

Received December 2, 2021, accepted December 27, 2021, date of publication January 4, 2022, date of current version January 26, 2022.

Digital Object Identifier 10.1109/ACCESS.2021.3140107

Multi-Layered Energy Efficiency in LoRa-WAN Networks: A Tutorial

IMANE CHEIKH¹, (Student Member, IEEE), RACHID AOUAMI², (Member, IEEE),
ESSAID SABIR^{1,3}, (Senior Member, IEEE), MOHAMED SADIK¹, (Senior Member, IEEE),
AND SÉBASTIEN ROY², (Member, IEEE)

¹NEST Research Group, LRI Laboratory, ENSEM, Hassan II University of Casablanca, Casablanca 20000, Morocco

²Department of Electrical and Computer Engineering, University of Sherbrooke, Sherbrooke, QC J1K 2R1, Canada

³Department of Computer Science, University of Quebec at Montreal (UQAM), Montreal, QC H2L 2C4, Canada

Corresponding author: Essaid Sabir (e.sabir@ensem.ac.ma)

ABSTRACT Emerging Internet-of-Things (IoT) applications are driving increasing demand for advanced services in wireless networks, prompting the development of new technologies to address the associated challenges. Energy efficiency of IoT standards is a key feature targeted by research efforts and industrial activities, leading to an extensive and growing number of innovative solutions. Low Power Wide Area Networks (LPWANs) define a class of wireless communication technologies seen as highly relevant for future IoT development given its long communication range, low-cost devices and interesting energy management. Long Range Wide Area Network (LoRaWAN) is acknowledged to be the dominant IoT communication technology. It has allowed broad deployment and unlocked new IoT applications such as smart cities, asset tracking, etc. This article provides a comprehensive tutorial on the LoRa standard, and surveys existing solutions, hot topics and future insights for building energy efficient IoT infrastructures and IoT devices. Indeed, energy efficiency is one of the key factors for successful and sustainable deployments of IoT applications. More precisely, this article discusses how to meet LoRa/LoRaWAN energy efficiency across physical layer, medium access control layer, and network layer. Subsequently, extensive pioneering solutions from related literature are compared and assessed. Finally, insightful conclusions are drawn, and open problems are listed at the end of this article.

INDEX TERMS LPWANs, LoRaWAN network, long-range, spreading factor, energy efficiency, physical layer, MAC layer, NET layer.

I. INTRODUCTION

A. MOTIVATION AND TRENDS

The Internet of Things (IoT) is an emerging ecosystem enabling a connected, sustainable and smart environment. Its growth is staggering, with billions of objects being deployed to sense, exchange and share relevant information about their environment. This emerging digital fabric acts as a bridge between physical reality and the Internet.

It is expected, according to CISCO,¹ that the number of active connected devices will hit 500 billions by 2030 empowered by the Fifth Generation (5G) of cellular wireless ecosystems. Besides, 5G is leveraged in enhanced Mobile Broadband communications (eMBB), enhanced

Machine-Type Communications (eMTC) and Ultra-Reliable Low-Latency Communications (URLLC). In fact, 5G is designed to support Machine-to-Machine (M2M), Device-to-Device (D2D) and Device-to-Everything (D2E) communication, the IoT and the Internet of Vehicles (IoV). Unlike previous cellular generations, there are specific provisions in 5G for such applications where low power, small form factor, and large numbers of connected devices are the norm. In fact, it was a specific intent of the standardization effort leading to 5G to incorporate IoT-friendly features in cellular standards (e.g., LTE-M, Narrowband-IoT, etc.) [1].

IoT development rests upon two broad classes of network access technologies. The first network class comprises high-throughput wireless networks, including Wireless Local Area Networks (WLANs) such as WiFi (802.11) and cellular networks. These are designed mainly to deliver high data rates with efficient spectrum usage. The second class comprises a

The associate editor coordinating the review of this manuscript and approving it for publication was Derek Abbott.

¹<https://www.cisco.com/c/en/us/products/collateral/se/internet-of-things/at-a-glance-c45-731471.pdf>

wide array of ad hoc wireless standards designed for wireless sensor networks, i.e. low-cost, ultra low-power devices, and characterized by low data rates and low duty cycle. The focus in this case is on energy efficiency and very simple transceivers.

While IoT technology is widely developed, substantial research effort remains to be invested to deal with massive connectivity and energy efficiency [2]. The IoT-5G marriage sustains implementing sensor-based IoT capabilities into robots, actuators and UAVs, to ensure shared coordination and reliable task execution with low latency [3]. Indeed, the incorporation of 5G [4] within IoT systems results in increasing the transmission rate, reducing transmission delay and guaranteeing network reliability and information security. IoT enables low-cost objects to access and exchange information globally over the Internet [5]. An overview of typical IoT application domains is listed in [6], including smart cities, healthcare, smart buildings, smart grid and smart industry (industry 4.0). For instance, IoT-enabled home automation is transforming our daily life, by automatically adjusting the temperature according to human presence, and the garage door opens automatically upon arrival. In the context of smart cities, cohesive communication between autonomous or semi-autonomous vehicles and infrastructure (e.g., traffic lights) leads to improved road safety. Thus, the IoT can both enhance quality of life and support global economic activity [7]. In concert with this vision, a number of questions must be addressed in the IoT's continuing evolution [8]:

- Can IoT ecosystems ensure connectivity anytime, anywhere and anyhow?
- How to ensure continuity of service and interoperability between different devices from various manufacturers?
- How can energy consumption be reduced to increase the network lifetime?
- How can a high level of security be provided with low-cost devices?
- How can the rapid evolution of the IoT concept be effectively managed within massive environments?

Low power wide area networks provide many solutions offering low cost technology, low power consumption and satisfactory connectivity to IoT devices. Contrary to 4G/5G or WiFi networks, LPWANs in general do not primarily focus on providing high data rates for IoT devices and/or low latency. Rather, the most desired features are energy efficiency, connectivity and low cost [9]. By design, 5G mobile networks are expected to overcome the limits of previous cellular standards while providing key technologies to support future IoT deployments. Meanwhile, LPWAN solutions are being used both to sustain and enable new requirements for IoT-critical service cases, notably low cost, low data rate, high scalability and energy efficiency [1].

B. RELATED SURVEYS AND OUR MAIN CONTRIBUTIONS

The academic and industrial communities are becoming increasingly interested in leveraging LoRaWAN's energy

efficiency. When searching for published papers that mention LoRaWAN energy optimization, academic databases such as IEEE Xplore, MDPI, and other digital libraries show significant surge patterns. Recent state-of-the-art surveys on LoRaWAN [10]–[13], to the best of our knowledge, address the challenges and open issues regarding the physical, MAC layer, and architectural aspects, setting the stage for LoRaWAN development. A comprehensive review of the energy efficiency of deployed approaches for efficient network operation, beyond the aspects studied in the existing literature, is, however, sorely lacking. A systematic review of the major search engines was performed for this paper in order to accurately represent the state of the art on LoRaWAN technology and efficient energy consumption in IoT devices.

Table 1 briefly summarizes recent research on LoRaWAN networks.

In this paper, LoRa networks are examined through extensive review of relevant literature to address questions regarding their behavior and specifically their ability to efficiently optimize energy consumption. The main contribution aspects of this work are summarized as follows:

- We provide a comprehensive tutorial covering fundamentals of LoRaWAN networks, and survey the literature dealing with energy efficiency across multiple network layers.
- We review existing solutions and discuss hot topics related to energy efficiency at the physical (PHY), Medium Access Control (MAC), and network (NET) layers of the LoRa standard.
- We discuss some of the challenges, open issues, and potential future research directions in optimizing LoRaWAN technology for efficient energy consumption.

C. PAPER ORGANIZATION

The remainder of this paper is organized as follows. Section II deals with the LPWAN concept, compares it to the cellular concept and provides an overview of the most widely known LPWANs technologies. We survey the main techniques and solutions for energy efficiency at LoRa's physical, MAC, and network layers in Sections III, IV and V, respectively. Section VI provides insightful discussions and presents some hot topics and research opportunities. Important concluding remarks are drawn in Section VII.

II. OVERVIEW OF LPWANs AND LoRaWAN

A. LoRaWAN STANDARD

The LPWAN technologies constitute a valuable complement and potential alternative to traditional cellular and short-range wireless technologies for a variety of emerging smart city and machine-to-machine applications [21]. Indeed, the three key ingredients of LPWANs (high energy efficiency, scalability, and coverage [22]) are well suited to the development of applications and services for the IoT. Many LPWAN technologies are currently available which have gained some

TABLE 1. Summary of recent related surveys.

Ref.	Year of Pub.	Target Theme	Lora Challenges Examined	Main Objective	Relevants OSI Layers
[10]	2021	UAV-based LoRa network	(a) The communication range and (b) packet loss rate when using UAVs.	A systematic review of real-time deployments of UAV-based LoRa communication networks.	PHY/ MAC
[11]	2021	LoRa PHY and LoRaWAN MAC	(a) LoRa PHY settings, interference, and deployment characteristics, (b) LoRaWAN MAC performance determinants, (c) ADR enhancements and alternative solutions, and (d) synchronized and time slotted schemes.	An overview of the literature investigating works on LoRa-based networks, both describing their behavior and classifying them according to their technological advances.	PHY/ MAC
[12]	2021	(LPWAN technologies) LoRaWAN, NB-IoT and LTE-M	(a) Power consumption, (b) security, (c) latency, and (d) throughput perspectives.	A comparative performance of LPWAN technologies.	PHY/ MAC
[13]	2021	LoRaWAN technology optimization	(a) Resource allocation, (b) network planning, and (c) mobility support.	A systematic review of the literature focusing on specific aspects that affect LoRaWAN performance.	PHY/ MAC
[14]	2020	LoRaWAN Confirmed traffic	Using the impact of the confirmed traffic, the authors studied the impact of (a) retransmissions, (b) confirmed traffic ratios, (c) SFs, (d) receive windows, and (e) multi-gateway networks.	A survey on confirmed LoRaWAN traffic literature for joint common themes, open challenges, and potential solutions.	MAC
[15]	2020	LoRa PHY and LoRaWAN MAC	Network performance analysis works of LoRa technology are listed here, and conclusions reached, in terms of (a) interference measurements, (b) multi-hop communications, and (c) communication range.	An overview of LoRa technology is given, along with relevant work on network performance in different scenarios.	PHY/ MAC
[16]	2020	LoRaWAN MAC methods	(a) Energy efficiency, success and coverage probability, (B) channel throughput of P-ALOHA, S-ALOHA and non-persistent carrier-sense multiple access (NP-CSMA), and (C) channel access enhancements for S-ALOHA, CSMA and Scheduled MAC.	A unified analytical model for performance analysis under three basic random access mechanisms is developed.	MAC
[17]	2020	ADR optimization	(a) Resource allocation scheme and (b) energy consumption.	A comprehensive review focusing on recent solutions for ADR as an optimization approach to improve throughput, energy efficiency and scalability.	PHY/ MAC
[18]	2020	LoRaWAN Mesh Networks	Multi-hop proposals for LoRaWAN	A comprehensive review with a comparative analysis and classification of multi-hop proposals for LoRaWAN.	NET
[19]	2019	LoRa PHY and LoRaWAN MAC	No paper classification is done, the authors review some selected articles about the challenges faced and the proposed solutions in terms of (a) impact of LoRa imperfect orthogonality, (b) interference measurements, and (c) communication range.	The main challenges and solutions along with the research opportunities.	PHY/ MAC
[20]	2019	LoRa PHY and LoRaWAN MAC	Authors explore research challenges in terms of (a) energy consumption, (b) communication range, (c) multiple access, (d) error correction, and (e) security.	Performance measurements	PHY/ MAC
This work	—	Energy Efficiency in LoRaWAN Networks	Energy efficiency across multiple network layers including (a) resource allocation, (b) MAC protocols and (c) multi-hop communications.	Comprehensive tutorial covering fundamentals of LoRaWAN network, and surveying the literature dealing with energy efficiency across multiple network layers.	APP/ NET/ MAC/ PHY

traction in the market, including SigFox, Weightless, Thread, NB-IoT, and LoRa, most of them designed to operate in subGHz Industrial Scientific Medical (ISM) bands [23]. Figure 1 graphically compares LPWAN technologies with other wireless technologies. In particular, the figure highlights the complementarity of LPWAN versus 3G / 4G cellular given that it features extensive range and coverage at a low cost, with very low power consumption and a simple ad-hoc infrastructure. However, these systems are limited in throughput and latency. These factors make LPWAN a very promising candidate for remote monitoring [24].

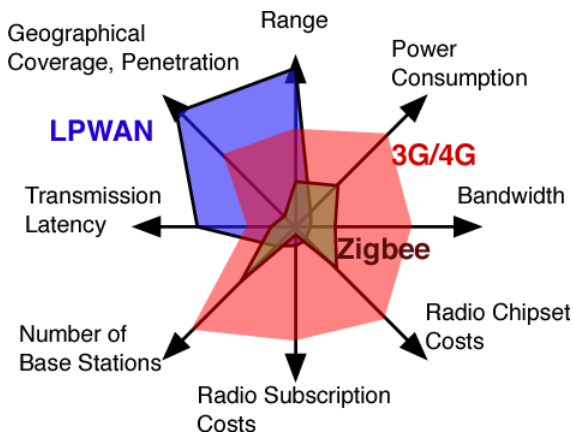


FIGURE 1. Comparison between LPWAN and cellular technologies [24].

In some cases, IOT usage may require highly particular functionalities, for which the features of LPWANs are required [25]. The main properties of LPWAN technologies required for the successful development of IoT systems are shown in Table 2 [26].

TABLE 2. Major properties of LPWAN technologies.

Main Properties
Long range of communication
Low power consumption
Low data rate
Low cost of device and deployment
Simplified network topology and deployment
Full coverage
Network scalability for the capacity upgrade

Among LPWAN standards, there are those operating in unlicensed bands (e.g., LoRa, SigFox, etc.), and those designed for licensed frequency bands as a component of cellular systems (e.g., NB-IoT, EC-GSM-IoT, LTE-M-IoT, 5G IoT, . . .) [27]. The suitability of an LPWAN technology for a specific application depends on requirements in terms

of range, data rate, coverage, power budget, network cost and scalability, Figure 2 compares the relative strengths of the most popular LPWAN technologies, thus providing guidance in selecting the best one for a particular scenario. For example, Long Range (LoRa) provides very long communication range, but no support for real-time data flow [28].

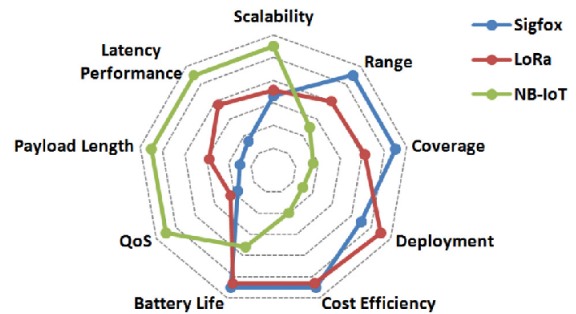


FIGURE 2. Comparison between LPWANs technologies [29].

- **Narrowband IoT (NB-IoT):** Refers to an LPWAN radio technology standard developed by the Third Generation Partnership Project (3GPP) to support a wide range of cellular devices and IoT services. Thus, NB-IoT devices with an average of 200 bytes per day can achieve battery lifetimes of 10 years while covering a distance of 1 km in urban areas and 20 km in rural areas. NB-IoT, unlike LoRaWAN, can support both low latency and high data rates [7].

- **Sigfox:** It is primarily used to establish IoT networks in situations where the volume of data transmitted is low. According to Sigfox² an uplink message might have a payload of up to 12 bytes and takes about 2 seconds to reach the base stations over the air, the range is long, up to tens of kilometers, and the current consumption is very low, averaging around 1–10 mA per transmission. Sigfox leverages the D-BPSK (Differential Binary Phase-Shift Keying), a low-complexity, narrowband modulation type. Its most important properties are its high spectral efficiency and its ease of implementation which, combined with a low bit rate, leads to inexpensive transceiver implementations [30], [31].

- **LoRaWAN:** In 2015, a group of approximately 500 companies formed the LoRa Alliance, resulting in the creation of a new LPWAN technology standard known as LoRaWAN, which defines the network and MAC stacks that allow network nodes to transmit messages to gateways. LoRaWAN guarantees secure and reliable communication, as well as extended battery lifetime and cost savings [32].

The primary goal of this paper is to present an efficient technology in terms of energy consumption, thus selecting and focusing on LoRaWAN technology. Authors in [33] define it as follows: “LoRaWAN is an energy efficient LPWAN technology designed to address power consumption and coverage issues in IoT applications”.

²<https://www.sigfox.com/en/what-sigfox/technology>

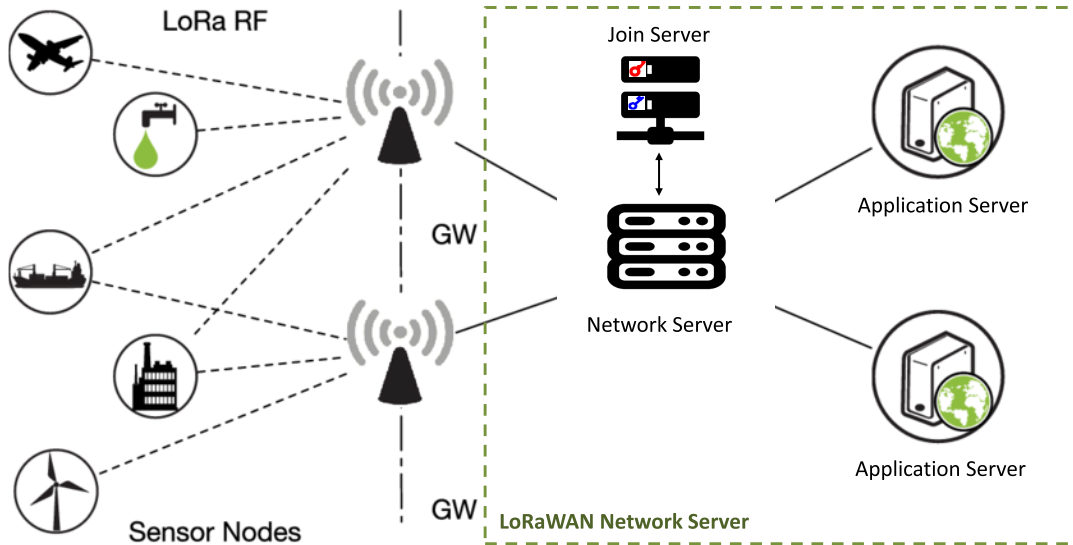


FIGURE 3. LoRaWAN architecture.

Table 3 summarizes the main technical specifications of LoRaWAN [34].

TABLE 3. Technical specifications of LoRaWAN.

Standard	LoRaWAN
Spectrum [MHz]	Unlicensed
Link Budget	154 dB
Modulation	CSS
Channel Bandwidth [kHz]	125-500
Maximum payload [bytes]	243
Power consumption	Very low
Battery life time 2000 mA/H	105 months
Topology	Star of stars
Security	AED CCM 128
Coverage Km	~5 in urban / ~20 in rural
Maximum Data rate	50 kbps in Uplink / 290 bps in Downlink
Transmission technique	ALOHA

Essentially, the LoRaWAN specification includes three primary elements: the network architecture, the physical layer, and the MAC layer [35].

- **Network Architecture:** The LoRaWAN network operates in a star topology, with end-devices (ED) communicating data to gateways (GWs), who then transmit it to a central network server (NS) via an IP connection [36]. This star topology greatly simplifies operation while also reducing network traffic for information routing [37].

- **Physical Layer:** Base LoRa is the physical layer of LoRaWAN and is centered on chirp spread spectrum modulation (CSS) combined with Forward Error Correction (FEC). There are five configuration elements at the physical layer that influence energy consumption, noise impact, and range, including: Bandwidth, Central Frequency (CF), Spreading Factor (SF), Coding Rate (CR), and Transmission Power (TP) [38].

- **MAC Layer:** The LoRaWAN standard defines a MAC layer that provides the media access control mechanism used to connect multiple devices to one or more gateways [39]. Three end-device classes are defined in LoRaWAN: Class A is the most energy-efficient for low power uplink traffic, Class B is for delayed downlink transmissions, while class C applies to end devices without energy constraints [40].

B. LoRaWAN ARCHITECTURE

LoRaWAN is an open protocol based on the LoRa modulation technology, represented by the physical layer in the OSI model. The LoRaWAN technology enables long-distance communication in rural (15-20 km) and urban (2-8 km) areas [39]. As shown in Figure 3, the topology of a LoRaWAN network is a star, with the GW exchanging and forwarding messages between the ED and the NS, whereby the NS serves as a relay point between applications running on the ED and the application servers. The ED communicates with the GW using LoRa, while the GW communicates with the NS using an IP protocol [41].

- **End devices (ED):** They are equipped with sensor nodes that can collect and transmit data to the gateways.

- **Gateways (GW):** They redirect the received data to the network servers.

- **LoRaWAN network server:** It consists of three main components: a network server, an application server, and a join server. The most important functions of the LoRaWAN network server are as follows [18]:

- *The Network Server (NS)*: It plays an important role in a LoRaWAN network, filtering duplicated packets, providing security, sending acknowledgements, and transferring data to the application server [42]. The NS forwards the messages to the Application Server and Join Server.
- *The Application Server (AS)*: The AS forwards all packets received from the network server to the specific associated application. Alternatively, an incoming message from an application is forwarded by the application server to the network server.
- *The Join Server (JS)*: The JS is responsible for the authentication process of the end devices, both for the generation and distribution of the authentication keys. Two network entry methods are allowed in LoRaWAN: Activation By Personalization (ABP) and Over-The-Air Activation (OTAA). These are described in some detail in Subsection E.1.

Application		
LoRa MAC		
MAC Options		
Class A	Class B	Class C
LoRa Modulation		
Regional ISM Band		

FIGURE 4. LoRaWAN protocol stack.

C. LoRaWAN PROTOCOLS STACK

The LoRaWAN protocol stack defines one mandatory and two optional classes at the MAC layer and corresponding to the various possible use cases. LoRa technology covers a series of ISM bands, which vary depending on the application case and the region in which the LoRaWAN nodes are deployed [43]. In [44], it is stated that these bands are unlicensed and require conditions in terms of maximum transmission power, duty cycle, and bandwidth. Additionally, in [45], they identify maximum duty cycle as a major challenge for networks using unlicensed bands, defining it as “the maximum percentage of time during which an end device can occupy a channel.” As a result, the end device’s emission is limited to these parameters. LoRaWAN’s duty cycle, depending on the frequency band used, could be 0.1%, 1%, or 10%, with a recommended duty cycle of less than 1%. For a value of 1%, the device must wait for 100 times the duration of the previous frame for a new transmission in the same channel [46].

In the current LoRaWAN protocol stack implementation, the application layer sits on top of the MAC layer, as shown

in Figure 4. The LoRaWAN application layer is not defined at all in the specification. The LoRaWAN application layer (for example, running on Loriot, IBM Bluemix, or Amazon AWS, to name a few platforms) includes useful functions for measurement services such as data analysis, long-term storage, and simple visualization. Cloud services and effective (customer-oriented) dashboards may be the most effective ways to maximize the impact of measurement results on the end user [47].

D. LoRaWAN PHYSICAL LAYER

1) LORA MODULATION

At the physical layer, the majority of LPWAN technologies employ two modulation techniques: Spread Spectrum (SS) and Ultra Narrow Band (UNB). In 1997, H.R. Walker proposed UNB communication and later developed modulation methods such as VPSK (Variable Phase Shifting Keying), advanced VPSK, VMSK (Very Minimum Sideband Keying), and PRK (Phase Reversal Keying) [48]. The UNB modulation technique provides significant bandwidth efficiency. Furthermore, it allows signal transmission at a very low bandwidth, best suited for small uplink traffic.

The SS technique, one of the oldest communication techniques, is used in military applications to provide secure communications, expanding the original signal over a large frequency band while maintaining the same signal power [26]. Another feature is the absence of an apparent peak in the spectrum, which merges with noise, making interference and interception difficult [21]. Its advantages include interference rejection, multipath suppression, multiple access code division, and high-resolution ranging. The SS transmission refers to a method in which the signal occupies more bandwidth than is required to send the information. Band spreading uses data-independent code and synchronized reception at the receiver side for despreading and subsequent data recovery [49].

LoRa, which as mentioned is the physical layer in LoRaWAN, achieves low power consumption and long-range communications via chirp spread spectrum modulation (CSS), a SS technique used to modulate the signal using chirp pulses (variable frequency sinusoidal pulses) [50]. Indeed, the CSS modulation used in LoRa converts each data symbol into a chirp, defined as a signal whose frequency increases or decreases linearly over time. A chirp also refers to a sweep signal, and each CSS symbol sweeps the bandwidth (BW) once [51].

2) LR-FHSS

Long Range-Frequency Hopping Spread Spectrum (LR-FHSS) is a new physical layer to address extremely long-distance and large-scale communication scenarios, such as satellite IoT. Semtech has announced LR-FHSS, a LoRa physical layer extension. Emerging use cases with increasingly larger and denser network deployments, such as satellite-scale LoRaWAN networks, are driving the exten-

sion. Its primary aim is to increase network capacity and robustness by using the Frequency Hopping Spread Spectrum (FHSS) modulation technique while maintaining the same communication range as LoRa. The LR-FHSS is a fast FHSS modulation used for uplink communication only; downlink communication is achieved with current LoRa because the same radios can switch between modulations [52]–[54].

3) SPREADING FACTOR

The spreading factor (SF) is the most relevant variable in the CSS system. The CSS order of modulation is given by $M = 2^{SF}$, indicating that each CSS symbol carries SF bits [55]. SF refers to the number of chirps required to encode a bit [56], providing a flexible trading range for the data rate [50]. In addition, it improves the spectral efficiency and capacity of the network. LoRa modulation employs six orthogonal SFs that provide different data rates. Because these factors are orthogonal, different spread signals can be transmitted simultaneously using the same frequency channel while maintaining communication performance and trading Time on Air (ToA) for communication range [57].

The SF is defined as:

$$SF = \log_2(R_c/R_s), \tag{1}$$

where:

- R_c is the chip rate,
- R_s is the symbol rate.

The SF can have six different values, ranging from SF = 7 to SF = 12 [40]. Then there is a compromise between the SF and the coverage range. The higher the SF, the larger the communication range is. As stated above, the SFs are orthogonal, which means the gateway can receive multiple transmissions simultaneously on different SFs [58]. The authors of [59] investigate the effects of imperfect orthogonality between multiple LoRa SF transmissions. The authors claim that a LoRa transmission can be interfered with by another SF transmission if the power of the interfering signal is significantly greater than the power of the reference signal. Indeed, the results show that this power difference threshold is about 16 dB. Such a power difference may occur when an interfering signal is close to a receiver or several interfering signals are received simultaneously. Another research study addresses the effect of interference on a LoRa network due to transmissions running concurrently while using the same SF. The results show that transmitting using different SFs may significantly impact LoRaWANs with high density [60].

Another study proposes a detailed analysis of the available uplink throughput on a LoRa network, considering the effects of co and inter-SF interferences. Two types of interference are involved in this scenario. The first type stems from the assumption that SFs are not perfectly orthogonal, leading to inter-SF interference. It follows that the transmission of packets using different SFs is subject to collisions. The second

type of collision derives from multiple nodes utilizing the same SF on the same channel, thus leading to co-SF interference. There are two different types of SF allocations: the SF-random type, in which the SFs are uniformly distributed, and the SF-distance type, in which the SFs are distributed by distance. They compute the maximum possible throughput and the probability of successful transmission, using expressions for perfect and imperfect SF orthogonality [61]. The data rate of LoRaWAN varies from 0.3 kb/s to 27 kb/s depending on the SF used [50].

According to the study [43], by sending a packet with a payload of 51 bytes every 10 minutes and assuming a capacity of 2400 mAh, the battery lifetime for SF7-SF10 can reach one year. Comparatively, the battery life for SF12 and SF11 is lower, ranging between 0.5 and 0.8 years. Furthermore, it is highlighted in [62] that the ToA, which refers to the duration of the packet transmission, is dependent on the value of the SF in use; if the SF increases, the ToA also increases, implying higher energy consumption. In [63], the authors estimate the ToA for a standard message with a payload of 51 bytes, as illustrated in Table 4.

TABLE 4. ToA for a standard message (51 bytes) in milliseconds.

SF	ToA (ms)
7	112.90
8	195.07
9	349.18
10	616.45
11	1150.98
12	2138.11

The actual ToA for a packet in a LoRa network can be defined as follows [64]:

$$ToA = T_{\text{preamble}} + T_{\text{payload}}, \tag{2}$$

where T_{preamble} is the preamble duration and T_{payload} is the payload duration. T_{preamble} can be calculated as follows:

$$T_{\text{preamble}} = (L_{\text{preamble}} + 4.25)T_s, \tag{3}$$

where L_{preamble} is the preamble length, T_s represents the symbol period, and

$$T_s = 1/R_s. \tag{4}$$

Based on the above formulas, we can conclude that the ToA of the LoRa packet is directly related to the SF. Hence, the choice of SF is a decisive factor to ensure proper network management.

4) LORA PHYSICAL LAYER FRAME

Figure 5 depicts the physical, MAC, and application layer LoRa frame structure [65]. The following fields are included in the LoRa packet [64]:

- **Preamble Field:** Serving for synchronization purposes and comprising eight successive reference chirps which indicate the packet modulation scheme, the preamble field is modulated with the same spreading factor as the rest of the packet.
- **Header Field:** Two operating modes are available. The number of bytes in the header field indicates the FEC code rate, the length of the payload, and the presence of CRC in the frame in the default explicit operational mode. In the second implicit mode of operation, it is understood that the code rate and payload in a frame remain fixed. This field is not included in the frame when using this mode, which helps to reduce transmission time. A 2-byte CRC field is also present, allowing the receiver to reject packets with invalid headers. The header field, including the CRC field, is 4 bytes long and has a coding rate of 1/2. However, the coding rate for the rest of the frame resides in the PHY header. Note that the length of the payload is determined by the first byte of the header field.
- **Payload Field:** The payload's size ranges from 2 to 255 bytes. This field also includes the following elements: MAC header (specifies the frame type, protocol version, and direction); MAC payload (including actual data); and MIC (corresponds to the digital signature of the payload).
- **CRC Field:** It is optional and contains Cyclic Redundancy Check (CRC) bytes to protect the payload from errors (2 bytes).

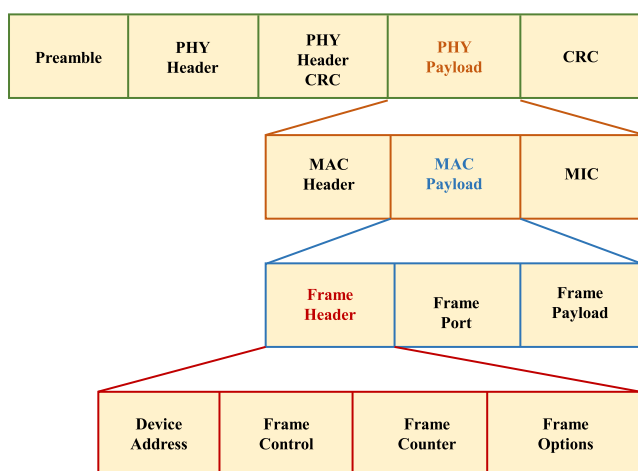


FIGURE 5. LoRa frame structure.

In [27], the authors highlight the single difference between the structure of uplink and downlink messages: the downlink messages do not contain the CRC field, as messages should be as short as possible to minimize the effect of any duty cycle limitations.

E. LoRaWAN MAC LAYER

As mentioned in the previous section, the LoRaWAN MAC (medium access control) layer allows communication between multiple end devices and their gateway(s). The gateway serves many devices and relays messages to a central server [66]. LoRaWAN defines the network protocol for LoRa-based devices [67]. Figure 6 depicts the use of two distinct keys in message transmission:

- **The network session key:** It is used to encrypt the frame and ensure that the message gets sent correctly and in its entirety for better communication. This key gets shared between the end device and the network server.
- **The application session key:** It is used to encrypt and decrypt the payload in the frame (application data messages) and to ensure security. This key gets shared between the end device and the application server [68].

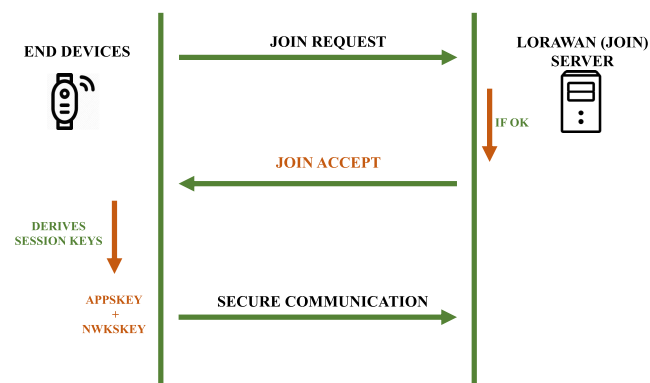


FIGURE 6. OTAA procedure.

1) MAC MESSAGES

Different message types are present in the LoRaWAN MAC Layer, and two joining procedures, **OTAA** and **ABP**, are included. One of these procedures must be executed by the end devices. In [27], it is stated that in order to join the LoRaWAN network and exchange data, the end device must perform an **Over-The-Air Activation (OTAA)** procedure, composed of two MAC messages exchanged between the end device and the network server (Join Request and Join Accept), and if the end device loses connection, it must repeat this procedure. Figure 6 shows the two MAC messages exchanged during an OTAA procedure.

In [67], the authors present the second type of joining procedure, **Activation by Personalization (ABP)**, a procedure that allows end devices to connect directly to the network without the need for a request-accept exchange. However, the first procedure used to join the network (OTAA) is qualified as the most appropriate and secure way for an end device to join the network. Once the connection is established, the end device starts sending and receiving data messages.

The messages received by the gateway can be the subject of an ACK (acknowledgment) by setting the ACK bit if requested or not, which means that in the first case, the

gateway sends an ACK to confirm the reception of the data messages, while in the second case, no confirmation is required [69]. Furthermore, in [70], it is indicated that for the first use case, two ACKs are received. The first ACK is sent on the same channel where the data was transmitted and T_1 after the reception of the frame, the second ACK is sent on the downlink channel after a timeout of $T_2 = T_1 + 1s$, and retransmission is performed if the end devices do not receive an ACK. In some cases, gateways are required to send an ACK as confirmation of the connection between them and the nodes. If multiple gateways receive the same message, one of them must respond by sending an ACK to the node in question [71].

2) MAC COMMANDS

MAC commands consist in control information sent by the gateway to the nodes. Each MAC command should trigger the appropriate response from the recipient nodes. Table 4 lists the MAC commands supported by LoRaWAN [72]–[74].

TABLE 5. LoRaWAN MAC commands.

Command	Description
LinkADR	Requests sent to end devices for modification of the data-rate, transmit power, repetition rate or channel.
LinkCheckReq	Sent by the end-device to validate the quality of the link.
LinkCheckAns	Provides an estimation of the received signal power as an indicator of the reception quality of the end-device.
DutyCycle	Sets the maximum duty cycle of a device for transmission.
RXParamSetup	Used to change the reception parameters of the device.
DevStatus	Used by the network server to reset the status of the device.
NewChannel	Allows modification of radio channel parameters.

3) MAC PROTOCOLS

It is clearly stated in [73] that energy-efficient use is primarily influenced by MAC protocols, designed to manage uplink and downlink messages, node mobility, and determining network scalability.

LoRaWAN is based on Pure-ALOHA (P-ALOHA), which allows node senders to select a SF and a transmission power for their messages. While the Listen before Talk (LBT) option is not excluded in LoRaWAN, the basic P-ALOHA scheme allows blind transmission at any time. Even though it is generally an inefficient protocol, pure ALOHA is still widely used because it offers multiple significant advantages, such as variable packet size, flexibility in starting transmission, and

no requirement for time synchronization. As a result, most (if not all) LPWAN technologies use pure ALOHA as their primary MAC protocol [75], [76].

This protocol poses a challenge when the number of nodes is growing considerably. Without a listen before talk strategy, after each message collision, these messages are retransmitted later. The presence of collisions and the necessity to retransmit lost packets will decrease channel capacity rapidly [77]. According to the authors of [78], the throughput of P-ALOHA channels can be used up to 18% of the total channel capacity. To overcome the challenges of P-ALOHA, the Slotted-ALOHA (S-ALOHA) protocol was introduced. The latter is a widely used MAC protocol in local wireless communications, where the channel time is divided into slots and end devices can only send packets at the beginning of a slot. If two or more nodes send their packets at the same time, a collision occurs, indicating that the data is not being sent correctly. Otherwise, the data is correctly transmitted and no collision occurs. It was mentioned that the throughput of S-ALOHA channels can use up to 37% of the total channel capacity [78].

In the context of extremely rich and valuable studies that employ the S-ALOHA protocol, the authors of [79] explore the distributed choice of retransmission probabilities in Slotted Aloha from a game theoretical perspective. Using a Markov chain analysis, they were able to obtain optimal and equilibrium retransmission probabilities and throughput, before evaluating the impact of adding retransmission costs. In parallel, the authors of [80] analyze the performance of the Slotted-Aloha-based uplink of a cellular system according to several power differentiation schemes and at another level, they deduce the expected throughput and delay in order to optimize and provide a stability analysis that will serve as an alternative study. Authors of [81] focus on the retransmission probabilities in LoRaWAN networks using the Slotted Aloha protocol with the goal of maximizing throughput while taking into account that the SFs are perfectly orthogonal. They have demonstrated that it is possible to achieve both satisfactory throughput and limited delays by fine-tuning the retransmission probabilities and correctly setting the MAC parameters. The authors of [82] consider a model for increasing the average system packet success probability (PSP) under Pure Aloha. To achieve this, they proposed an optimization model aiming to maximize the average PSP of the system, via a sub-optimal SF allocation method that takes into account the effects of interference using the same or different SFs.

F. LoRaWAN NET LAYER

The LoRaWAN employs a single-hop routing model, in which gateways in the center communicate and transmit messages from terminal devices to the network server. The gateways are linked to the Internet network via WiFi, 4G, or Ethernet, allowing data to be sent to the network server via IP. It is possible to bring together different end-devices and gateways in the same geographical area by isolating frequency communications as well as virtual channels within the

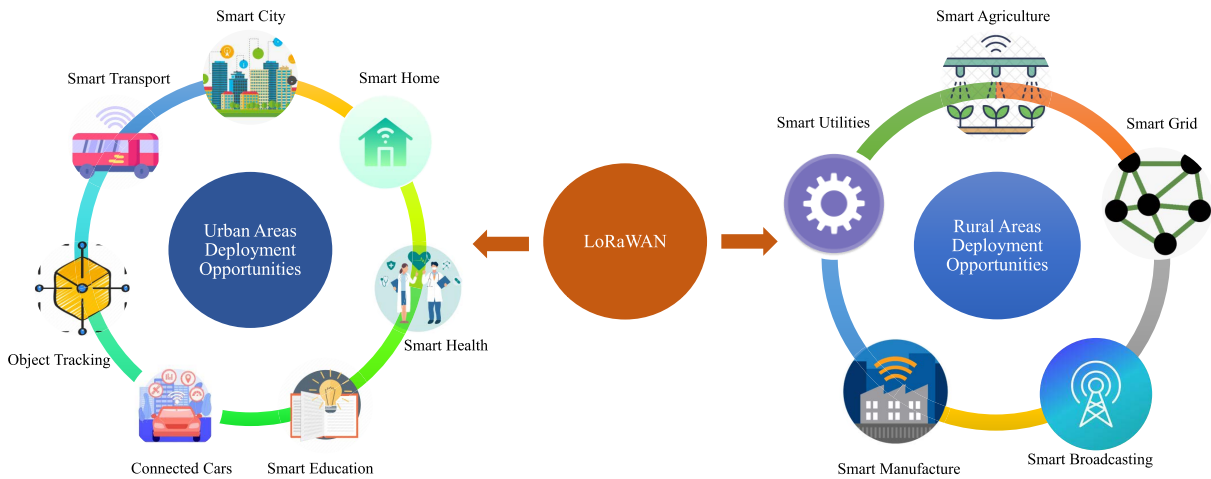


FIGURE 7. LoRaWAN deployment opportunities and verticals.

same frequency channel, keeping in mind that transmissions with different SFs are orthogonal due to the spread of the spectrum [83].

The single-hop model has several limitations, including the fact that gateways are both complex and expensive to maintain, particularly for a wide range of communication types [84]. Indeed:

- Several gateways must be installed throughout the area.
- Existing GWs require purchasing and installation of communication modules to connect to the Internet.
- A monthly fee is incurred if the gateway connects to the Internet via a private telecommunications network.

They are also required to listen to all channels at the same time and to be constantly connected to the Internet [85].

G. LoRaWAN DEVICES AND APPLICATIONS FIELDS

LoRa networks have been widely deployed for a variety of applications and research systems. LoRa’s openness makes it an extremely suitable choice for various IoT deployments. Common IoT applications include smart buildings, smart cities, smart agriculture, smart metering and water quality measurement [12], [20]. Furthermore, paper [86] claims that the acquisition costs of LoRa-enabled devices, as well as mobile devices and gateways, are low.

In [38], a performance study and analysis of the capabilities of a currently available LoRa transceiver is performed, followed by a description of the transceiver’s characteristics and a demonstration of its efficient use in an extended application scenario. Certain features, such as simultaneous non-destructive transmissions and carrier detection, have been demonstrated to be useful. The demonstration clearly shows that six LoRa nodes can form a network covering 1.5 ha in a built-up environment, with a potential lifetime of two years on two AA batteries, providing data in five seconds and with 80% reliability.

Figure 7 identifies LoRaWAN deployment opportunities in both urban and rural areas.

H. LoRaWAN SERVICES

In the LoRaWAN network, each device has different classes that define its capabilities. In fact, three classes are defined by the LoRaWAN Alliance and create a trade-off between network downlink communication latency and battery life. Figure 7 depicts the three LoRaWAN network classes.

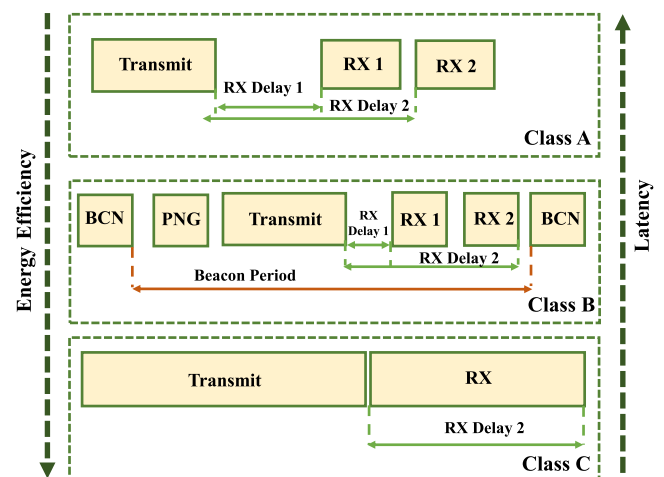


FIGURE 8. LoRaWAN end devices classes.

The three classes can be used together in the same network, and end nodes can switch between them [87]. The three classes are as follows:

- *Class A “All”*: This is the class supported by all devices in the LoRaWAN network and the most energy-efficient. It can optimize battery life to last for years. Aloha-type access to the channels is used. Furthermore, two downlink windows (RX1 and RX2) are available after every uplink communication. Otherwise, the end devices

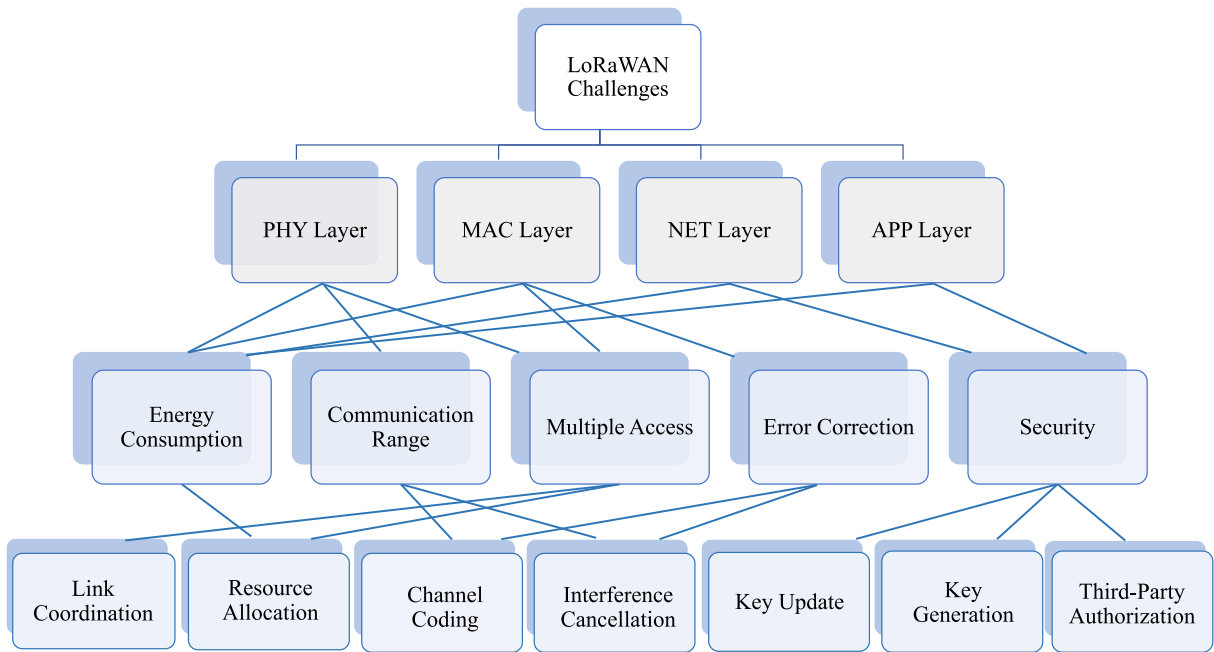


FIGURE 9. LoRaWAN main challenges per layer.

are in sleep mode. The device can only receive a message from the gateway during these two windows.

- *Class B “Beacon”*: Similarly to Class A, while end devices receive messages in time-synchronized scheduled receive slots, the gateway transmits a beacon at periodic intervals to synchronize all end devices on the network. When a terminal device receives a beacon, it can open a short reception window called a “Ping Slot” in a previewed form during a regular time slot. In terms of latency and power consumption, Class B offers a balanced solution [88].
- *Class C “Continuous”*: For this class, the receive window is always open, it is only closed when the end device is transmitting. It is used for real-time applications, so the energy consumption is higher. Among the three classes, Class C has the lowest latency for the ED [89].

I. LoRaWAN CHALLENGES

The authors of [20] discuss the research challenges of LoRa networking and divide them into five major components:

- *Energy Consumption*: The most significant feature of LPWAN is their high energy efficiency. This becomes an important parameter in extending the life of end devices. LoRa networks are expected to operate for 5-10 years with minimal maintenance. As a result, power consumption becomes a significant challenge for LoRa networking.
- *Communication Range*: A long communication range is also an essential component of LoRa technology. Current LoRa technology is based on chirp spread spectrum, which is less susceptible to interference. LoRa

networking is and will be used in a variety of settings, including homes, hospitals, schools, and forests. End devices will be placed in locations that are open to the air. With such diverse deployment conditions, signal attenuation, propagation losses, and fading must be mitigated in order to improve signal penetration and thus the coverage of LoRa networks [90], [91].

- *Multiple Access*: The goal of LoRa networking is to connect thousands of end devices to the network while communicating over a limited region and spectrum. Depending on the application, the possibilities for these end devices transmitting data concurrently vary. Multiple access issues involve two distinct aspects: link coordination and resource allocation.
- *Error Correction*: LoRa technology is used to transmit data over long distances. While the message is being transmitted over the air, the data may become corrupted or lost due to channel effects, environmental conditions, or collisions. Current solutions fall into two categories: channel coding and interference cancellation.
- *Security*: Security is a major concern in all computer communications. The eavesdropping, selective forwarding, and node impersonation are all examples of security attacks.

Figure 8 summarizes the challenges associated each layer of LoRaWAN networks.

As previously stated, energy efficiency is the most important feature of LPWAN technologies. It follows that evaluating the energy efficiency of LoRaWAN is paramount. Unlike previous surveys on LoRa technology, this work focuses on the evaluation of energy consumption at the different layers of the OSI model.

III. ENERGY EFFICIENCY AT PHYSICAL LAYER

LoRa is the physical layer used in LoRaWAN to achieve low energy consumption and long-range communication, due to its very appealing advantages. The LoRa PHY layer is gaining popularity among researchers.

In this section, we examine the energy consumption of the most relevant research works from both the network (configurable radio parameters) and the device (resource allocation) perspectives.

A. NETWORK SIDE

According to the authors of [92], [93], five parameters at the physical layer affect energy consumption and range:

- **Bandwidth (BW):** It is the amplitude value related to the frequency domain for the channel used; a higher BW results in a higher data rate and, as a result, a shorter transmission time. A higher BW, on the other hand, means lower sensitivity since more noise is included. Most LoRa networks use a channel with a bandwidth of 125 kHz, 250 kHz, or 500 kHz.
- **Central Frequency (CF):** It is spread over different frequency channels by exploiting the implementation of pseudo-random channel hopping. CF values depend on local frequency regulations, while LoRaWAN gateways typically support eight channels, whereas IoT devices usually support at least 16 channels. Specifically, CF can be configured in the range of 137 to 1020 MHz, depending on the legislation in the geographic region [94].
- **Spreading Factor (SF):** LoRa uses six different programmable SFs, ranging from 7 to 12. This allows up to six nodes to transmit on the same channel at the same time. In [95], it is noted that increasing the SF value without changing the transmission power causes the energy consumption to increase more rapidly. Higher SF values result in a lower bit rate, but higher sensitivity. Overall data rates in use are determined by regional specifications. Table 5 shows the possible data rate (DR) for the EU 863-780 MHz ISM Band [65].

TABLE 6. Data rates in EU 863-780 MHz ISM band.

Data Rate	SF	Channel, width (kHz)	Coding Rate	PHY bit rate (bps)	RF sensitivity (dBm)
0	12	125	4/6	250	-137
1	11	125	4/6	440	-136
2	10	125	4/5	980	-134
3	9	125	4/5	1760	-131
4	8	125	4/5	3125	-128
5	7	125	4/5	5470	-125
6	7	250	4/5	11000	-122

- **Coding Rate (CR):** It represents the redundancy used in FEC codes to provide interference protection. A lower CR provides better protection, but it increases

transmission time, as indicated by:

$$CR = 4/(4 + p), \quad \text{with } p \in \{1, 2, 3, 4\}. \quad (5)$$

- **Transmission Power (TP):** Power control options are limited, with only six values available: 2, 5, 8, 11, 14, and 20 dBm. For the LoRa system deployed in the EU 863-870 band, the maximum TP value for use is 14 dBm in accordance with ETSI regulations.

The following is a collection of recent research on the above-mentioned parameters:

In [94], the impact of parameter selection on power consumption and communication reliability is detailed, and an algorithm capable of rapidly identifying a good transmission parameter setting is proposed. The challenge here was to determine the setting that minimizes the cost of transmission energy while also satisfying the required communication performance, thus creating a balance between network performance and energy consumption. This work is a first step toward developing an automated mechanism for selecting LoRa transmission parameters.

The authors of [96] create an energy model to estimate and optimize wireless sensor energy consumption. Based on LoRaWAN Class A, the proposed model integrates the modeling of sensor node units, specifically the processing and sensor units, using a true IoT application. Furthermore, many different LoRaWAN transmission modes are investigated in order to select the best mode that can optimize energy consumption. Moreover, a comprehensive optimization study of LoRaWAN parameters such as SF, CR, BW, communication range, and TP is discussed with the goal of maximizing sensor lifetime. In [56], an analysis of the performance of the LoRaWAN network is presented, including discussion of the impact of various spreading factors and the power used in transmission frames. The experiment was carried out by sending packets with the same payload at various spreading factors and power settings. The results show that using higher spreading factors and increasing transmission power reduces observed packet loss.

In [97], the authors assess the energy consumption of the sensor nodes, taking into account three factors that influence energy consumption: transmission distance, data transfer/collection, and stability. The proposed simulation system considers three nodes with a LoRa base station, and the duration of the communication test is approximately seven days. Three communication parameters, SF, CR, and distance, are then varied to study their effect in isolation, i.e. when one parameter is varied, the others are kept constant. The results showed that when the SF is high, the power consumption is also high, whereas when the CR is low, the power consumption is low, when performing a power consumption and node transmission data measurement according to the LoRa protocol.

LoRa Backscatter is a CSS modulated system with data transmission distances of up to 2.8 km and a power consumption of only 9.25 watts at a data rate of 37.5 kbps. When compared to standard LoRa technology, this system

reduces power consumption by nearly 1000 times. The solar panels mounted on the passive RF chips can be used to power them [98].

The authors of [99] present a PLoRa (Passive Long-Range) communication technology that provides long-range connectivity for IoT devices based on ambient excitation, removing the need for any dedicated excitation source. The PLoRa tag is battery-free and generates energy from radio signals and ambient light, allowing it to communicate with active LoRa nodes and gateways over long distances in three distinct modes. The experimental results show that the prototype PLoRa PCB tag is able to backscatter an ambient LoRa transmission impinging from a closely situated LoRa node (20 cm) to a gateway as far as 1.1 km away, delivering 284 bytes of data every 24 minutes indoors, or every 17 minutes outdoors. However, the detection range of PLoRa packets is limited to 50 m, so there remains considerable room for further improvement.

Monitoring these physical layer parameters is an important factor in ensuring an efficient and controlled use of energy in a LoRaWAN network [100].

B. SENSOR/IoT DEVICE SIDE

1) RESOURCE ALLOCATION

We present a comprehensive analysis of the most significant results of the state-of-the-art on energy efficiency of allocation mechanisms. We classify existing works into two types of approaches: (a) Single parameter allocation and (b) Multiple parameter allocation, as described below.

a: SINGLE PARAMETER ALLOCATION

In a LoRaWAN network, a node cannot predict the distance between it and a gateway at first, but it can estimate the distance by observing the power signal received from a downlink transmission. If the received signal power of a downlink transmission is very high, it can reduce the SF of its next transmission to save power. This SF allocation scheme is known as the lowest possible SF allocation scheme [101]. It is important to note that ECC techniques are used in the LoRa physical layer to ensure noise and interference resistance and to increase receiver sensitivity [66]. On this basis, the LoRaWAN specification includes an Adaptive Data Rate (ADR) mechanism that allows a network server to select both the data rate and the transmission power provided to each node. Furthermore, the authors of [102] state that the ADR mechanism serves two critical purposes:

- Increase the global network capacity,
- Extend the battery life of the nodes.

The transmission power is dynamically assigned to a node based on its distance from the gateway, thus increasing battery life. The authors of [103] state that the ADR mechanism reduces energy consumption per payload byte by a factor of 5. The ADR is mentioned by authors of [104] as being used for both energy savings and communication range extension. The ADR is accomplished by employing orthogonal different

SFs and varying transmission power. These orthogonal SFs allow multiple LoRaWAN end devices to operate on the same frequency channel at the same time. When the transmission power is consistently higher than the sensitivity, the ADR algorithm has the ability to increase the SF whose SNR margin is too low, or even decrease it. This algorithm is required for ED movement during the NS SF selection process.

The ADR scheme [100] operates asynchronously at the LoRa node and the network server. Most of the complexity of the ADR mechanism is assigned to the network server, with the goal of keeping the nodes as simple as possible. The node-side ADR algorithm is specified by the LoRa Alliance, while the corresponding algorithm on the network server is determined by the network operator. The ADR algorithm on the network server can decrease the SF and change the TP, while the node can only increase the SF. The part of the ADR performed at the node (ADR-NODE) is primarily intended to increase the SF (and thus reduce the data rate) if the uplink transmissions cannot reach the gateway. Thus, if a downlink frame is not received within a configurable number of frames, the node increases the SF of the next uplink frame. This increases the transmission range and therefore the probability of reaching a gateway. Further and improved alternative SF allocation techniques were reported as detailed below.

In [72], the authors propose two algorithms, EXPLoRa-SF and EXPLoRa-AT, to outperform the basic ADR approach. The first algorithm has the advantage of allowing users to choose SF based on the total number of connected devices. The second algorithm aims to use an innovative “ordered water filling” approach that allows the spreading factors to be distributed in order to balance the ToA of the packets transmitted by the system’s end devices based on groups of spreading factors. The results show that using this last technique is very efficient, especially under high load conditions when the system supports thousands of nodes or high message rates. But there is no evaluation of the energy consumption of the proposed algorithms.

The authors of [105] propose a new method for an efficient allocation of the SF in a LoRaWAN network designed specifically to improve network scalability. Compared to the conventional method, the new method increases network scalability and improves data delivery probability while increasing average power consumption by 1 to 8%. In [101], an open source discrete event simulator is presented to analyze the performance of the LoRaWAN network and to investigate different schemes for SF allocation. Two machine learning solutions, the intelligent Decision Tree Classifier (DTC) and the intelligent Support Vector Machine (SVM), are described. The results show that the proposed systems can improve the overall performance of LoRaWAN networks, but the nodes use their maximum transmission power, which is an area for future improvement of the proposed schemes in order to reduce the nodes’ energy consumption.

The authors of [106] suggested a lightweight learning approach suited to the communication parameters of IoT

TABLE 7. Energy efficiency of SFs allocation methods using one configurable parameter.

Ref.	Adjusted Parameter	Allocation Scheme	Advantages	Drawbacks	Energy Consumption	Energy Efficiency
[105]	SF	—	Maximizes the correct packet delivery rate (PDR), improves the scalability of the network.	The average power consumption is raised by 1 to 8%.	Increases by 1% for a network using two SFs, while for six SFs the average consumption is increased by 8%.	*
[101]	SF	Intelligent DTC and SVM schemes	A solution based on machine learning which improves the performance of LoRaWAN; good simulation results in terms of packet delivery rate (PDR).	It is always assumed that the nodes use the maximum transmit power for uplink transmission.	Both schemes consume slightly more energy, approximately a 1% increase.	**
[100]	SF	ADR-NODE	Running at the node, using orthogonal different SFs; Increase the global network capacity; Extend the battery life of the nodes.	With a highly loaded network, the number of collisions increases.	Highly efficient in terms of energy consumption.	***
[106]	SF	Light-weight distributed learning approach	A learning solution to adapt device communication parameters to the environment in order to maximize energy efficiency and data transmission reliability.		The proposed scheme reduces energy consumption per data transfer by more than 50%, while increasing the probability of success by 30%.	***
[107]	SF	—	A new algorithm proposed to improve the energy efficiency of ADR.	Totally ignores the slow convergence time of the ADR, which is impacted by the variable channel conditions [108].	The energy efficiency is approximately doubled compared to the basic algorithm.	***
[109]	SF	E-ADR	Improves the ADR mechanism by taking into account the position of mobile devices and their trajectories in order to have a dynamic allocation, and minimize the transmission time and energy consumption as well as the packet loss for mobile devices.	E-ADR is not suitable for applications where some nodes follow random/unknown trajectories because it was designed for known mobility patterns.	The gain on energy consumption is increased by approximately 60.23%, due to the reduction of waiting packets (3 instead of 20) and its ability to re-adapt the configuration more quickly.	***
[110]	SF	VHMM-based E-ADR	An E-ADR extension to include unknown random mobility patterns, extremely efficient in terms of PLR and energy consumption.	There has been no investigation into the scalability of the proposed mechanism in a large network.	The authors present the total energy consumed over the number of received packets, as well as the impact of the retransmission threshold on energy consumption; for both results, the proposed solution has a very low energy consumption.	***

(*): Very Low; (**): Low; (***) : High ; (****): Very High.

devices and reaching energy efficiency and reliability goals. In this regard, this approach assigns SFs based on the distance between the IoT device and the gateway. A new proposed algorithm to improve the energy efficiency of the ADR scheme is presented in [107], where a comparison with the baseline ADR algorithm is performed, showing that the new proposed algorithm is superior in terms of energy consumption, with many cases showing more than 100% efficiency improvement. Paper [109] improved the ADR mechanism by proposing a new allocation scheme called Enhanced-ADR (E-ADR) that can perform dynamic allocation procedures,

thus optimizing network transmission time, reducing energy consumption, and decreasing overall packet loss. The performance of E-ADR was evaluated with Waspote-SX1272 devices and gateways using several mobility models in a smart farm scenario. The results demonstrate that E-ADR can reduce, and in some situations, eliminate packet loss and support mobility procedures. In addition, the gain on energy consumption is increased by approximately 60.23%. The same authors in [110] propose an expanded version of E-ADR to deal with unknown mobility patterns. This E-ADR extension, known as VHMM-based E-ADR, predicts

the node trajectory using a Variable-order Hidden Markov Model (VHMM). It was built on the Wasp mote SX1272 hardware platform. The experimental results show that it is very efficient in terms of packet loss rate (PLR) and energy consumption.

Table 7 lists some of the SF allocation strategies that have been used to improve the performance of LoRaWAN networks and their energy consumption compared with the standard solution using a single configurable parameter.

b: MULTIPLE PARAMETER ALLOCATION

The ADR algorithm implemented at the network server, designated ADR-NET, allows the network server to modify the TP and SF for the end nodes' uplink data transmissions. It should be noted that the network server does not increase the SF (it does not reduce the data rate), as this is done by the LoRa node through ADR-NODE [100]. A major study on the introduction of new algorithms for the allocation of SFs and TPs in LoRaWAN is reported in [93], where two algorithms are presented, the first being the SensitivitySF allocation and the second being the AssignmentSF allocation, with the goal of maximizing the throughput of each SF level and thus improving the overall network performance. The simulation results show that the proposed algorithms can significantly improve network performance when compared to the basic ADR strategy, with the AssignmentSF algorithm, in particular, systematically ensuring a high success rate for any traffic load incurred.

The authors of [111] propose a system for allocating SFs and TPs in LoRaWAN networks. The goal of this system was to improve the packet error rate (PER) for users far from the base station and to make these networks more equitable. The main idea behind this algorithm is to assign different SFs and control the power at different nodes to ensure that signals do not interfere with one another. The PER for the overall network is reduced by 42% in simulation using this technique in NS-3, and the PER of end devices remote from the gateway is reduced by 50%. The authors of [112] defined a novel resource allocation mechanism to dynamically adjust the LoRaWAN CF and SF parameters for reducing collisions while increasing the PDR. Correspondingly, this work provided a heuristic to find the optimal CF and SF parameters by investigating the RSSI and the distance between the gateway and the IoT device. By this means, the gateway could receive the transmitted packet and with sufficient power in the selected SF value. Furthermore, it assigns more IoT devices to the lower SF values so as to reduce the interference. In terms of energy consumption, the proposed scheme consumes 20% more than the basic ADR. The authors of [113] presented a resource allocation scheme for raising the PDR by fine-tuning the LoRaWAN radio parameters. Specifically, a Mixed Integer Linear Programming (MILP) formulation was implemented to achieve ideal values of SF and CF, taking into account the network traffic specifications. The authors explored the network traffic specifications to increase the Data Extraction

Rate (DER) along with reducing the packet collision rate and energy consumption in LoRaWAN. Another interesting study is presented in [114] where a resource allocation mechanism is presented based on a joint TP and CF assignment approach, and is called low-complexity Matching Channel Assignment Algorithm (MCAA). It aims to ensure throughput fairness among IoT devices, especially where multiple devices are connected. To formulate channel assignment, they treated IoT devices and channels as two sets of selfish players seeking to maximize their utilities. A channel assignment algorithm was proposed based on distributing the channel access decision site to users. Consequently, the LoRaWAN gateways achieved the optimal TP for IoT devices when sharing the same CF with the users in the same channel. The simulation results indicated that the resource allocation mechanism obtained 80% better performance than the baseline method, while being much simpler complex. The authors of [115] improved the basic ADR by dynamically designating the radio parameters, SF and TP, and using the OWA operator. This work focuses on increasing the network noise resilience and PDR in dense IoT scenarios through recognition of the nature of OWA decision making and PLR metric, reaching low energy consumption for all channel conditions.

The Fair Adaptive Data Rate (FADR) [117] algorithm manages the allocation of SFs and TPs of the nodes, with the goal of ensuring a fair data extraction rate between all nodes while limiting excessive TPs. It optimally combines SFs and TP levels while also ensuring node longevity by limiting excessively high TP levels. Furthermore, simulations show that when applied to highly congested cells, the FADR is 300% fairer than the minimum airtime allocation method, while consuming nearly 22% less power. In [119], the authors examined a novel resource allocation mechanism to adjust the allocation of SFs and TPs targeting the effects of co-SF and inter-SF interference. The authors optimized the SF and TP allocations to maximize the average data rates. In addition, the joint SF intractability and TP assignment problem was addressed by dividing them into two sub-problems: (i) SF assignment with fixed TP and (ii) TP assignment with fixed SF. From the simulation results, it is shown that the proposed mechanism improves the fairness, data rates, and throughput performance when compared to the baseline algorithms. In [116], a resource allocation algorithm for LoRaWAN is introduced, which involves energy harvesting. The authors also provide a model to optimize SF allocation, energy harvesting duration and power devices for IoT transmission. The paper presents two SF allocation algorithms using fairness or unfairness of IoT devices. The simulation results showed that the unfair SF allocation algorithm maximized the minimum rate. Furthermore, the imperfect SF orthogonality did not affect the minimum performance rate. Finally, the authors came to the conclusion that throughput performance is strongly affected by co-SF interference and not by the energy deficiency.

The authors in [118] focus on the LoRaWAN protocol since its modulation technology can use different SFs to

TABLE 8. Energy efficiency of SFs allocation methods using multiple configurable parameters.

Ref.	Adjusted Parameter	Allocation Scheme	Advantages	Drawbacks	Energy Consumption	Energy Efficiency
[111]	SF and TP	—	Improves the packet error rate for users remote from the base station and to ensure that these networks are more fair.	The average power consumption is high.	Using high TP consumes more energy.	*
[93]	SF and CR	SensitivitySF allocation	Maximizes the throughput of each spreading factor level hence improving the overall performance of the network.	It is restricted by sensitivity values and associated service radii.	The proposed system uses the maximum TP, which results in high energy consumption.	*
[93]	SF and CR	AssignmentSF allocation	Ensures a high success rate for any traffic load incurred.	It should be run at regular intervals or during certain events, such as having a number of EDs joining the LoRaWAN cell.	The proposed system uses the maximum TP, which results in high energy consumption.	*
[112]	SF and CF	CORRECT and MARCO	An adaptive solution to manage the setting of the best LoRaWAN parameters in order to reduce the channel utilization, packets collision and therefore maximize the number of packet collisions.	The proposed models are more costly, since they allocate the devices proportionally.	Consumes more energy (almost 20% more), since they allocate the devices proportionally, although it is possible to allocate with a SF that consumes less energy.	*
[116]	SF and TP	—	General framework that considers interference between users transmitting at the same time on non-orthogonal waveform codes, maximizes the minimum rate of LoRa users harvesting energy from an external source to allow operation and uplink transmissions.	Users transmit with a maximum TP.	The proposed system uses the maximum TP, which results in high energy consumption.	*
[113]	SF and CF	MILP	Optimizes CF and SF pair assignment with an average 6.6% increase in DER over the standard LoRaWAN assignment.	No support for scenarios with longer transmission distance and more gateways.	The scenario with the standard LoRaWAN assignment, which was set to SF value 7, achieved 2.9 times lower energy consumption than the proposed solution.	**
[114]	SF and CF	MCAA	A low-complexity channel assignment algorithm to make the LoRa network scalable by distributing the channel access decision making at the LoRa node.	The proposed power allocation scheme is a centralized approach	Energy consumption related to power allocation is alleviated in LoRa devices by implementing a gateway to execute the power allocation algorithm, achieving a good compromise between system performance and battery life of LoRa devices.	***
[115]	SF and TP	ADR-OWA	In the proposed algorithm, Ordered Weighted Averaging (OWA) is used as a decision making method able to consider the channel condition in the configuration of transmission parameters.	No evaluation of the effect of the number of gateways number on the performance of the algorithm.	It has low power consumption for all channel conditions. However, for low noise channels, ADR-OWA's energy consumption is slightly higher. The reason is the use of a pessimistic approach, which configures the transmit power of the nodes a little higher with low noise.	***
[100]	SF and TP	ADR-NET	Running at the network server, using orthogonal different SFs and different TP; Increase the global network capacity; Extend the battery life of the nodes.	With a highly loaded network, the number of collisions increases.	Highly efficient in terms of energy consumption.	****

TABLE 8. (Continued.) Energy efficiency of SFs allocation methods using multiple configurable parameters.

[117]	SF and TP	FADR	Manages the allocation of SFs and TPs of the nodes, ensures the longevity of the nodes by limiting excessively high transmission power levels.	FADR is based on the assumption that all nodes are initiated with the same transmission power.	Consuming nearly 22% less energy.	***
[118]	SF and TP	Multilayer virtual cell based resource	Offers efficient sharing of spectrum to address the problem of reducing the overall data rate of the network.	Energy efficiency decreases as the spreading factor increases along with the decrease in the number of virtual cells.	Derives the optimal TP to maximize energy efficiency.	***
[119]	SF and TP	—	A joint SF and power allocation scheme for maximization of the minimum uplink throughput of the end devices, subject to co-SF and inter-SF interference, and power constraints.	The use of the quadratic approximation does not necessarily guarantee a better local optimum than that offered by the linear approximation.	The energy savings offered by the proposed power optimization strategies reach up to 37.43%.	***
[120]	SF, BW and TP	APRA	An adaptive priority-based resource allocation mechanism to enhance LoRaWAN scalability and energy consumption in a dense IoT scenario.	No dynamic change of radio parameters in case of network modification.	APRA successfully improved power consumption by 95% and increased the battery discharge time of the end device by up to 5 years, while ensuring high packet delivery and low delay for high priority applications.	***

(★): Very Low; (★★): Low ; (★★★): High ; (★★★★): Very High.

achieve more flexible communications, and they propose a new resource allocation scheme based on Spatial Time Division Multiple Access that uses multi-layer virtual cells (STDMA), allowing for more efficient resource allocation. A numerical analysis of the optimal power consumption to achieve the highest data rate is presented, allowing for the adjustment of the cellular radius depending on the communication distance. The results show that the proposed model outperforms the conventional system in terms of data rate and power optimization. Paper [120] proposes an Adaptive Priority-based Resource Allocation (APRA) mechanism to enhance LoRaWAN scalability and energy consumption in a dense IoT scenario, where simulation results show that APRA successfully improved power consumption by 95% and increased the battery discharge time of the end device by up to 5 years, while ensuring high packet delivery and low delay for high priority applications.

Table 8 lists some of the SFs allocation strategies that have been proposed to improve the performance of LoRaWAN networks and their energy consumption compared with the standard solution using multiple configurable parameters.

The authors of [121] propose a model for estimating the lifetime of LoRa monitoring nodes. They also evaluated the cost of battery replacement and damage penalty costs. For longer sensing intervals, the damage penalty is more significant than the cost of battery replacement. In addition to an analysis of the use of energy from renewable energy sources

available in the industrial environment, a cost-benefit study of harvesting energy in terms of battery life and replacement costs is included.

IV. ENERGY EFFICIENCY AT MAC LAYER

The MAC layer is one of the most extensively investigated research areas in the IoT network field. Based on our review of the literature, several mechanisms have been proposed to improve the performance of MAC protocols in order to optimize them. This section investigates the energy efficiency of the LoRaWAN MAC layer on both the network and node sides.

A. NETWORK SIDE

1) MAC PROTOCOLS

As previously stated, the choice of MAC protocol affects energy consumption. LoRa MAC layer protocols are classified into two groups: centralized-synchronous protocols and contention-based protocols. It has been demonstrated that the energy efficiency of synchronous protocols is 3 to 4 times greater than that of contention-based protocols [122]. A collection of frequently-cited works in the literature that address the energy consumption of MAC protocols forms the basis of the overview below.

In order to achieve a correct balance between energy consumption and network performance, the authors of [123] propose an Adaptive Duty Cycle Medium Access Control

(ADC-MAC) protocol. In fact, the LoRaWAN network uses the ALOHA protocol to allow arbitrary access to the channel without regard to the duty cycle, node energy or traffic load. The proposed protocol's main idea is to dynamically set the node's duty cycle by specifying three factors: node load, node energy, and channel busy rate. The authors also make it clear that the wireless transceiver module dominates the energy consumption at the sensor node. In this regard, a wide range of duty cycle mechanisms in MAC protocols have been developed as promising solutions for controlling the wireless transceiver and, as a result, lowering energy consumption. Such efforts include: synchronous duty cycle protocols (S-MAC [124], T-MAC [125], EX-MAC [126]), asynchronous duty cycle protocols (Wise-MAC [127], PW-MAC [128]).

The authors of [40] propose an additional MAC protocol to solve the problem of decoding superimposed LoRa signals in the case of orthogonal SFs with the same receiving power. Previous research [61], [129], [130] has shown that signals are not completely orthogonal when using different SFs. While using the same SF and channel, the stronger signal may be captured due to the difference in receiving power; otherwise, under similar receiving power conditions, a collision is generated and all signals are considered lost. The proposed beacon-based MAC protocol is the Collision Resolving-MAC (CR-MAC) protocol, in which the collision resolution technique is used to decode the superposed LoRa signals. Two algorithms have been developed, the first for decoding two slightly desynchronized superimposed LoRa signals, and the second for three or more, and the CRC field is used to improve the collision resolution technique. The simulation results show that the CR-MAC protocol achieves significant improvements in terms of energy efficiency and latency levels.

The authors of [131] propose a Carrier Sense Multiple Access (CSMA) protocol for a LoRa network as an alternative to the random-access protocol ALOHA, with the goal of minimizing collisions in LoRa transmissions for short and long messages, with extremely interesting results in terms of both power consumption and delay.

A significant amount of effort was expended in [73] to propose a new MAC protocol called RS-LoRa, with the goal of improving the reliability and scalability of the LoRaWAN network. This RS-LoRa MAC protocol is divided into two steps: the first is handled by the gateways, in which a gateway schedules the nodes in its cell by dynamically specifying the authorized received signal strength and SFs for each channel, and the second is handled by the nodes, in which the nodes decide on the transmissions based on the scheduling information provided by the gateway. The transmission power, SF, channel, and timing of data transmission are all determined by the nodes themselves. The nodes are divided into different groups using the proposed light scheduling, and each group uses a common transmission power to reduce the capture effect. This MAC protocol proposal significantly reduces the number of packet collisions in the network by improving reliability and scalability. In terms of energy consumption, it is

clear that RS-LoRa introduces supplemental power consumption measures. However, it should be noted that in RS-LoRa, authorized SFs are determined by the gateway based on network preferences; the gateway can choose between reliability and energy consumption. The authors of [132] proposed including the distributed queueing (DQ) algorithm in LoRa, called the DQ-based MAC protocol, to improve the scalability and operability of LoRa networks. In order to evaluate the performance of the new MAC protocol, a comparison between DQ-LoRa, P-ALOHA, and CSMA was done, and the results showed remarkable performance in terms of throughput, average delay, and average power consumption. DQ-LoRa is more efficient than P-ALOHA in terms of power consumption, and can achieve power savings of up to 48% when the number of packets transmitted is high.

In [133], the authors introduce, develop and evaluate FCA-LoRa, a new MAC protocol designed to improve reliability and collision avoidance in LoRa networks. It is based on the diffusion of beacon frames through the network gateway aiming to synchronize communication with terminal devices and to optimize channel utilization using different SFs. The simulation was performed using OMNeT++, showing that FCA-LoRa increases the performance of the traditional LoRaWAN scheduling method regarding throughput and collision avoidance. However, since LoRa end devices listen almost continuously to the available frequency channels, FCA-LoRa could raise some serious issues regarding power consumption. In another study, the authors proposed a real-time protocol called RT-LoRa for industrial monitoring and control applications. The protocol uses a Multiple Listening Before Talk (mLBT) mechanism that allows the detection of channels several times in a time slot [134].

In [135], the authors present EF-LoRa, a LoRa networking solution that can provide equitable power consumption between end devices based on smart allocation of various network resources such as frequency channels, SFs, and TP, ensuring balanced power consumption between LoRa network end devices and extending the network's life. According to simulation results, the proposed EF-LoRa solution can improve the energy fairness of existing LoRa networks by 177.8% and achieve higher energy efficiency fairness than existing LoRa and RS-LoRa networks.

The authors of [136] propose a new MAC protocol that dynamically adapts the LoRaWAN MAC layer to changes in traffic load. This protocol, known as the Traffic-aware Energy efficient MAC protocol (TREMA), can switch between asynchronous and synchronous schemes based on changes in probed traffic. The protocol TREMA eventually expands the maximum capacity of LoRa implementations while also ensuring that the most energy-efficient access scheme is always chosen.

A new MAC protocol, called Deterministic Group Acknowledgment Transmissions in LoRa networks (DG-LoRa), designed to improve the scalability of LoRaWAN networks through deterministic GACK transmissions is introduced in [139]. The authors evaluate the

TABLE 9. Energy efficiency of MAC protocols.

Ref.	MAC Protocols	Advantages	Drawbacks	Energy Consumption	Energy efficiency
[73]	RS-LoRa	Improves the reliability and scalability of the LoRaWAN network; reduces the number of packet collisions; SFs are determined by the gateway according to the network preferences, the gateway can make choices between reliability and energy consumption.	In case of RS-LoRa packet transmission, the average power consumption is high. The gateway has the ability to choose between network reliability and power consumption.	The average power consumption is high.	*
[133]	FCA-LoRa	Synchronizes communication with terminal devices and optimizes channel utilization using different SFs. increases the performance in terms of throughput and collision avoidance.	Listens most continuously to the available frequency channels, which could lead to serious problems regarding power consumption.	The power consumption is high due to continuous listening to the available frequency channels.	*
[134]	RT-LoRa	Uses a Multiple Listening Before Talk (mLBT) mechanism that allows the detection of channels several times in a time slot.	The device constantly checks the channels, which makes it less efficient in terms of energy consumption.	Less efficient in terms of energy consumption due to continuous channel checking.	*
[77]	Pure-ALOHA	Gives the nodes sender the possibility to choose a SF, a channel and a transmission power.	Affected by packet collisions and duty cycle limitations, Pure-ALOHA is more energy efficient when the traffic load is low.	P-ALOHA increases the battery life of the node when traffic is low.	**
[78]	Slotted-ALOHA	The channel time is divided into slots, end devices are only able to send packets at the beginning of a slot.	Unsuitable for applications where high reliability in data transmission is needed.	Significantly reduces the collision rate, resulting in better energy efficiency.	***
[131]	CSMA	Minimizes collisions in Lora transmissions for short and long messages; reduces power consumption and delay.	Clearly increases sending latency.	At high traffic loads, the proposed model has a significantly reduced energy consumption.	***
[132]	DQ-based MAC	Enhances the scalability and operability of LoRa networks; achieves power savings of up to 48% when the number of packets transmitted is high compared to the pure ALOHA protocol.	Less efficient in terms of energy consumption than CSMA.	Achieves power savings of up to 48% when the number of packets transmitted is high compared to the pure ALOHA protocol.	***
[137]	TS-LoRa	An efficient mechanism that allows nodes to autonomously and securely deduce their slot number in the frame with high reliability and guaranteed delay.	The additional energy cost of synchronization is the major issue when designing synchronous communication protocols.	A higher number of nodes indicated that TS-LoRa has lower energy consumption than the confirmable version of LoRaWAN without incurring a compromise in packet delivery rate, whereas for confirmable traffic there is an additional energy cost to maintain acknowledgements.	***
[123]	ADC-MAC	Achieves a correct balance between energy consumption and network performance ; dynamically set the duty cycle of the node by specifying 3 factors including: node load, the node energy and the channel busy rate.	Linked to the 3 indicators indicated.	In ADC-MAC protocol, each node tries to avoid premature "death", thus extending the lifetime of the network. The main idea is to maintain the sleep state to extend lifetime of the node and to use residual energy as much as possible to transmit emergency information.	***
[135]	EF-LoRa	Proposes a mathematical model of energy efficiency in multi-gateway LoRa networks; Provides equitable power consumption between end devices based on a smart allocation of the various network resources, such as frequency channels, spreading factors and transmission power.	An increase in the convergence time of the EF-LoRa algorithm linked to the deployment of a greater number of EDs and GWs.	EF-LoRa can improve the energy efficiency of existing LoRa networks by 177.8%.	***

TABLE 9. (Continued.) Energy efficiency of MAC protocols.

[138]	On-demand TDMA	An energy-efficient network architecture and a highly efficient on-demand TDMA communication protocol for IoT, addressing both the energy efficiency and latency of standard LoRa networks.	The resulting system cost increases slightly due to the addition of an extra wake-up receiver module.	The network reaches a round-trip latency of milliseconds, with the sensing devices consuming less than 46 mJ when active and 1.83 μ W during inactive periods, and lasting up to three years on a 1200 mAh lithium-polymer battery.	***
[136]	TREMA	Dynamic adaptation of the LoRaWAN MAC layer to traffic load variations, increases the maximum achievable throughput and maximizes the energy efficiency of the device.	Large simulation campaigns are needed to establish the deployment fingerprint before implementing the mechanism.	TREMA aims to dynamically synchronize and desynchronize LoRa deployments according to variations in traffic load, thus adapts network capacity and always maximizes energy efficiency. It offers good energy efficiency when the generated traffic is high. In contrast, pure asynchronous ALOHA scheme is more efficient when the generated traffic is low.	***
[139]	DG-LoRa	Supports about five times more connections to the LoRa network by achieving a 5% data drop rate, provides low overhead by reducing the number of data frame retransmissions.	The primary concern of DG-LoRa is to allocate SFs and time slots to maximize the number of responses via GACK transmission.	Reduces the number of retransmissions by more than three times compared to the legacy LoRaWAN network, enabling low-power operation of end devices and thus optimizing energy consumption.	***
[40]	CR-MAC	Collision resolution technique is employed to decode the superposed Lora signals; CRC field is used to improve the collision resolution technique that has been adopted.	With a high number of end devices, the risk of multiple end devices choosing the same sub-lot is high, thus reducing the CR-MAC coding rate and overall throughput.	The CR-MAC protocol outperforms LoRaWAN with a gain of up to 50% for small networks and up to 90% for large networks. Furthermore, using SF12, the CR-MAC protocol shows a large gain compared to LoRaWAN. The gain amounts to 84% for small networks and 92% for large networks.	***

(*): Very Low; (**): Low ; (***) : High ; (****): Very High.

performance of DG-LoRa using a Monte Carlo simulation and then compare it to existing LoRaWANs in terms of data drop rate and number of retransmissions. Their numerical results show that DG-LoRa supports about five times more connections to the LoRa network by achieving a data drop rate of 5%. In addition, DG-LoRa provides low overhead by reducing the number of data frame retransmissions. In [137], the authors propose Time-slotted LoRaWAN (TS-LoRa) as a new approach to time slot communication over LoRaWAN. TS-LoRa allows nodes to self-organize the scheduling of time slots within frames. Experimental results with 25 nodes show that TS-LoRa can achieve packet delivery rate above 99%, even for the most remote nodes. Furthermore, the simulations with a higher number of nodes indicated that TS-LoRa has lower energy consumption than the confirmable version of LoRaWAN, without compromising the packet delivery rate. The authors of [138] present a new network architecture and an on-demand Time Division Multiple Access (on-demand TDMA) MAC protocol exploiting short-range wake-up radios and a LoRa physical layer. On-demand TDMA provides an efficient broadcast and unicast service for data transmission and collection, thereby improving the

performance of LoRa networks and achieving 100% packet delivery rate by eliminating the possibility of packet collisions.

Table 9 summarizes and evaluates the energy consumption of different MAC protocols used in LoRaWAN networks.

B. SENSOR/IoT DEVICE SIDE

The energy consumption of the end device is a very decisive factor for the network's correct and efficient performance [103], in the context of extremely rich and interesting work done to increase energy efficiency at the MAC layer level, as detailed below.

1) SCHEDULING OF LoRa-BASED TRANSMISSIONS

Authors of [66] propose a transmission scheduling algorithm at a central node, which defines when a given IoT device is allowed to transmit. They reduce message size by implementing a probabilistic structure using Bloom filters, which encodes time slots designed to decrease the synchronization for packet length and send more information to IoT nodes. The time slots are assigned according to the traffic requirements of the IoT nodes and contextual information,

such as periodicity, synchronization or clock drift. Using the central node, they synchronized the uplink transmission of the IoT devices. In terms of power consumption, the results show that the synchronization process will use less than 3 mAh of additional battery per end node over a period of one year, for synchronization periods longer than three days. This is less than the battery capacity used to transmit packets that will be lost in an unsynchronized network due to collisions. The authors of [140] present a scheme for scheduling node communications in slots of different sizes based on the SF. This approach enables transmissions with the same SF to be scheduled in other slots. On the other hand, transmissions with different SFs can be processed in parallel, thus preventing collisions. The first algorithm, called “Global Algorithm,” calculates the schedule for all communications. The second algorithm, called “Light,” schedules only the first transmission for each individual node and replicates it in subsequent frames. Under this setting, the IoT device maintains the same SF in successive transmissions with the preference for the shortest schedule. The simulation results show an improvement of up to 250% in terms of energy consumption associated with a packet delivery rate of nearly 100%.

In [141], a transmission scheduling mechanism based on temporal mappings is presented. The authors use the joining process of a new device to provide information about the periodization of transmissions. This enables gateways to schedule transmissions while avoiding collisions. The results obtained from NS-3 simulations show that, differently from LoRaWAN and CSMA, the collision rate decreases when the packet delivery rate increases, with slightly increased energy consumption.

2) ALLOCATION SCHEME

In [142], a new ADR algorithm called CA-ADR is proposed for the LoRaWAN network to assign data rates to EDs by taking the collision probability at the MAC layer into account. The new algorithm was compared to two benchmark solutions using simulation and experimental approaches under different performance metrics. Their findings show that CA-ADR outperforms the standard solution in networks that are not severely constrained by connectivity issues.

Paper [143] proposes CARA (Collision Avoidance Resource Allocation), a new algorithm designed to increase the capacity of LoRaWAN networks while decreasing the number of collisions. The CARA algorithm divides the wireless medium’s capacity into resource blocks that correspond to a channel and a SF. Transmissions in different resource blocks will not collide due to the orthogonality of the SFs in LoRa. Furthermore, CARA benefits from the existing joining procedure for parameter exchange and synchronization, which eliminates any subsequent communication between the final devices and the network. At another point, a comparison was made between the ADR and the proposed SF assignment algorithm. When compared to the ADR algorithm, CARA provides a significant increase in throughput. Another sig-

nificant result is that, while the proposed solution slightly increases overall transmission time, resulting in a slight increase in power consumption compared to the ADR proposed in the LoRaWAN specification, it ensures more equitable resource sharing.

The authors of [144] explore a different approach to data collection in LoRaWAN, and propose a Fine-grained scheduling approach to ensure Reliable and Energy-Efficient (FREE) data collection in LoRaWAN networks data collection in LoRaWAN networks. This approach is based on buffering data at the terminal devices and collecting it in scheduled mass transmissions at appropriate times. Instead of transmitting the data directly, this system assigns SFs, TPs, time slots, and frequency channels. Finally, they evaluate the performance of the proposed system. The numerical results show that the lifetime of the devices is estimated to be more than ten years, regardless of the type of traffic and the size of the network.

3) DATA MANAGEMENT

The frequency and payload size of data transmission affect energy consumption. The authors of [145] add that for a given day, the number of transmissions is linked first and foremost to the device’s energy consumption. As the payload size grows, so does the number of symbols per packet, resulting in an additional energy cost per transmitted packet. It is also reported in [103] that the energy consumption in the case of unacknowledged uplink traffic is greater than when the acknowledgement is transmitted in the first reception window. In the primary use case, the end node without receiving ACK must keep both reception windows open as well as the transition phase between the two, compared to the second case, where the reception of the ACK packet is a one-time event. The latter allows the node to enter sleep mode immediately after receiving an ACK, and the transition phase between the first and second reception windows is avoided. Such a strategy will aid in the reduction of energy consumption.

It is very clearly marked in [89] that each synchronization procedure directly affects energy consumption through the excessive load of synchronization messages and their transmission frequency, whereas LoRaWAN end devices are frequently asked to share a common time base. This work consists of determining a trade-off between the expected synchronization uncertainty and the energy available in the LoRaWAN. On this basis, an algorithm was developed to generate comparative curves between energy efficiency and uncertainty, while taking into account a synchronization mechanism that occurs on demand following (a posteriori) synchronization. The trade-off proposal is applied to two scenarios related to industrial applications: the Time Division Multiple Access (TDMA) system and the predictive maintenance framework.

The authors of [147] present Charm, a new system that aims to improve not only the battery life of end devices but also the coverage of LPWAN networks. Charm is a solution

TABLE 10. Aggregation techniques used in LoRaWAN network.

Ref.	Aggregation Technique	Advantages	Drawbacks	Energy Consumption	Energy Efficiency
[146]	AggACK	Frame aggregation method for ACK, LoRaWAN network server makes use of ACKs that contain cumulative ACK information about multiple data and multiple users; It guarantees reliable data transfer with a very small number of ACKs; If a frame collision occurs, AggACK ensures improved throughput.	High level of latency.	AggACK requires additional user nodes power consumption.	**
[145]	Adaptive data aggregation and retransmission algorithm	Based on aggregating data from successive periods and then transmitting the data using a single LoRa packet.	Lead to a higher latency in data transmission since the data must be transmitted only after the aggregation is complete.	With a data rate of 1, it is possible to guarantee an extended lifetime of more than five years for 6-minute time intervals with a 1000 mAh battery.	***

(*): Very Low; (**): Low ; (***) : High ; (****): Very High.

designed to ensure that multiple LoRaWAN gateways pool their received signals in the cloud on a consistent basis for the purpose of detecting weak signals that cannot be decoded by any individual gateway. Indeed, a new gateway hardware and software design has been developed, consisting of precisely detecting the specific sections of the received signal that must be sent to the cloud. The obtained results provide intriguing benefits in terms of range and end node battery life.

In [145], the authors propose an adaptive data aggregation and retransmission algorithm for transferring traffic data from sensors, and the results were analyzed to provide an estimated lifetime of sensor device radios. The proposed algorithm works by aggregating data from successive periods and transmitting it in a single LoRa packet. Because the data must be transmitted only after the aggregation is complete, such aggregation will result in higher latency in data transmission. This higher latency is accompanied by a reduced overall energy cost due to the reduced number of transmissions. It has been demonstrated that even with a data rate of one transmission per time interval, a 1000 mAh battery can guarantee a lifetime of more than five years with time intervals of 6 minutes.

The authors of [146] present AggACK, a frame aggregation method for ACK running on LPWAN networks. The LoRaWAN network server employs the proposed method by sending ACKs that contain cumulative ACK information for multiple data and multiple users. User nodes open their reception windows synchronously via the network server, causing the network server to simultaneously broadcast the cumulative information of ACKs to the user nodes during the same ACK. Unlike the standard LoRaWAN, it ensures reliable data transfer with a very small number of ACKs.

Table 10 lists the aggregation techniques used in LoRaWAN networks.

The LoRaWAN network in its basic configuration is unable to maintain reliable communication, and a loss of transmitted frames is possible due to channel effects as well as terminal device mobility. The authors of [148] performed a detailed

measurement of a new LoRaWAN network to identify the spatial and temporal properties of the LoRaWAN channel. According to the collected data, frame losses are very high and occur when end devices move away from a gateway. When the end device is about 6 km from the nearest gateway, it can be as high as 53%. In fact, the loss of a frame results in the loss of data. Given that an IoT application is typically data-driven, the resulting data loss must be minimal, and thus data recovery from IoT applications is required. To accomplish this, they created and implemented the DaRe application-layer coding scheme. The need for such a system is further motivated by the ALOHA media access technique used in LoRaWAN, which will undoubtedly result in numerous collisions resulting in frame loss. DaRe is a system that incorporates new techniques to improve data recovery while lowering overhead costs. DaRe does not recover lost frames, but it does allow data recovery from lost frames at the application level using FEC. The results show that with a coding rate of 1/2 and a frame loss of up to 40%, 99% of the data is recoverable. In comparison to repetition coding, DaRe provides 21% more data recovery and can reduce power consumption during transmission by up to 42% for 10-byte data units. Furthermore, DaRe provides greater resistance to burst frame loss.

4) UNMANNED AERIAL VEHICLES (UAVs)

Unmanned Aerial Vehicles (UAVs), also known as drones, are now being used in a wide range of novel applications, particularly in the telecommunications domain. Paper [149] discusses some promising benefits of UAVs in wireless environments, such as UAV-assisted wireless charging, in which a UAV could be (re)charged on the fly via wireless power transfer while flying near a charging station. A UAV, on the other hand, could wirelessly transfer energy to depleted ground IoT devices. At another level, authors of [150] present a novel use of UAV with an energy harvesting module to extend the network's lifetime. As a result, the UAV can be used as an energy source for depleted IoT devices. On the one hand,

the UAV charges the depleted ground IoT devices, beginning with those with a battery level less than a certain threshold. The UAV station, on the other hand, collects data from IoT devices that have enough energy to transmit their packets, and during the same phase, the UAV extracts and harvests energy from the RF signals transmitted by IoT devices.

Numerous studies, including [151], use UAVs on the LoRaWAN network to collect data from LoRa sensors. The authors of [28] investigate the UAV-based gateway (GW) that can improve the reliability of LoRaWAN communication in urban scenarios. However, neither study focuses on the power consumption and lifetime of the LoRaWAN terminal device. The authors of [152] highlight the energy efficiency of a LoRaWAN using UAV technology to collect periodic sensor data reports. The simulation results show that a UAV-based GW can reduce the average power consumption for network communications by up to 59%, depending on the trajectory or speed of the UAV.

5) LINEAR WIRELESS SENSOR NETWORK

The authors of [153] investigate the energy consumption of a specific type of WSN known as Linear WSN. According to [154], this type of WSN differs significantly from a standard WSN in that the sensor nodes are fixed in one dimension. Such WSNs are used for monitoring a wide range of applications, including transmission lines and pipelines. Linear WSN requires a unique network architecture, and its power consumption varies. The authors of [153] also proposed an energy consumption model based on a network architecture tailored for a linear wireless sensor network, as well as a comparison of two widely used wireless communication protocols, LoRaWAN and ZigBee. Based on this model, the LoRaWAN network outperforms ZigBee network in terms of energy efficiency.

V. ENERGY EFFICIENCY AT NET LAYER

The network layer's primary function is to transmit data packets from a source to a given destination. This section provides a literature review on LoRaWAN energy efficiency at the network layer. Numerous authors proposed multi-hop LoRaWAN solutions where several devices act as relays for other devices. The routing mechanism is a crucial factor for a multi-hop LoRaWAN since it has the potential to affect network performance in terms of throughput, reliability, latency, and energy consumption. While some works propose mechanisms that use intermediate nodes, such as a simple relay that only uses the LoRa physical layer, others propose routing protocols, resulting in more complex mesh networks. This section will go over these approaches in-depth.

A. NETWORK SIDE

1) ROUTING MODELS

As previously stated, the energy required to transmit a packet decreases as the distance between devices decreases. The following is a collection of works that are more closely related to the routing model used for the LoRaWAN network.

The energy efficiency of the star and mesh topologies was investigated by the authors of [95]. They also propose a method for determining the best associations between spreading factor, transmission power, distance, and bandwidth. In terms of energy consumption, they conclude that the best choice between direct and multi-hop transmission is determined by the sender-to-gateway distance. The authors of [155] present an energy consumption model for single-hop and multi-hop LoRaWAN networks. In the multi-hop approach, the authors consider a network formed by several rings around the gateway. The simulations are performed in MatLab, and the authors conclude that in the multi-hop scenario, nodes near the gateway consume more energy than nodes farther away. In the single-hop scenario, however, nodes near the gateway have higher energy efficiency. One more theoretical work has been introduced in [156] for various multi-hop configurations for LoRa networks with three hops to the gateway. When compared to traditional single-hop LoRaWAN, the results showed that some topologies could improve packet delivery ratio and energy consumption. The authors of [157] consider a standard LPWAN with a TDMA MAC layer. They suggest a Distance-Ring Exponential Stations Generator (DRESG) framework for evaluating performance and establishing optimal routing connections in the uplink for multi-hop communications. Their results indicate that multi-hop may improve network lifetime and balance energy consumption across all nodes in the network. The same researchers suggest a protocol stack for LPWANs called HARE in [158], which allows for single-hop and multi-hop connections. It is formed of many techniques at various communication layers, such as network synchronization, adaptive transmission power level, TDMA channel access, network association process, and energy-aware routing protocol. The protocol was tested on real hardware platforms and demonstrated high reliability and low energy consumption.

To improve the range and quality of LoRaWAN communications, the authors of [159] propose the implementation of a forwarding device that allows LoRaWAN to be used for multi-hop communications. To assess the impact of an additional communication hop, tests were performed with Class A and Class C devices. It has been demonstrated that the addition of a forwarder improves signal strength while significantly lowering the power consumption of the final device, resulting in a longer battery life. In [160], authors propose using a simple relay device to expand the LoRaWAN coverage area in rural areas. The authors recommend deploying relay nodes in areas that are not covered by the gateway and propose a simple and direct message forwarder as well as a synchronization mechanism. They demonstrate that the addition of the relay node to deliver packets reduces energy consumption. They also notice an improvement in coverage and reliability. The authors of [161] compare and contrast two architectures for multi-hop LoRaWAN in smart cities. An end device acts as a relay node in the first architecture to extend the coverage area. In the second architecture, known as star-of-stars, a group of remote devices forms a cluster

and sends data to a cluster gateway, which acts as a relay and sends the data to a central gateway. The authors implement a prototype of both architectures, but no new forward mechanism is presented. The results show that two or three hops consume less energy than single-hop communication. Furthermore, this paper discusses some challenges as well as future work for multi-hop LoRaWAN networks.

In [84], a study on the implementation of a multi-hop network for LoRaWAN communication that provides low cost and high coverage is proposed. The proposed method involves sending packets to the Internet via multiple gateways in order to overcome the problem of the gateway using a private telecommunication network as a way to access the Internet, which requires a monthly fee. The network configuration includes: gateways, which are classified as hopping gateways (HGW), main gateways (MGW), and the network server.

In terms of energy efficiency, we can conclude from the preceding works that the most energy efficient routing model is determined by the distance between the sender and the gateway. Table 11 provides a comparison between single-hop and multi-hop routing models.

TABLE 11. Routing model for LoRaWAN network.

Routing model	Advantages	Drawbacks
Single-hop	Gateways located in the center communicate and transmit directly messages from the terminal devices to the network server.	Gateways require simultaneous listening to all channels and continuous connection to the Internet, which wastes power.
Multi-hop	Improve the range and quality of LoRaWAN communications; Improves the signal strength and considerably reduces the power consumption of the end-device.	Redundancies are expected in case of several transmissions reaching the gateway via different relay paths, resulting in a waste of battery power.

2) ROUTING PROTOCOLS

Routing is the process of looking for and selecting a path to send messages from a source to a destination. In the presence of multiple routes, an algorithm manages path selection, taking into account one or more performance metrics to select the links and nodes that will serve as the destination path. Sensors are typically powered by small capacity batteries that operate autonomously over a limited lifetime, which can be extended using energy recovery techniques. As a result, one of the primary challenges of WSN routing protocols is to create energy-efficient paths between sources and sinks [85].

Numerous studies, focusing on routing protocols, have been conducted to improve the LoRaWAN network, as detailed below.

In [38], an IoT protocol for LoRa transceivers called LoRaBlink is proposed. This protocol addresses many issues that are required for the deployment of IoT applications but are not addressed by existing LoRa protocols, such as reliable and energy-efficient multi-hop communications. It is also intended for low-latency and bidirectional communication. It combines MAC and routing via beacons to enable time synchronization and distance reporting based on the number of hops to the gateway or sink. The authors of [162] propose using the Concurrent Transmission (CT) protocol in LoRaWAN networks, resulting in the CT-LoRa protocol. The CT is a new flood routing protocol that has been successfully implemented in IEEE 802.15.4 networks. The protocol does not require the use of a routing table, and the flooding mechanism ensures node synchronization. The proposed indoor scenario results demonstrated that the protocol improves LoRa coverage and achieves a reliable packet delivery rate. While the authors do not present an energy consumption analysis of the protocol, it is indicated that numerous works have confirmed that regardless of the energy consumption, reliability, or latency viewpoint, CT provides better or comparable performance compared to state-of-the-art multi-hop protocols. The authors of [85] provide a detailed analysis of the definition and evaluation of a multi-hop routing protocol based on the Destination-Sequenced Distance Vector (DSDV) routing protocol, which is designed to increase the coverage of LoRaWAN installations and enable full interoperability with standard LoRaWAN gateways. The proposed routing protocol makes use of the LoRaWAN beacon to deliver LoRaWAN packets from end nodes to gateways with the fewest hops possible. The proposed system was tested in linear topologies and bottlenecks and evaluated using packet delivery rate (PDR) and throughput as performance metrics. Overall, the results indicate the viability of such an extended LoRaWAN multi-hop system. The throughput values obtained are generally adequate for most IoT applications.

The authors of [165] describe a new version of the routing protocol for LoRa mesh networking, which provides a multi-point networking connection between gateways to achieve greater coverage. The proposed protocol is tailored to the needs of LoRa networks and devices, and is based on HWMP (Hybrid Wireless Mesh Protocol) and AODV (Ad Hoc Remote On-Demand Vector Routing). The protocol is evaluated only from the perspective of route construction time. The authors of [164] propose an energy-efficient multi-hop communication solution (e2MCh) in which routes are built based on energy consumption, residual battery life, and traffic rate. The simulation results demonstrate a 15% energy consumption gain when compared to single-hop LoRaWAN. In [166], the authors control the ancient underground water distribution systems in Siena, Italy, using multi-hop linear communication over LoRa. The authors use a simple routing protocol and synchronization mechanism, with end devices using a wake-up time transmission scheme to save energy. They proved that the proposed solution is dependable, and that the synchronization mechanism cuts energy consumption

TABLE 12. Energy efficiency of routing protocols.

Ref.	Routing Protocols	Working Concept	Advantages	Drawbacks	Energy Consumption	Energy Efficiency
[162]	CT-LoRa	The protocol does not require the use of a routing table, and the flooding mechanism ensures node synchronization.	The protocol improves LoRa coverage and achieves a reliable packet delivery rate.	Due to the obvious inevitable time and carrier frequency offset between transmitters, it is not applicable to all wireless standards. Even if the colliding packets have the same content, there are a number of non-ideal effects that reduce receiver reliability.	No power consumption analysis for the CT-LoRa protocol is provided, it is stated that the CT protocol consumes significantly less power than other multi-hop protocols due to the duty cycle accuracy enabled by the well-programmed TDMA mechanism.	*
[85]	A simplified version of DSDV	The proposed protocol is a simplified version of the DSDV routing protocol. The proposed solution classifies nodes into two types: routing nodes and leaf nodes, where the routing devices are not energy constrained.	The proposed solution is feasible even for duty cycle limitations and the achieved throughput values are satisfactory for most IoT applications.	The authors make the assumption that routing nodes are not energy constrained.	No energy consumption analysis, the authors assume that routing nodes are powered while leaf nodes are energy constrained.	*
[38]	LoRaBlink	It integrates MAC and routing, via beacons to enable time synchronization and reporting the distance based on the number of hops to the gateway or sink.	reliable and energy efficient multi-hop communications; designed to support low-latency and bidirectional communications.	If several transmissions reach the gateway via different relaying routes, this results in redundancy and therefore waste of battery power.	To improve system power consumption, beacon messages are sent infrequently. Although this is not the most energy efficient protocol.	**
[85], [163]	RPL	Exploits control messages that are distributed in the WSN, including the sender's rank on the root node, which minimizes a certain measure such as power, number of hops, number of expected transmissions (ETX) or other.	The protocol is not based on advance knowledge of the network topology.	Link capacity limits do not allow it to be employed in a LoRaWAN setting in the absence of significant adaptation.	The proposed objective function used by the RPL will be able to choose the routing path that minimizes ToA. By choosing the path with the shortest ToA, power consumption can be reduced, extending the network's lifetime.	***
[164]	e2McH	e2McH determines each LoRa device's energy consumption, traffic rate, and residual battery life and instructs a specific LoRa device to communicate in a multi-hop configuration to a nearby LoRa device.	The proposed method extends the battery life of LoRa devices in dense urban and sub-urban environments.	In the Line of Sight (LoS) propagation link, all nodes are evaluated.	The simulation results demonstrate a 15% energy consumption gain when compared to single-hop LoRaWAN.	****

(*): Very Low; (**): Low ; (***) : High ; (****): Very High.

by half when compared to a non-optimal wake-up time. In some applications, such as mines and pipelines, a linear topology may be the only viable option. In [163], the first proposal for a routing protocol in a LoRa network using a standard IP stack was introduced. They developed a novel MAC layer to deal with IPv6 Routing Protocol for Low Power and Lossy Network (RPL) routing protocol, and concluded that enabling RPL over LoRa is a step in the right direction that needs to be better tested. It is demonstrated that by selecting the path with the shortest ToA, power consumption can

be reduced, thereby increasing network lifetime. For WSN, a multitude of routing protocols are available. A hierarchical protocol is intended to achieve the best possible balance of scalability and performance. When sensor nodes are associated with multi-hop communication, the power consumption of the sensor nodes in hierarchical routing is extremely low [167].

Table 12 examines a selection of protocols that are adapted to the LoRaWAN network and are referenced in the literature.

3) NETWORK SLICING

Network slicing has emerged as one of the most important 5G innovations, gaining traction in both academia and industry due to its ability to allow different IoT devices and applications to coexist on top of a shared physical network infrastructure. Network slicing, in general, makes use of virtualization and softwarization substrate technologies to dynamically orchestrate physical networking resources (bandwidth, pathways, virtual network service chaining, placement). Network slicing helps to create end-to-end virtual network instances (networks slices) that are isolated on top of a shared physical network system [168], [169]. In this context, the literature includes several works for improving LoRa energy consumption through network slicing, as detailed below.

Authors of [170] study the factors associated with IoT dense deployment scenarios, especially when faced with the difficult task of using network slicing for a LoRaWAN gateway, as this results in performance degradation caused by the physical limitations of these gateways. For the efficient deployment and isolation of network slices in LoRaWAN physical gateways, the authors used a software defined networking (SDN)-based architecture tailored to network slicing. They also used a slice-based optimization method to improve the scalability and configuration of the LoRaWAN. It employs Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) and Gaussian Mixture Modelling (GMM) algorithms to determine the best network slice configuration strategy for maximizing QoS benefits while minimizing energy consumption and reliability costs. The numerical results demonstrate the efficiency of the method used to enable optimal decision-making in realistic LoRaWAN scenarios for slice configuration with respect to other decision techniques (static, dynamic-adaptive, and dynamic-random).

The authors of [171] investigate network slicing over various SF configurations in order to assess system performance and determine which one best serves LoRa devices in each slice. At a higher level, a dynamic inter-slicing technique is designed in which the bandwidth is similarly reserved on all LoRa gateways based on a maximum-likelihood estimation (MLE) [172], and this is then improved and extended with an adaptive dynamic method that evaluates each LoRa gateway independently and reserves its bandwidth after applying MLE to the devices in its range. Both dynamic slicing suggestions will be compared to a simple fixed slicing strategy in which the GW's bandwidth is reserved equally between slices. Finally, an energy model for LoRaWAN is integrated into NS3 based on LoRa energy specifications to evaluate the energy consumed in each slice, and an intra-slicing algorithm that reaches the QoS requirements of each slice in isolation is proposed. The results demonstrate that as the number of nodes increases, so does the total energy consumed across all simulated slices.

4) MULTI-RATs INTEGRATION

Gateways that allow multiple RATs (also known as multihoming) have the potential to provide alternative communication opportunities via various wireless networking technologies, allowing IoT devices to send data. As a result, multihoming gateways must include control functions capable of selecting the best RAT interface for targeting IoT data based on a variety of factors such as current network conditions and specifications [173]. The authors of [174] propose a novel distributed approach to solving the RAT selection problem, based on matching game theory, which can achieve a stable connected devices-RATs association. The proposed matching game assignment enables IoT devices with limited energy budgets to improve their energy efficiency and reduce data transmission costs over the serving RAT while incurring very little signaling overhead.

Around this perspective, we present below the most intriguing works that make use of a Multi-RATs system with a LoRaWAN network and have demonstrated efficient energy consumption.

Authors of [173] explore the viability of developing a multi-RAT LPWAN device capable of meeting transmission requirements in an NB-IoT co-existence scenario. The authors built a device prototype that includes an NB-IoT chipset that handles communication events and implements the LoRaWAN module. The dual-RAT LPWAN device was tested in a commercial NB-IoT and a private LoRaWAN environment at Brno University of Technology in the Czech Republic. According to the results, the NB-IoT chipset consumed more than 200 mW on average to keep the network synchronized. The LoRaWAN transceiver, on the other hand, consumed less than 60 mW due to the lower transmission power, despite the longer transmission time.

The authors of [175] created an analytical model for assessing the performance of license-free IoT-based networks, especially in scenarios where the same radio spectrum is used by one or more concurrent radio access technologies (e.g., LoRaWAN and Sigfox). This allowed the authors to perform analytical modeling of transmission success probability and key performance indicators (KPIs) in terms of delay and battery lifetime. It was possible to evaluate system performance when subjected to interference by measuring the interference of a scenario in which different communication technologies coexist. The authors used simulations with analytical models to evaluate the performance of a reference license-free technology. Given its exposure to interference caused by another transmission device that uses the same frequency, the scenario was simulated using a simplified form of LoRaWAN. The simulation results show that the presence of competing technologies significantly degraded the system's performance. The authors solved this problem by demonstrating that it is possible to mitigate the interference caused by the coexistence of transmission devices through joint reception. The latter can significantly extend battery life, especially over short distances.

In [176], the authors propose a game theory-based model in which end nodes implement multiple radio transceivers (e.g., LoRa, Wi-Fi, and BLE) to allow data processing at the network edge and connect multiple networks using different radio technologies. They integrate it into LoRaBox using auction-based techniques described in a previous work [177]. The system is composed of a test solution that supports LoRaWAN, BLE, and Wi-Fi. Depending on the signal strength, radio, and application requirements, the system can switch between multiple radio technologies adaptively.

B. SENSOR/IoT DEVICE SIDE

Network Coding (NC) is a promising technique for increasing throughput and decreasing latency in LoRaWAN networks. Its main advantage is that it reduces the number of repeated transmissions by minimizing packet loss. The authors of [178] go into great detail about the methods and techniques used for Instantly Decodable Network Coding (IDNC), which is applied to LoRaWAN. It is possible to state that by simulating and implementing the proposed system, a significant reduction in joint delay, delivery time, and power consumption is observed.

In paper [179], two practical alternative methods for increasing the probability of decoding a message in the presence of interference are used. The first method employs directional antennas to improve signal strength at the receiver level without requiring additional transmission power. The second method employs multiple base stations to improve the probability that at least one of them decodes a received message successfully (diversity reception). Both methods have advantages and disadvantages in terms of cost, deployment method, and maintainability. The simulation results show that, as expected, using each method has the potential to improve the performance of the LoRa network under interference conditions. However, it has been demonstrated that the use of multiple base stations outperforms the use of directional antennas. For example, in an environment with 600 nodes interspersed through four other LoRa networks of 600 nodes each, it is discovered that using three base stations raises the Data Extraction Rate (DER) from 0.24 to 0.56, while using directional antennas raises the value to 0.32.

Some IoT applications, for example, may still require certain reliability guarantees. The authors of paper [180] approach this problem through a low complexity encoding/decoding technique based on fountain codes. The main advantage of using encoding techniques when using LoRa technology is that no changes to the fundamental PHY technology are required. The encoded message is transmitted by the end devices via the radio access network to the application servers responsible for decoding the message. Each packet is assigned a sequence number, which allows the application server to determine which packets have been lost. These packets can then be recovered after a sufficient number of subsequent packets have been delivered successfully to ensure that the established redundancy is used for decoding. Static Context Header Compression (SCHC) is a header compression

scheme that allows for fragmentation and is particularly suited to LPWAN technologies [181]. The authors of [182] discuss the impact of SCHC compression and fragmentation on the LoRaWAN network, evaluating several compression and fragmentation configurations aimed at ensuring efficient packet transmission. The results demonstrate the benefits of SCHC, including a significant improvement in reliability for LPWAN links operating at lower data rates. However, fragmentation can result in a loss of efficiency in terms of data and power.

VI. HOT TOPICS AND NEW INSIGHTS

It is clear from the preceding sections that considerable work on improving energy efficiency within the LoRaWAN network has already been performed. However, many issues remain unresolved to enable efficient energy use in the LoRaWAN network, leading us down an interesting research path. Table 13 summarizes all axes addressed by layer and section, as well as the associated open research areas.

A. DENSE/ULTRA-DENSE NETWORKS

Energy consumption control for the nodes is a primary issue faced in a dense/ultra-dense network. The latter requires a higher number of gateways and certainly a more dense deployment of end devices, hence leading to more interference and consequently more collisions and delays. These collisions have a significant impact on battery life.

B. SERVICE/DEVICE HETEROGENEITY

Given the various types of devices used in a LoRaWAN network supporting a variety of services, managing and controlling the power consumption of heterogeneous devices from different vendors would be necessary, posing a challenge in the dynamic integration of heterogeneous devices and services, where interoperability needs to be maintained.

C. CROSS-LAYER DESIGN

Cross-layer design is the process of designing protocols that leverage the dependencies between protocol layers to achieve better performance. This approach contrasts with the traditional layered approach, where the protocols in each layer are designed independently of each other [183]. The idea in this context is to explore and create solid and efficient cross-layer communication to improve network performance, particularly as it relates to node energy consumption, by fully utilizing the interactions between the layers.

D. MULTI-RATS ACCESS

The coexistence of heterogeneous technologies distributed over various types of hardware is a research area that has emerged due to the explosive growth of IoT devices. Multiple radio access technologies (RATs) are highly future-oriented wireless network technologies requiring sophisticated coordination and collaboration between nodes and between RATs to achieve an integrated architecture where the multiple RATs operate as a single cohesive virtual radio access network. According to the reviewed literature, several researchers

TABLE 13. Summary of layered topics from the reviewed literature on LoRa and LoRaWAN and open research areas.

Section III : PHY Layer	Section IV : MAC Layer	Section V : NET Layer
<ul style="list-style-type: none"> Configurable radio parameters selection. Resource allocation. 	<ul style="list-style-type: none"> MAC Protocols. Scheduling of LoRa-based transmissions. Allocation scheme. Data management. Unmanned Aerial Vehicles (UAVs). Linear wireless sensor network. 	<ul style="list-style-type: none"> Routing models. Routing protocols. Network slicing. Multi-RATs interaction.
Open Research Areas		
<ul style="list-style-type: none"> Improved energy consumption through optimized settings. Dynamic parameter selection to optimize energy consumption. Cross technology interference. 	<ul style="list-style-type: none"> Adaptive retransmission strategy. Node energy management in dense/ultra-dense networks. Machine learning and AI on the edge. 	<ul style="list-style-type: none"> Low power mesh network solutions. Energy / Performance trade-off. Energy consumption and mobility.

have examined strategies to enable the coexistence of LoRaWAN with different wireless technologies to satisfy the requirements of next-generation IoT applications that use LPWAN technologies. As a result, more significant gains occur while preserving the benefits derived from independent use of the network. By combining LoRaWAN with other wireless network technologies, multiple-RAT devices can solve transmission bandwidth and rate-limiting issues. Multi-RAT can improve reliability by providing critical data transmission over multiple media at the same time. However, the addition of multi-RAT devices holds the possibility of introducing a significant new challenge: how do we deal with the interference caused by the coexistence of different technologies that use the same wireless spectrum? Co-channel interference leads to information loss or packet retransmissions, which affect various IoT applications, in addition to wasting energy, increasing latency, and even reducing the effective bit rate. Several studies have highlighted the advantages of allowing LoRaWAN to coexist with other LPWAN technologies, but they have failed to address the issue of interference. Alternatively, further research exploring the interference effects on large-scale and heterogeneous LPWAN deployments is needed [13].

E. TRANSMISSION PARAMETERS SELECTION

To begin with, the distribution of SF resources among nodes is becoming a critical issue. Increasing the node's SF should be carefully calculated because higher SF means longer ToA, and longer ToA increases the probability of collision with other high-frequency transmissions. The challenge is to propose a single SF assignment rule for each possible LoRaWAN topology, given that each network is unique and requires different methods to optimize the SFs of its nodes. Furthermore, the studies conducted to solve this problem use extremely high transmission power, resulting in higher energy consumption. It is necessary to propose an allocation scheme capable of optimizing SFs in an energy-efficient model.

Secondly, the literature assumes that SFs are perfectly orthogonal, with few studies examining the impact of imperfect orthogonality. It is therefore of interest to conduct research that considers the non-orthogonality of SFs.

Finally, the LoRaWAN network provides a high flexibility level: the NS can select the SF to be used by the various nodes, the transmission/reception channels, and the duration of the reception windows. It is thus possible to support reliable communications while meeting the requirements for communication reliability, delay, energy efficiency, and system capacity with the proper configuration of these parameters. The task at hand is to implement a system that allows us to automate the selection of LoRa transmission parameters based on the operating mode of each network to optimize and improve performance.

F. PACKETS RETRANSMISSIONS

The ALOHA access scheme is used in the LoRaWAN network, allowing any end device to send packets at any time by simply making a link request. Given that terminal devices are deployed in a non-scheduled mode and that the LoRaWAN network uses a device-controlled communication mode, simultaneous communications could potentially interfere with each other, resulting in packet transmission failure without a suitable access scheme. Failure to communicate results in a decrease in energy efficiency. Investigating the probabilities of retransmissions over the LoRaWAN network using various SF allocation approaches based on the MAC protocol used to provide an analysis of the overall system performance is an important direction to pursue.

G. ENERGY/PERFORMANCE TRADE-OFF

Most works targeting the performance improvement of LoRaWAN networks focus on finding a good trade-off between network performance and energy consumption. In several studies, the authors have to choose between a spe-

cific feature to be improved (scalability, reliability, security, etc.) and energy consumption. It is necessary to find a model that maintains a good equilibrium.

VII. CONCLUSION

This paper provides a comprehensive tutorial on LoRaWAN networks. Namely, we provide a detailed background on the LoRa standard, its architecture, its communication protocol stack, its end devices, and its services. Then, we survey the main research works on energy efficiency at the physical, MAC, and network layers of LoRa systems. Specifically, we highlight the most important works on the power consumption of LoRaWAN networks, while focusing on the network specific characteristics that are attributed to these specific layers. This tutorial aims to review pioneering research works and draw insights on how to optimize LoRa capabilities both from the network and the device perspectives. We finally present some research opportunities and open problems.

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IMANE CHEIKH (Student Member, IEEE) received the B.Sc. degree in networks and telecommunications from the Faculty of Sciences and Technics (FSTS), Hassan first University, Settat, Morocco, in 2016, and the M.Sc. degree in computer science and logistics from the Higher School of Textile and Clothing Industries (ESITH), Casablanca, Morocco, in 2018. She is currently pursuing the Ph.D. degree with the National Higher School of Electricity and Mechanics (ENSEM), Hassan II University of Casablanca, Networking, Embedded Systems and Telecom Research Group (NEST). Her current research interests include wireless networking and mobile communications (5G and beyond), the IoT, performance evaluation, smart cities, energy efficiency, and low-energy networks.



RACHID AOUAMI (Member, IEEE) received the M.S. and Ph.D. degrees in electrical engineering from ENSEM, Hassan 2 University, Casablanca, Morocco, in 2012 and 2017 respectively. Since 2018, he has been a Postdoctoral Fellow in electrical computer science at 3IT, Université de Sherbrooke, Quebec, Canada. Most recently, he is a Research Assistant with RioTinTo and Sherbrooke University on projects from improving health care diagnoses to making autonomous wireless devices and robots. His current research interests include performance analysis, power saving algorithms, and optimization in wireless sensor networks.



ESSAID SABIR (Senior Member, IEEE) received the B.Sc. degree in electrical engineering and automation from the Mohammed V University of Rabat, Morocco, in 2004, the M.Sc. degree in telecommunications and wireless engineering from the National Institute of Posts and Telecommunications, in 2007, the Ph.D. degree (Hons.) in networking and computer engineering from the University of Avignon, France, in 2010, and the Habilitation degree (Hons.) from the Hassan II University of Casablanca, in 2014. He was a Contractual Assistant Professor at the University of Avignon, from 2009 to 2012. Currently, he is a Full Professor with the Department of Electrical Engineering, National Higher School of Electricity and Mechanics (ENSEM), where he leads the Networking Embedded Systems and Telecom research Group. He is/was the main investigator of many national projects, and has been involved in several other national and international/European projects. His research interests include wireless networks and mobile communications, 5G and beyond, the IoT, infrastructure-less networking, ultra-reliable low latency communications, wireless artificial intelligence, and networking games. His work has been awarded in many international venues, such as IEEE 5GWF'21, IEEE IWCMC'19, and IEEE WF-IoT'20. His Ph.D. thesis has been funded by an excellence scholarship from INRIA-France. He was a recipient of the Excellence Scholarship from the Moroccan government. As an attempt to bridge the gap between academia and industry, he founded the International Conference on Ubiquitous Networking (UNet) and co-founded the International Conference on Wireless Networks and Mobile Communications (WINCOM). He serves as an editor, an associate editor, and a reviewer for many international journals. He organized numerous events and served as the general chair, the TPC chair, and other executive roles in many major international events.



MOHAMED SADIK (Senior Member, IEEE) received the Ph.D. degree in electrical engineering from the National Polytechnic Institute of Lorraine (INPL), Nancy, France, in 1992. He has been a Full Professor with the Department of Electrical Engineering, National School of Electrical and Mechanical Engineering (ENSEM), since 2008. He was the Chair of the Electrical Engineering Department and the Chair of the Research and cooperation Department, ENSEM, from 2013 to 2019. He has founded and led the Networks, Embedded Systems and Telecom (NEST) Group Research, since 2011. He is currently the Chair of the Laboratory of Research in Engineering (LRI Lab.). His previous research activities are part of the development of autonomous biomedical systems. He is interested in codesign, modeling and synthesis of embedded systems, autonomous/intelligent systems with applications to smart farming, smart health, smart environment, smart and green energy, and smart grid management. His current research interests include protocols design, *ad hoc* networking, networking game, pricing and networking neutrality, image processing, machine learning and deep learning, and security in the cloud. He published several peer-reviewed papers in reputed international journals and conferences and some book chapters. He served on the technical program committees for many international conferences (and as a reviewer of several journals). He has co-founded the International Symposium on Ubiquitous Networking (UNet).



SÉBASTIEN ROY (Member, IEEE) received the B.Sc.A. and M.Sc. degrees in electrical engineering from the Université Laval, Quebec, QC, Canada, in 1991 and 1993, respectively, and the Ph.D. degree from Carleton University, Ottawa, ON, Canada, in 2000. From 2000 to 2002, he was a National Sciences and Engineering Research Council of Canada (NSERC) Postdoctoral Fellow with Université Laval. In 2007, 2009, 2011, and 2018, he was an Invited Professor with the École Nationale Supérieure de Sciences Appliquées et de Technologie (ENSSAT), Lannion, France. In 2015, he was an Invited Professor with the Institut National de Sciences Appliquées (INSA), Rennes, France. From 2002 to 2012, he was an Assistant Professor with Université Laval, where he has been an Associate Professor, since 2005, and a Full Professor, since 2010. In 2012, he joined the Electrical and Computer Engineering Department, Université de Sherbrooke, Sherbrooke, QC, Canada, where he is currently a Full Professor. He was the Department Chair from the Université de Sherbrooke, from 2016 to 2017, where he is working on system-oriented and implementation aspects of signal processing for advanced wireless communications. He is a Co-Founder and a Co-Leader of the Center of Excellence in Integrated Intelligent Systems (CESIIUS), Université de Sherbrooke. He has been active in industrial consulting and was involved in the organization of several international conferences. He received the Award for Post-Graduate Research Excellence from the Canadian Institute for Telecommunications Research (CITR), in 2000. He was a recipient of multiple teaching awards and is active in industrial collaboration.

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