in order that results will be compared in spectrogram of the modulated signal shown Fig5.
In the first case when the SF=7, the signal is spread over a relatively narrower bandwidth.
In the second case when the SF=10, the signal is spread over a wider bandwidth compared to SF=7.
In the last case when the SF= 12, the signal is spread over the widest bandwidth among the others.
The range of LoRa transmissions is influenced by spreading factors. With lower spreading factors the range of transmissions will reduce . In fact, by adjusting the spreading factor, the network can dynamically control the data rate for each end device, but with an associated impact on the communication range.

Additionally, spreading factors serve as a mechanism to manage network congestion. These factors are orthogonal, ensuring that signals modulated with different spreading factors and transmitted simultaneously on the same frequency channel coexist without interference, enhancing overall network efficiency.

We can conclude, that increasing the spreading factor (SF) generally leads to a more robust communication system with increased resistance to interference and longer range. However, the data rate will be reduced as we can see in table 2. LoRa modulation is seen as a distinctive modulation technology, offering an exceptional long-range communication capability that finds widespread appeal in various applications.

Table 2: The corresponding spreading factor for each data rate

Spreading Factor	Bit rate in bps		
	Cr=4/5	Cr=4/6	Cr=4/7
7	5469	4557	3906
8	3125	2604	2232
9	1758	1465	1256
10	977	814	698
11	537	448	384
12	293	244	209

In the LoRa technology, Table 2 represents the relationship between spreading factor and code rate for a bandwidth=125 kHZ. When the spread factor is set to a high value, the bit rate is reduced. For example, if the specifed Spread Factor is 7, the bit rate is 5469 bps for CR=4/5. When the spread factor is set to 12, the bit rate drops to 293 bps. The code rates 4/7, 4/6, and 4/5 offer different levels of error correction capability and data rates as we can see in Table 2. When the SF increases, the error correction capability increases as well, but the data rate decreases.

V. CHALLENGES OF LORA COMMUNICATION

Even if the LoRa has several advantages, there are many problems that can be cited.

A. Interferences :

As the number of IoT devices using the ISM band increases, the focus on LORA communication systems has grown due to their suitability for such applications. However, the high level of interference in this band presents a significant challenge to the efficient deployment of these systems.
In the architecture of LoRa IOT networks when the transmission between the End device and the Gateway will be the presence of various interfering sources can lead to additional noise being introduced into the original signal, compromising the effectiveness of the communication system.[19]

B. Scalability :

LoRa installations facilitate the interconnection of numerous endpoint devices involved in activity detection. To assess the scalability of this technology, it is crucial to evaluate its capacity. Hence, studies have been conducted to examine the capability of LoRaWAN in both individual port facilities and urban deployments. Based on an analysis of the transmission speed and propagation distance, it is recommended that urban-scale LoRa implementations utilize the highest possible bit rate. Therefore, if the connection speed is lower than the maximum rate, the terminal occupancy per unit area remains unaffected under the given assumption [19].

C. *Security :*

Given the rapid growth of LoRa connections and the recognition of its vulnerabilities, ensuring privacy and security becomes paramount. However, the unique physical attributes of LoRa can expose new and dangerous attack vectors that pose challenges to effective defense. Additionally, the substantial power efficiency requirements of LoRa make implementing reliable defense mechanisms difficult. Moreover, while physical layer security techniques hold the potential for comprehensive protection, their limited robustness restricts their widespread application. For example, existing key creation methods often result in only two valid parties emerging over an extended querying period, rather than accommodating multiple parties Since LoRaWAN is a relatively new protocol, its security level has not undergone thorough examination in academic literature. [20].

VI. DISCUSSION & FUTURE RESEARCH DIRECTIONS

Integrating LoRa into solutions used in smart cities, such as waste management, air quality monitoring, parking management, and traffic control, can enhance operational efficiency, improve public services, and promote sustainability by offering dependable long-distance communication, and creating a connected efficient ecosystem. Despite its numerous advantages, LoRa technology can face many challenges for example, signal interference, concurrent transmission collisions and security issues. In this regard, future works will focus on enhancing the security of an ecosystem based on LoRa technology to provide efficient solutions for smart cities.

VII. CONCLUSION

Several LPWAN technologies are currently competing to deliver the extensive connectivity needed in a world where everyday objects are expected to connect wirelessly to communicate with each other. This article provides a global analysis of one of these technologies which is the LoRa networks. Due to its great potential for enabling robust long-range communication in large-scale IoT networks, LoRa became one of the most prominent LPWAN applications. In this work, we have presented the history of LoRa deployments and analyzed its performance based on its basic parameters: code rate, spreading factor and bandwidth. Besides, a comparison between LoRa with other technologies has been done. Finally, the challenges that can face this technology are discussed.

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