A Survey on Scalable LoRaWAN for Massive IoT: Recent Advances, Potentials, and Challenges

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Abstract-Long Range (LoRa) is the most widely used technology for enabling Low Power Wide Area Networks (LPWANs) on unlicensed frequency bands. Despite its modest Data Rates (DRs), it provides extensive coverage for low-power devices, making it an ideal communication system for many Internet of Things (IoT) applications. In general, LoRa radio is considered as the physical layer, whereas Long Range Wide Area Networks (LoRaWAN) is the MAC layer of the LoRa stack that adopts star topology to enable communication between multiple End Devices (EDs) and the network Gateway (GW). The Chirp Spread Spectrum (CSS) modulation deals with LoRa signals interference and ensures long-range communication. At the same time, the Adaptive Data Rate (ADR) mechanism allows EDs to dynamically alter some LoRa features such as the Spreading Factor (SF), Code Rate (CR), and carrier frequency to address the time variance of communication conditions in dense networks. Despite the high LoRa connectivity demand, LoRa signals interference and concurrent transmission collisions are major limitations. Therefore, to enhance LoRaWAN capacity, the LoRa alliance released many LoRaWAN versions, and the research community provided numerous solutions to develop scalable LoRaWAN technology. Hence, we thoroughly examined LoRaWAN scalability challenges and the state-of-the-art solutions in both the PHY and MAC layers. Most of these solutions rely on SF, logical, and frequency channel assignment, while others propose new network topologies or implement signal processing schemes to cancel the interference and allow LoRaWAN to connect more EDs efficiently. A summary of the existing solutions in the literature is provided at the end of the paper by describing the advantages and drawbacks of each solution and suggesting possible enhancements as future research directions.

Index Terms—LoRaWAN, LPWAN, Massive IoT, Spreading Factor, Adaptive data Rate, Sigfox, NB-IoT.

I. INTRODUCTION

The Internet of Things (IoT) is a powerful and omnipresent technology advancing seamless networking in our twenty-first-century lives, allowing various objects to connect to the core network and exchange information. People can manage or monitor the behaviour of things remotely from systems that are hundreds of kilometres away using various types of IoT technologies. IoT-based systems have proliferated in the last few years in both academics and industry, providing multiple new applications such as smart homes, smart transportation, smart hospitals, and smart cities [1], [2], [3]. Based on these emerging applications, the number of IoT devices is expected to grow from 7 billion in 2018 to 22 billion in 2025 [4].

As a result, establishing intelligently efficient, adaptable, and cost-effective IoT systems in the context of a massive-IoT paradigm is becoming a complicated task due to the increasing number of IoT connectivity demands and various application requirements [5]. For this reason, connectivity becomes the core of IoT networks which is provided by a variety of wired and wireless (terrestrial and non-terrestrial) communication technologies.

Among different connectivity solutions, Low-Power Wide-Area Network (LPWAN) has established itself as the go-to connection option for IoT networks due to its long communication range, low energy consumption, and low cost. LPWAN protocols can provide connectivity for many low-power battery-operated devices for delay-tolerant applications with limited throughput per device. Due to these traits of LP-WAN, IoT-based applications, machine-to-machine networks, and wireless sensor networks (WSNs) are projected to use



Fig. 1: Massive IoT use cases enabled by LPWANs technologies

TABLE I: A comparison of the most popular LPWAN technologies [6], [7]

LoRa	SIGFOX	NB-IoT	LTE-M	
Proprietary (PHY), Open (MAC)	Proprietary	Open LTE	Open LTE	
Unlicensed		Licensed		
Sub-GHz ISM	Sub-GHz ISM	Cellular band	cellular band	
CSS	D-BPSK	$\frac{\pi}{2}$ -BPSK, $\frac{\pi}{2}$ -QPSK	BPSK, QPSK, 16QAM, 64QAM	
1%	140 msg/day	-	-	
433, 868, 915MHz	868, 915MHz	700-2100MHz	700-2600MHz	
125, 250, 500 kHz	100, 600 Hz	200 kHz	1.4 MHz	
1 – 10 km	10 – 40 km	15 km	11 km	
10 years	10 years	10 years	10 years	
multi-operator, Self deploy- ment	-	In Band, Guard Band LTE and GSM Standalone	In Band LTE	
LoRaWAN	No	3GPP Release 13	3GPP Release 12	
AES-128	AES-128	LTE security	LTE security	
	Proprietary (PHY), Open (MAC) Unlicensed Sub-GHz ISM CSS 1% 433, 868, 915MHz 125, 250, 500 kHz 1 – 10 km 10 years multi-operator, Self deployment LoRaWAN	Proprietary (PHY), Open (MAC) Proprietary Unlicensed Sub-GHz ISM Sub-GHz ISM CSS D-BPSK 1% 140 msg/day 433, 868, 915MHz 868, 915MHz 125, 250, 500 kHz 100, 600 Hz 1 - 10 km 10 - 40 km 10 years 10 years multi-operator, Self deployment - LoRaWAN No	Proprietary (MAC) Proprietary (PHY), Open (MAC) Proprietary (PHY), Open (MAC) Open LTE Unlicensed Lice Sub-GHz ISM Cellular band CSS D-BPSK π/2-BPSK, π/2-QPSK 1% 140 msg/day - 433, 868, 915MHz 868, 915MHz 700-2100MHz 125, 250, 500 kHz 100, 600 Hz 200 kHz 1 - 10 km 10 - 40 km 15 km 10 years 10 years 10 years multi-operator, Self deployment - In Band, Guard Band LTE and GSM Standalone LoRaWAN No 3GPP Release 13	

LPWAN. Figure 1 shows some massive IoT use cases that are enabled by LPWAN technologies. The LPWAN protocol uses binary phase-shift keying (BPSK) and chirp spread spectrum (CSS) as physical layer modulation schemes that tolerate interference and propagation noise to permit long-distance transmission [8], [9]. Also, LPWAN nodes use in general low-quality and low-cost circuit configuration to meet the low-cost requirements [10]. In addition, LPWAN employs adaptive asynchronous random-access protocols on the medium access control (MAC) layer, such as the pure ALOHA protocol with additional acknowledgement mechanism due to its efficiency and simplicity as mentioned in LoRaWAN v1.0 specification [11].

Several LPWAN technologies have their own set of technical features, business models, and deployment strategies. We can classify these LPWAN technologies into two categories based on the spectrum used. First, Narrowband IoT (NB-IoT) and LTE-M standardized by the 3rd Generation Partnership Project (3GPP) operate on the licensed spectrum. These technologies provide high Data Rates (DRs) and BW and assure Quality-of-Service (QoS) at the cost of deploying complex protocols that associate high energy consumption and increased costs [12], [13]. Second, Sigfox and LoRaWAN standards operate on the unlicensed spectrum and compete to build their networks as quickly as possible. To enhance resistance against interference from other systems, devices in this latter category send a small signal over a larger frequency spectrum, enabling long-range communication with low power consumption. However, this strategy wastes the common spectrum and often encounters significant self-interference issues, limiting total network capacity, and scalability [14].

Among all of the above LPWAN technologies, LTE-based technologies, such as NB-IoT and LTE-M, improve the cell capacity and extend the devices' range to transmit/receive a small

amount of data over a small BW. However, conventional LTEbased solution is costly regarding the high power consumption of devices, having complex protocols used to manage their functionality, and having a high cost of deployment [15]. IoT systems targeting LTE-M intended to preserve battery power due to LTE-M nodes' low power consumption, increasing the battery life up to 10 years. Devices in the LTE-M release operate with 1.08MHz BW, equivalent to 6 LTE physical resource blocks. LTE-M can coexist with LTE services within the same BW, deploying different features to extend its coverage, such as TTI bundling, repetition, and narrowband retuning. By reducing the complexity of IoT EDs, LTE-M has quite a low cost compared to 2G/3G/4G technologies [16]. The other LTE-based LPWAN technology is NB-IoT, one of the most popular ones developed by 3GPP as part of Release 13. Although it is part of the LTE standard, it has a novel air interface, maintaining the essential requirements to reduce devices' cost and limit battery usage. Hence, NB-IoT lacks several capabilities of LTE, like Handover, channel quality maintaining, carrier aggregation, dual connection, and some other features. NB-IoT operates under three modes such as inband, guard-band, and stand-alone. The stand-alone mode uses a GSM frequency with a BW of 200 kHz between guard bands of 10 kHz. While for the guard band and in-band operations modes, the new guard band and resource block of LTE are used. Mainly NB-IoT is intended to improve indoor coverage and enable the connectivity between many low-throughput devices, achieving low latency and excellent service quality [17].

The second type of LPWAN technologies that operate in the unlicensed band is SigFox and LoRa. SigFox uses an ISM spectrum of 200 kHz BW with 868 or 915MHz as central frequency depending on the geographical area. The usage of the ISM band, especially inside the European region, imposes

TABLE II: Acronyms used in this paper

Acronym	Meaning
ADR	Adaptive Data Rate
AES	Advanced Encryption Standard
AoA	Angle of Arrival
BLE	Bluetooth Low Energy
BPSK	Binary Phase-Shift Keying
BW	Bandwidth
CD	Code Rate
CDF	Cumulative Distribution Function
CRC	Cyclic Redundancy Check
CSMA	Channel Sensing Multiple Access
CSS	Chirp Spread Spectrum
DR	Data Rate
ED	End Device
FEC	Forward Error Correction
FFT	Fast Fourier transform
GW	Gateway
ISM	Industrial, Scientific, and Medical band
LEO	Low Earth Orbit
LoRaWAN	Long Range Wide Area Network
LoS	Line of Sight
LPWAN	Low-Power Wide-Area Network
mLBT	multiple Listen-Before-Talk
NLoS	Non-Line of Sight
NOMA	Non-Orthogonal Multiple Access
NF	Noise Figure
NS	Network Server
PSLV	Polar Satellite Launch Vehicle
R_b	Bit Rate
R_c	Chirp Rate
R_s	Symbol Rate
RSSI	Received Signal Strength Indicator
RX	Recieving Windows
SF	Spreading Factor
SNR	Signal to Noise Ratio
SIC	Successive Interference Cancellation
SIR	Signal-to-Interference Ratio
S-ALOHA	Slotted ALOHA
TDoA	Time Difference of Arrival
TP	Transmission Power
TX	Transmission Windows

some restrictions in terms of duty-cycle of 1%, which means that devices can only deliver 140 uplink messages of 12 bytes. Besides, the end node can only receive four messages only per day in downlink with an 8 bytes payload [18]. Unlike LoRa, SigFox is a network operator that allows the IoT devices far away to transmit their collected data to a SigFox server. Therefore, SigFox services are only offered to limited countries (45 countries worldwide).

Due to its easy and low-cost deployment and remote maintenance requirement, LoRa has been identified as the most suitable LPWAN technology to ensure wireless connectivity for massive IoT networks. LoRa is known for its worldwide availability due to its usage of the specific sub-ISM band for communication. That helps the deployment of private networks without engaging external operators, which means that the service provider will install and operate all the network equipment. In this scenario, a relay entity may be in charge of numerous IoT devices deployed around it to sense and collect data from the target area. Nevertheless, sporadic traffic pattern congestion and collision may arise since multiple IoT

devices may simultaneously attempt to access the network and transmit their data. Our survey aims to discuss the recent advances and challenges of a scalable LoRa network for massive IoT; more details are presented in the subsequent sections; refer to Table I for a complete comparison between the aforementioned LPWAN technologies. Table II shows the meaning of acronyms used in this paper.

A. Related Surveys

Due to the importance of LoRaWan for providing connectivity to low-power devices, some specific surveys are available that focus on various aspects. This section covers multiple surveys on LoRaWAN and identifies the niche area of collision avoidance and interference management in LoRaWaN networks. For instance, reference [28] reviews LoRaWAN architecture by describing the main components such as EDs, GWs, network, and applications. In addition, [28] presents a classification of the existing LoRaWAN attacks such as the authentication, availability, integrity attacks, as well as discusses some of the recent countermeasures to face the vulnerabilities mentioned above. Besides this, the drawbacks of LoRaWAN v1.1, which was released in 2017 to overcome these vulnerabilities, are discussed in detail. Then, Alfonso et al. briefly overview LoRaWAN routing protocols and the challenges facing multi-hope communication implementation [35]. Authors in [27] provide a general introduction to LPWAN technologies, especially the most popular one, which is the LoRaWAN, and perform a comparison between Sigfox, NB-IoT, LoRaWAN, and the conventional networks in term modulation schemes, used frequency, coverage, BW, and the energy consumption. In [27], the authors also analyze the LoRaWAN architecture using the layered OSI reference model where LoRa is identified as the physical layer and LoRaWAN as the MAC layer protocols. The authors in [32] surveyed the most popular LPWAN technologies such as Sigfox, DASH7, and LoRa. They summarized the general advantages of LoRa and the limitations when used for image transmission. Recently, the authors in [31] provided a brief overview of using machine learning with LoRa to enable remote Smart-Home monitoring.

Authors in [40] explain in detail the working process of the Long Range-Frequency Hopping Spread Spectrum (LR-FHSS) as an extension of the LoRa physical layer. A comparison between the most popular LPWAN technologies (LoRaWAN, NB-IoT, DASH7) has been provided in [26], especially discussing how the mobility of things can be handled by these technologies knowing that in general, they consider only the fixed interconnected things. Besides LoRa, more technologies enabling LPWAN are identified in [26] such as DASH7, SigFox, Wi-SUN, which are based on an unlicensed frequency band. Recently, UAV-based LoRa communication network deployment has been reviewed in [39], where a UAV can be deployed in this architecture as an ordinary LoRa node or as a LoRa GW targeting either communication or localization application. Mohammed et al. [29] discussed the challenges limiting LoRaWAN technology toward sufficiently deployed in an ultra-dense network.

LoRaWAN can self-adapt its configuration to enhance its performance in terms of reliability, radio range, delay, through-

TABLE III: A summary of the most relevant related surveys

Surveys	Technologies	Nb Ref	Year	Short Description	
[19]	LoRa, NB-IoT	15	2017	Provide a comparison between LoRa and the NB-IoT in terms of physical features network architecture and MAC protocol.	
[10]	SIGFOX, LoRa, INGENU RPMA, TELENSA, QOWISIO	94	2017	Surveys the design and techniques employed by different LPWAN technologie offer wide-area coverage to low-power devices	
[20]	LoRa	22	2017	Evaluate LoRa modulation while considering the IoT requirement	
[21]	LoRa, NB-IoT	18	2017	Survey the current research and provide a comparative study between LoRa and NB-IoT in terms of energy efficiency, reliability and coverage	
[22]	LoRa	40	2018	Evaluate the usefulness of LoRaWAN technology in the field of IoT	
[23]	LoRa	132	2018	Provides an overview of published paper in IEEE explore database between 2015 and 2018, related to security, Physical and MAC layer	
[24]	LoRa	58	2019	Explore different applications of LoRa and design a solution integrating Edge computing to enhance the performance of IoT-based applications	
[25]	LoRa, NB-IoT	15	2019	Provides a brief overview of LPWAN enabling technologies such as NB-IoT and LoRa	
[26]	LoRa, DASH7, SigFox, Wi-SUN	68	2019	Addresses the mobility of things and their connectivity in different LPWAN technologies	
[27]	LoRa	157	2019	Gives a general introduction to LoRaWAN technology by discussing issues related to the architecture, MAC protocols, ad provides open research opportunities.	
[28]	LoRaWAN	205	2020	Provides a survey on LoRaWAN security and privacy vulnerabilities	
[29]	LoRa/LoRaWAN	39	2020	Reviews the challenges facing LoRaWAN in ultra-dense network	
[30]	LoRa/LoRaWAN	52	2020	Reviews the recent research on Adaptive Data Rate algorithms for LoRaWAN technology	
[31]	LoRa	15	2020	An overview of LoRa-Based smart home using artificial Intelligence	
[32]	LoRa	27	2020	Aimes to highlight the available LoRa-based methods in the literature used to transfer images	
[33]	LoRa	39	2020	Analyses the performance of LoRa technology applied for vehicular communication using both experimental and simulation results	
[34]	LoRa / LoRaWAN	137	2020	Surveys briefly LoRa-related issues and their recent solutions as energy consumption communication range, error correction and multiple access	
[35]	LoRaWAN	15	2020	Provides an overview of LoRa-based multi-hop communication network and summarize different routing protocols designed to this end	
[36]	LoRaWAN	73	2020	Surveys the recent application of LoRaWAN that require confirmed traffic	
[37]	LoRaWAN	139	2021	Presents a systematic review of the existing LoRaWAN optimization solution that aims to improve the IoT networking performance	
[38]	LoRa/LoRaWAN	31	2021	Provides an extended review and experimental evaluation of the latest ADR for LoRaWAN network	
[39]	LoRa / LoRaWAN	89	2021	Reviews the current research focused on UAV-based real-time LoRa communication	
[40]	LoRa	15	2021	Provides a reference explanation of Long Range-Frequency Hopping Spread Spectre (LR-FHSS)	
[41]	LoRaWAN	119	2022	Discuss the common features distinguishing different LPWAN technologies and defining their employability regarding the target scenario.	
[42]	LoRaWAN	183	2022	Gives a general insight into the energy efficiency in LoRaWAN networks, proposing some research directions in this context.	
Our Survey	LoRa/LoRaWAN	238	2022	We provide a survey on scalability challenges and the proposed solutions to assist LoRaWAN deployment in massive IoT networks	

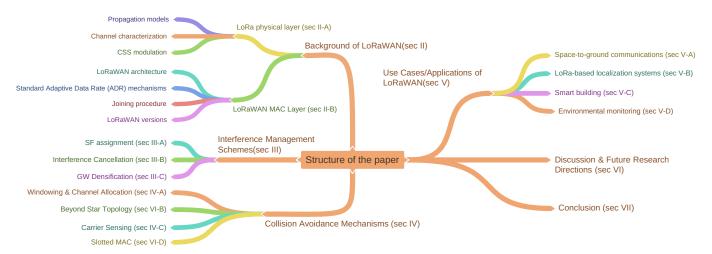


Fig. 2: Structure of the paper

put, and power consumption. This is performed through using different DRs allowed by ADR mechanism according to these parameters: Spreading factor (SF), BW, Coding Rate (CR), and Transmission Power (TP) [43]. Authors in [38] provided a survey on different ADR enhancements existing in the literature and compared their performance in a mobile node scenario. While [30] survey the optimization solutions for ADR. From a network perspective, authors in [44] distinguished five factors categories that should be considered to evaluate the capability of LoRa to serve a crowded deployment efficiently: physical layer characteristics, deployment and hardware features, ED transmission settings, LoRa MAC protocols, and application requirements. These parameters defined as performance determinants have been reviewed in [44]. A systematic review of the existing LoRaWAN optimization solutions provided in [37], such as the optimized aspects includes the co-existence of IoT devices and applications, resource allocation mechanisms, MAC layer protocols, network planning, and mobility issues.

The LoRa use-case in vehicular communications has been evaluated through a comparative study of the experimental and simulation results in [33]. Authors in [25] provide a brief overview of the most popular LPWAN technologies such as LoRa and NB-IoT. In [24] the authors reviewed various LoRa applications, mainly to propose its integration with edge computing for IoT. These later were obtained from the simulation in NS-3 based on the following three metrics: Packet Delivery Ratio (PDR), packet inter-reception time, and Received Signal Strength Indicator (RSSI). A survey on LoRa networking issues was provided in [34] as well as some solutions to enable its practical deployment.

The review presented in [36] studies LoRaWAN use cases that require confirmed traffic and discusses the viability of the actual traffic for the scenario where the data transfer is infrequent. A general survey on LoRaWAN technologies and their application fields was presented in [23] that analyzes to distinguish between the physical layer performance and network-level performance. Another general generalized survey on LoRa is presented in [10] (published in 2017), which focuses on the performance of different technologies enabling LPWAN. The authors of [19], [21] provided a comparative

study of LoRa and NB-IoT; it was found that LoRa based on unlicensed spectrum advances NB-IoT in terms of battery lifetime, capacity, and cost. In contrast, licensed NB-IoT advances LoRa in QoS, latency, reliability, and range. Table III presents a brief comparison of the above surveys with our work.

B. Motivation and Contributions

Unlike the surveys mentioned above that focus on comparing different LPWAN technologies or providing a general review of LoRa technology where the security issues and the energy efficiency is the main subject, our work reviews LoRaWAN scalability issues facing its deployment for massive IoT. The contributions of this work are summarized as follows:

- First, we review the LoRaWAN system and its features from the PHY and MAC layers perspective.
- Next, we discuss the issue of LoRa signals interference appearing when several EDs transmit their signals simultaneously using the same combination of LoRa PHY layer parameters. Moreover, we present different solutions proposed in the literature to overcome this issue and classify them into three categories: SF assignment, Interference cancellation, and GW densification.
- Then, we investigate existing collision avoidance schemes in the literature to tackle collided LoRa concurrent transmissions at the MAC layer level. We also categorized the current solutions such as windowing & channel allocation, beyond start topology, carrier sensing, and slotted MAC protocols.
- Afterwards, we present several use cases and applications
 of LoRaWAN that may involve massive IoT such as,
 space-to-ground communications, LoRa-based localization systems, smart buildings, and environmental monitoring.
- Finally, we discuss the proposed solution drawbacks, remaining open issues, and potential future research direction for LoRaWAN deployment in ultra-dense IoT networks.

C. Organization

The rest of the paper is organized as follows: in section II, we start by describing the LoRa physical layers specifications, including LoRa modulation, SFs, and the propagation models. Moreover, section II presents the LoRaWAN architecture as well as the EDs classes and the joining procedure. Schemes to manage and overcome Lora signals interference are discussed in section III. Section IV outlines the current collision avoidance mechanisms to allow concurrent LoRa transmission in dense deployments. The latest use cases and applications of LoRaWAN are classified and reviewed in section V. Finally, we conclude the paper in section VI by discussing the advantage and drawbacks of the proposed solutions to enhance the LoRaWAN capacity and allow its deployment in dense networks and identifying the remaining open questions in this field. (Figure 2 provides a general overview of the paper structure.)

II. BACKGROUND OF LORAWAN

This section describes the specification of LoRa technology that influences its capacity to serve high dense networks as massive IoT networks. It presents the first step to understand the challenges facing the deployment of LoRa in a massive IoT network.

A. LoRa physical layer

LoRa network relies on two key components, LoRa and LoRaWAN, such as LoRa present the physical layer modulation while LoRaWAN the MAC layer protocol. Combining these two components results in a low-power and cost-effective wide-area network. We discuss the PHY and MAC layer issues separately in the following sections.

1) Propagation models: A network planner's ability to effectively predict LoRa signal behaviour in the target environment is a critical part of efficient network deployment. It allows predicting the ED coverage, which helps decide the number of GWs required for a set of EDs. Propagation models are the most frequent method for doing so due to their ability on estimating the received signal strength based on the path loss calculation. Based on the derivation of the resulting path loss, wireless propagation models can be split into three categories: (i) empirical, (ii) deterministic, and (iii) stochastic; more details are provided in [18]. To date, a variety of propagation models for wireless technologies have been presented, with the majority of them coming from three key sources: (i) standards, (ii) vendors/operators, and (iii) academics. Okumura-Hata model [45] is one of the most frequently used propagation models in LoRaWAN. In contrast to the Okumura model [46], which depicts empirical results characterizing the impacts of propagation over a variety of parameters in Tokyo, the Hata model [45] produced mathematical equations that correlate to the Okumuras results for different parameters. This helped facilitate the propagation impact analysis using computer simulations, where the path loss is computed depending on characteristics such as frequency range 150-1500 MHz, distance range 1- 20 km, and antenna height.

TABLE IV: The corresponding spreading factor for each chips/symbol, SNR limit, and data rate for LoRa communication over a channel of 125 kHz BW

Spreading Factor	Chips/Symbol	SNR limit	Data Rate
7	128	-7.5 db	5469 bps
8	256	-10	3125
9	512	-12.5	1758
0	1024	-15	977
11	2048	-17.5	537
12	4096	-20	293

COST 231-Hata-Model [47] is a variation of the Hata model to extend its frequency range. The path loss prediction model is based on the basic system characteristics, where the frequency varies from 1500 to 2000 MHz, the distance between the EDs and GWs ranges from 1 to 20 km, while the antenna height is in 1-10 m and 30-200 m. COST-231 Walfish-Ikegami model referred to COST-WI [48], is a hybrid of the Walfish and Ikegami models that enhance path loss prediction by taking into consideration more variables to define large and medium-sized urban environments [49], namely the road widths, building heights, building spacing. Other propagation models were evaluated in [50], [51], [52] for the LoRaWAN use cases in urban, indoor, and outdoor environments, which are not in the scope of this paper.

2) Channel characterization: Establishing the Signal-to-Noise Ratio (SNR) threshold SNR_{th} , which is based on how to compute the receiver Sensitivity (S), is the critical component of LoRa wireless communication systems. There are different SNR_{th} for each SF that is valid in the absence of interference for accurate demodulation of received signals. Table IV shows the dependency of SNR limit to LoRa features as the SFs, DR, and the numbers of chips per symbol. The noise floor power level divided by the receiver sensitivity yields this threshold. According to the SNR threshold for each SF provided by Semtech's report, the SNR_{th} changes by 2. 5 dB for every single increase in SF. The receiver sensitivity of a LoRa transceiver using the Bandwidth BW is calculated as follow for each SF:

$$S = -174 + 10.\log_{10}(BW) + NF + SNR_{th} \tag{1}$$

Where NF = 6 is the noise figure tolerance at a GW and is fixed for a hardware implementation, while -174 dBm is the thermal noise density impacted mainly by the receiver temperature.

The CSS modulation supports variable data transmission rates using quasi-orthogonal SFs. As a result, depending on the field of deployment, the system is designed to swap DRs to efficiently enhance its transmission range or power consumption to optimize network performance over a constant BW. The symbol rate and the bit rate are given in function to the BW at a certain SF. As a result, increasing the BW by a factor of two essentially doubles the transmission rate. The

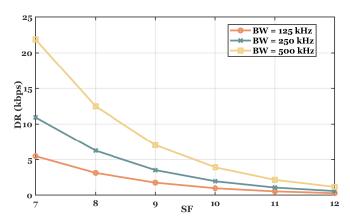


Fig. 3: Data rate versus Spreading factor for CR =4/5

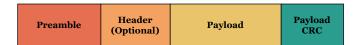


Fig. 4: LoRa frame structure

relationship between the symbol bit rate R_s , BW, SF, and the conventional bit rate R_b .

$$R_s = \frac{BW}{2^{SF}} \tag{2}$$

$$R_b = BW * R_s * FEC \tag{3}$$

Where FEC is the LoRa modem's Forward Error Correction rate, which protects against symbol errors caused by interference. Chirp rate denoted by R_c can be calculated in function of symbol rate as follow

$$R_c = BW * R_s = \frac{BW^2}{2^{SF}} \tag{4}$$

FEC necessitates the insertion of error correction bits (redundant bits) to the transmitted data. Although FEC reduces data throughput, it improves receiver sensitivity. Because the rejection gain fluctuates from 16 to 36 dB, signals from various SFs are considered periodically orthogonal. As a result, LoRa may allow up to six simultaneous transmissions on a single channel using six different adjustable SFs ranging from 7 to 12. The LoRa signals are protected from interference by adapting the coding rate (CR), such as robust system uses greater CR. Although, similarly to the SF, a greater CR value means a long packet can be transmitted using high energy consumption, such as CR takes value from {4/5, 4/6, 4/7, 4/8}. DR parameter in LoRa is calculated using the SF, BW, and CR as follow:

$$DR = SF \times \frac{BW}{2SF} \times CR \tag{5}$$

Figure 3 plots results of DR in function of the SF and the BW provided by Equation 5. It shows that high BW ensures an increased DR while increasing the SF decreases the DR due to the long transmission range of high SF.

A preamble, an optional header, the data payload, and an optional Cyclic Redundancy Check (CRC) field are all part of the physical layer packet structure (Figure 4). The preamble

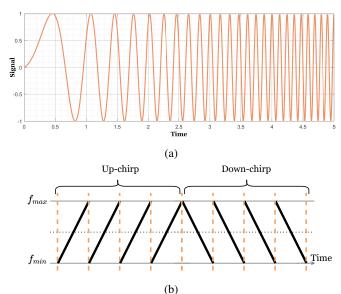


Fig. 5: LoRa chirp signal

is needed to synchronize the receiver with the transmitter, and it can be between 10 and 65,536 symbols in total. The first four symbols of the preamble are fixed, while the remaining are programmable, with a minimum of six symbols and a maximum of 65,532 symbols. The payload length, the payload CR, and the header CRC are all included in the optional header. The header's presence is determined by the header mode (explicit or implicit), and it is deactivated in the implicit mode only when payload length, CR, and CRC settings are known in advance or fixed. Consequently, the time on air of the packet decreases. In the explicit mode, the payload length in bytes, the payload FEC coding rate, and the header CRC are all included in the header. FEC is always used to secure the header, with the greatest coding rate of 4/8. The payload may contain either MAC layer information related to LoRaWAN standard or data packets [53].

3) CSS Modulation: Semtech has released the LoRa physical layer in 2014 that adopts a modulation variant of CSS [54]. CSS enables it to reach large distances while resisting interference, fading, and Doppler effects. Frequency Shift Keying (FSK) modulation may also be employed. Although FSK achieves low-power consumption, it falls short of LoRa CSS's communication range. CSS consists of modulating the information-carrying signal in the form of a series of chirp pulses and passing it through a FEC mechanism before the transmission. A chirp is defined as a temporal profile of the frequency response that shifts from one frequency f_0 to f_1 during time interval T (Figure 5a). We can distinguish two types of chirps in LoRa as shown in [55], first where the frequency linearly increases from the minimal frequency $f_{min}=-\frac{BW}{2}$ to the maximal frequency $f_{max}=-\frac{BW}{2}$ called base chirp (Figure 5b). Second is the down-chirp whose frequency shifts from f_1 to f_2 , the base chirp's complex conjugate.

In CSS, a modulator generates multiple chirps for different digital inputs, each with a distinct temporal shift from the

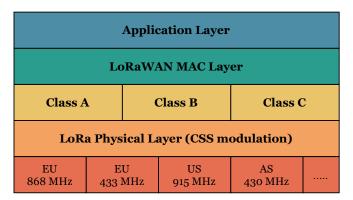


Fig. 6: LoRa technology overview

base chirp. CSS uses a sequential series of rising and falling chirp pulses to transmit data, such as chirp is a symbol, and the symbol time is the length of time between chirps. Unlike the direct sequence spread spectrum, CSS spreads frequencies using chirp pulses rather than pseudo-random code sequences. The number of bits encoded for a symbol is the SF (ranging from 7 to 12). For instance, if the SF is 7, it is feasible to send 7 bits and 256 distinct patterns over one symbol; if SF is 8, it is possible to send 8 bits and 512 different patterns. The initial frequency of the chirp indicates the values taken by the symbol. SF can be calculated based on the number of chirps N as follows:

$$SF = \log_2(N) = \log_2(\frac{R_c}{R_s}) \tag{6}$$

where $N = \{128, 256, 512, 1024, 2048, 4096\}$, and R_c, R_s are the chirp and symbol rate, respectively.

Besides modulation, LoRa communication performance may be adjusted by modifying other PHY layer configuration parameters such as the TP, Bw, SF, and coding rate (CR). Bw can take different values from 125; 250; and 500 kHz, a higher value means that packet may be sent with a high DR but for a shorter distance due to low receiver sensitivity. Greater SF implies a lower signal-to-noise ratio required to achieve reliable communication. Consequently, while the distance between transmitter and receiver grows, Bw must be lowered and SF increased to transmit longer packets at the cost of higher energy consumption.

B. LoRaWAN MAC Layer

LoRaWAN (MAC) protocol is an open-sourced protocol that works built on the top of LoRa [11] physical layer and is standardized by the LoRa Alliance Figure 6. It aims to manage the medium access control mechanism to allow communication between numerous devices and the network GWs. Devices in LoRaWAN networks access the wireless channel randomly in a pure Aloha mode, as stated in the LoRaWAN standard, and must comply with a precise duty cycle. If the hidden node problem is taken into consideration, and the listen-before-talk phase is skipped for energy savings, the Aloha MAC protocol usage will be justified [56].

1) LoRaWAN architecture: The LoRaWAN network features in a star-of-star topology [57], it is composed of three main components: network servers (NS), GWs, and EDs, which means that EDs may only connect with LoRaWAN GWs and not with each other directly as peer to peer (Figure 7). A central network server is responsible for connecting all the GWs in the network. Only the LoRaWAN GWs can deliver collected data packets from end nodes to the network server, encapsulating them in UDP/IP packets. The network server can transmit downlink packets and MAC instructions to EDs if necessary. Furthermore, communication ends at application servers that may or may not be hosted by third parties. A specific network server can support many application levels. Figure 3 depicts the LoRaWAN network architecture that resulted. Although communication is bidirectional in LoRaWAN, it is strongly suggested to communicate over the uplink. Knowing that GW collects data from the nearest EDs in its communication range, a collision may occur in receiving multiple messages simultaneously over the same channel.

LoRaWAN defines three classes of EDs [58]:

- Class A devices have fundamental features that every ED must have to join the LoRaWAN network. In this Class, each uplink transmission is followed by two short receive windows wherein the ED watches for the incoming downlink traffic to enable the bidirectional connection. As a result, the ED initiates downlink communication, pushing each downlink transmission to wait for the duration of the uplink transmission. The first and second downlink receive windows begin for 1 and 2 seconds, respectively after the uplink broadcast ends. The network server is in charge of scheduling downlink traffic and performing timing control. Because they are asleep most of the time, Class A EDs use the least amount of energy [59].
- Class B EDs provide extra receive windows to augment downlink possibilities at predetermined periods. GWs will send downlink beacons to synchronize Class B EDs and inform the network server when specific EDs listen for downlink communication. Class B devices require more power than Class A devices because they must open more receive windows, although those windows are not used for downlink communication.
- This Class C type of device has practically continuous open receive windows that close during broadcasting.
 As a result, Class C has the highest power consumption.
- 2) Standard Adaptive Data Rate (ADR) mechanism: ADR is one of the essential features of LoRaWAN, which aims to reduce the energy consumed by the EDs to transmit data while maximizing its throughput by adjusting its DR (consequently the SF as shown in Table) and the TP. ADR can manage transmission parameters at both EDs and NS sides [60]. The server developer created the NS algorithm, whereas the LoRa Alliance established the ED algorithm. EDs are responsible for deciding whether or not ADR should indeed be employed. Once the NS is turned on, it will regulate the device's transmission parameters and transmit the specified ADR commands to the ED. Also, the device should verify if the NS is still receiving its uplink frames

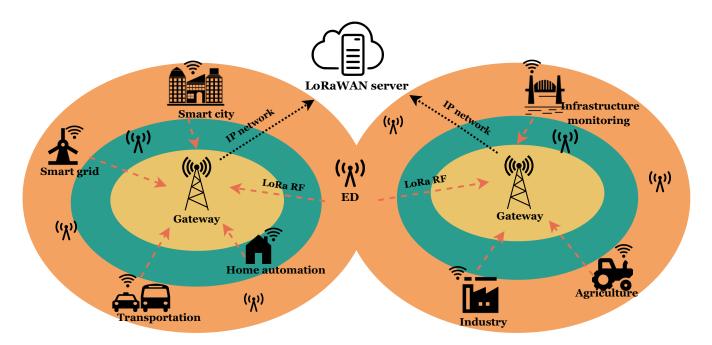


Fig. 7: Legacy LoRaWAN architecture: EDs deployed in the target area in the context of any IoT use cases such as smart grid smart city or infrastructure monitoring. Each ED uses its LoRa link to transmit the collected data into the GW, Whereas this latter forwards the aggregated data into the server via an IP network link.

regularly; if not, it should adjust its SF on its own. In a Lo-RaWAN, DR adjustment enables easy network scalability by deploying additional GWs. Moreover, ADR may significantly enhance the network capacity since the SF factor management allows the transmission of multiple packets simultaneously using different SF, which are orthogonal [61]. The ADR mechanism was designed for LoRaWAN to regulate the end nodes' transmission settings to increase the packet delivery ratio. The TP is defined for the UP-link (from ED to GW) based on the environmental conditions.

The ADR mechanism allows EDs to dynamically manage the used data rata and its TP, relying on the link budget estimated in the UL communication alongside the SNR threshold necessary for correctly decoding the received data packets at the allowed DR. The NS maintains the ADR for the fixed end nodes based on previously received packets over the UL communication, also known as "Network-managed ADR" or "Static ADR". In the case of mobile EDs, NS ADR does not function properly due to time variance of channel attenuation resulting from device movement; as a result, the ADR is performed on the side of the ED, which is called "blind ADR" [62]. Besides, ADR LoRaWAN networks may use adaptive modulation techniques with various communication channels and modem transceivers at GWs to simultaneously receive numerous messages from the channels. Every single signal adopts a different SF, orthogonally separated as enabled by the spread spectrum [63]. Under a very crowded network and time-variance channel circumstances, therefore, ADR performance will be significantly reduced [64], [65]. Furthermore, because EDs are mobile, topology changes often, affecting the link quality between EDs and a GW.

3) Joining procedure: New EDs must undergo an activation procedure to join and authenticate themselves to the Lo-RaWAN network. To this end, two-session keys are exchanged between the EDs and the NS throughout this activation procedure. LoRaWAN protocol provides two modes of activation. The first one is Over-The-Air Activation (OTAA), while the second is the activation by personalization [66]. In over-theair activation, the joining procedure is performed between the EDs and the NS to participate in the data communication process. This process consists of exchanging messages of join request and join accept. ED starts the process by sending the joining request to NS, consisting of devEUI, AppEUI, and a DevNonce. LoRaWAN uses this latter to drop some joining requests where the DevNonce is similar; by this, the system can identify some reply attacks. When the join server successfully receives the join request, a join accepts message will be sent to the ED, including the JoinNonce newly generated. Using the previous information of request message fields and Join-Nonce, Application session key (AppSKey) and Network session keys (NwkSKeys) will be created by the join server to enable device access LoRaWAN services [67]. The Application session key will encrypt data transmitted by the EDs, while the integrity will be ensured by using the Network session key. Note that those keys will be dynamically assigned to EDs at each join process, improving network security and introducing additional complexity to the join process. However, there is no need for joining in the activation by personalization process since the AppSKey and NwkSKeys are fixed and pre-stored on the EDs. The application and network keys are unchangeable regarding the activation session. This process reduces the complexity of the join process and reduces the exchanged messages to access the network while weakening the security level of the LoRaWAN network.

4) LoRaWAN versions: Different versions of LoRaWAN were released to enhance its performance in terms of security, scalability, and real-time long-range communication regarding the new advancement in resource-constrained IoT devices. The first stable version (LoRaWAN v.1.0) was released in 2015 [11]. The LoRa Alliance issued a few minor changes to the standard throughout the following years to face the growing demand for LoRa-based communication systems [68], [69]. Although there are two most critical versions, LoRaWAN v1.0.3 [70] and LoRaWAN v1.1. LoRaWAN v1.0.3 was released (in July 2018) as the most recent version that solves some problems found in its predecessors (LoRaWAN v1.0.1 and LoRaWAN v1.0.2) while also overcoming some performance restrictions in LoRaWAN v1.1 [71]. It adds some MAC commands as Beacon timing request/answer that devices can use as a substitute, also it provides support for class B devices. LoRaWAN v1.1, introduced in October 2017, aims to overcome some security issues appearing in the previous versions as the weak keys encryption and management and support some solutions to the main LoRaWAN security attacks as packet modification eavesdropping and ACK spoofing. Besides this, it supports handover roaming for resource-constrained and battery-powered IoT devices.

III. INTERFERENCE MANAGEMENT SCHEMES

The increasing number of connected IoT devices working within the ISM band makes the LoRa communication system the main focus of applications, where the high interference level is the major challenge for efficient deployment [72]. In contrast, applications operating in a controlled spectrum incur less interference since a single operator controls and dominates the QoS management task. Thus, future IoT networks designed to work with LoRa should consider the significant impact of different types of LoRa interference and the characteristics of the propagation environment. As such, a framework that estimates reliable network coverage based on real interference measurement was designed in [73] that depicts the spectrotemporal behaviour records of the shared band traffic acquired by a software-defined radio.

In LoRa-based IoT networks, the ED may transmit its source data several kilometres to the GW. Although, when considering transmission in a dense environment, multiple sources will interfere with the original signal adding noise drastically reducing the LoRa-based system's performance. Various studies evaluated this technology for long-distance communication and considered different types of interferences. The immunity region where the interference impact does not reach LoRa communication was identified in [74] through the empirical model of distance-interference trade-off. Their experiments showed that 14 dBm interference level resulted in a total packet loss. LoRa performance in terms of error probability was studied in [75] where an accurate error probability of received LoRa chirp through additive white Gaussian noise channel was estimated. Differently, the works in [76], [77], [78], [79] provide Bit Error Rate (BER) expression for both orthogonal and quasi-orthogonal LoRa signals. To identify the interference level that may influence the IoT ED deployment in the cities of Aalborg and Denmark, authors in [80] performed a measurement study through the European ISM band of 863-870 MHz. The outcome of this study identified that signals above 863-870 MHz have the probability of 22-33% of interference.

The authors in [81] discussed the limitations of the LoRa ability on providing free collision communication for a great number of devices deployed in a wide area with a low number of GWs. These devices are obliged to share the communication medium to transmit their captured data. For this reason, LoRa employs a combination of its features such as SF, BW, CR, and centre frequency. Nevertheless, a limited number of devices can be supported through the standard LoRa modulation, which presents the capacity limits of the LoRa communication system. When surpassing this limit, interference occurs in the system that decreases its performance. In this direction, a detection scheme of the inter-system interference was designed using the density ratio estimation [82]. Generally, interference facing LoRa signals were classified in two categories: cotechnology interference, where two LoRa-enabled devices transmit their data to the same GW via the same communication channel, and inter-technology ISM interference depicts the coexistence of different technology besides LoRa communicating via the shared unlicensed ISM bands [83], [84], [85], [86], [87]. In the following, we discuss various interference management schemes for LoRaWAN.

A. SF assignment

Spreading factor assignment allows LoRa to control its transmission sensitivity using an ADR scheme that manages, in addition, other physical layer parameters as TP of ED and CR. For example, a high SF corresponds to a few chirps sent per second, which means a few data are encoded per second. Therefore, a high SF allows to LoRa-enabled ED to transmit through long-distance but with high collision probability due to the low DR transmission. For scalable and fair LoRa Network, a relay control scheme was suggested in [88] for this purpose. Fairness consists of equalizing the success probability at each SF region while the scalability is allowed by multiple relay nodes using similar SF to overcome interference in dense star topology-based networks where ED communicate directly with the GWs to transmit their source data through the LoRa communication channel. The analytical model of the success probability suggested in this work to manage the relay operation considers the signal-to-interference ratio (SIR) and signal-to-noise ratio (SNR) independent factors. Furthermore, the coverage probability through the overall network and the minimum success probability corresponding to each SF region were maximized to ensure fairness. RSSI values were used in the relay selection mechanism, which helps decide whether to forward the received packet from the source ED.

LoRa performance enhancement was the target of [89], [90] by designing an efficient SF allocation scheme based on the RSSI values and the SIR. A heuristic SF allocations method was designed in [89] aimed to prove the need of assigning larger-than-needed SFs. Sequential Waterfilling was used to

design a sophisticated SF assignment scheme [90], which is an enhancement of the previous work [89] of the same authors. Fairness was ensured by equalizing the Time-on-Air of the transmitted packets using different SFs. Also, SFs across different GWs were balanced considering the channel capture effect. Stochastic-geometry was used to design a heuristic SF allocation algorithm [91] where the expression of the packet success probability was derived for co-SF interference scenarios regarding the SNR values. Similarly, success and coverage probabilities are estimated in [92] while reducing the computation complexity required to obtain these probabilities for any interference type compared to the previous work. It did not take into consideration the imperfect LoRa feature orthogonality. Fairness in terms of energy harvesting time duration was targeted in [93] by optimizing the SF assignment and the TP of all LoRa-enabled ED. The energy harvesting time and the allocated power are both optimized either for single or multiple uplinks transmission. For the first case bisection method was employed to optimize the allocated power while suboptimal power allocation was obtained using the concave-convex procedure.

Authors in [94] proposed sharing the same SF by different LoRa users for a limited time duration. For this reason, a game theory approach was employed to manage the assignment of the same SF for different ED for different time durations of the communication process in order to avoid interference between ED transmitting simultaneously via the same SF. The solution of this game consists of finding the equilibrium point where all users maximize their utilities (also called by the gain) which correspond to the minimum interference level. This kind of game is generally used to model the interaction between different players (LoRa users in our case) to find the best policy that maximizes the overall gain of our system. The mobility of ED makes the SF assignment a challenging task due to time-variance in uplink transmission properties. Authors in [95] suggested a scheme to proactively allocate the SF for each LoRa user, either static or mobile. In the case of mobile nodes, the SFs are re-scheduled based on the received signal strength from the target GW. This reduced the ToA and enhanced the packet success ratio by reducing the packet loss and retransmission. Only mobile nodes with a specific pattern were considered in the enhanced-ADR [96] to provide a dynamic allocation to minimize the packet loss as well as the transmission time of each LoRa transmitter. Authors in [97] answer the question of if a high SF is needed for robust LoRa communication over a rapid time-varying channel. They benefit from the exponential correlation of Rayleigh fading on the frame error rate of a LoRa receiver employing the CSS modulation to transmit its frame. They observed that the robustness of LoRa ED deploying high SF and transmitting over rapidly-varying channels decreases when the payload size increases. Measurement performed in [98] over a public LoRaWAN network deploying multiple GWs to receive data from different LoRa ED deployed in a medium-sized city. The aim was to characterize the communication channel by identifying the multipath fading, loss burstiness, frame length, and the FEC required for robust LoRa communication. This was employed to optimize the performance of the target

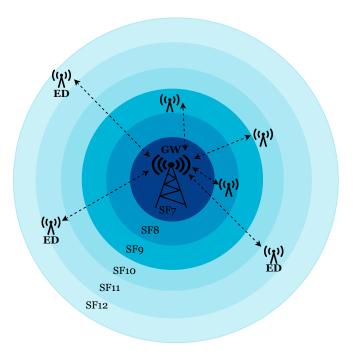


Fig. 8: SF assigned to EDs based on their distance from the GW such as nearest ones use the lowest SF to transmit their data

LoRaWAN network in terms of reliability and Time-On-Air by adjusting the SF and the number of frame repetitions. Three different sensitivity regions have been designed in [99] to characterize the immunity of the LoRa communication system against interference and the multipath fading issues. This categorization was performed based on the major LoRa features: SF, BW, and CR. The white region depicts the immunity against both interference and the multipath fading; the light-grey region means that the system is immune to the multipath issues but vulnerable to the interference. The LoRa communication system is susceptible to both phenomena in the dark grey region.

Legacy schemes assign SF according to the distance of the ED from the GW for dense LoRa-based IoT network deployments (as shown in Figure 8) such as equal-intervalbased method [100], equal-area-based scheme [101] and the Random scheme where the SFs are assigned randomly without regarding the LoRa ED location. Using the equal-intervalbased scheme the interval $[d_s, d_{s+1}]$ using this formula $(d_{s+1}$ d_s) = R_c/S where is determined using the following formula when using equal-area-based scheme, $d_s = R_c(s-1)/S$. Where R_c is the region index's coverage radius of single GW and S. Numerous works focused on analyzing LoRa performance under different scenarios including massive IoT connectivity harsh communication environment, multiple and single GWs deployments [102], [103], [104]. Contrarily to the distance-based SF assignment, authors in [102] analyze the performance of ADR, which allocates the TP and the SF based on the channel state. Keep working on singlecell LoRaWAN system restrict this study to small town or villages LoAWAN deployment scenarios. Thus, an analytical LoRaWAN model was described and validated through Monte Carlo simulations. Co-technology Interference was covered in the performance evaluation of LoRa receiver [103], the advantage of multi-hop LoRa network on ensuring wide network coverage and enhancing the indoor penetration compared to the single-hope LoRa network. This advance is due to the use of relays to advance packets into the destination, which allows extending the network capacity by using different SF to transmit to the GW or forward the received packets. In addition, the SIR required to enable SFs orthogonality was evaluated, LoRa immunity against interference resulting from transmitted time-synchronized packets by multiple ED using similar SF. Experiments were conducted [104] to evaluate the LoRa packet reception performance. A trade-off between the physical parameter and the packet reception performance was identified under a negative SNR. Packet length showed a great influence on the LoRa performance; this fact was used to design a transmission scheme that manages the reliability, transmission delay, and energy consumption.

B. Interference Cancellation

In general, based on the features enabled by the LoRa CSS modulation (SF, TP, CR, BW), a LoRaWAN GW is supposed to decode multiple superposed received LoRa signals transmitted using different SFs. Although some works showed that LoRa signals sent with different SFs are not entirely orthogonal [103], [105], this is true as long as the network density is lower than the LoRaWAN capacity defined by the combination of different physical layer parameters where LoRa can ensure reliable connectivity through the network. One of the pioneering works to suggest the use of interference cancellation is [106], where the aim was to enable efficient communication in the presence of concurrent transmissions and enhance the MAC layer capabilities. Authors in [106] explained how realistic the Interference Cancellation (IC) is and feasible in practice, though signal processing schemes should be adapted to follow these changes. A mathematical model presented in [107] as an extension of [108] that models the LoRaWAN channel access process taking into consideration the capture effect. The proposed model enhances the network capacity and provides reliable LoRa-based transmission. This is due to its accurate data transmission process description regarding the power difference of signals received simultaneously from multiple LoRa transmitters. This model has usually been used in the literature to evaluate the LoRaWAN network performance under different use cases, including the case where they consider the Okumura-Hata propagation model [109], [110], [111], [112].

Authors in [113] suggested two methods to decode the overlapped LoRa signals; the first one works on desynchronized transmitters while the second requires the transmitters to be slightly synchronized. Their performance evaluation proved that the proposed algorithms enhance the overall throughput, especially the first algorithm, which improves throughput significantly, while the second one only decodes the strongest signals. The first algorithm regarding the desynchronized transmitters consists of the following steps to decode the received overlapped frame: the receiver uses the preamble detection to detect the reception of two overlapped signals and identify the symbol frontier of each one of them. The second steps consist of comparing the updated previous frequencies and the new frequencies based on the data decoding. This comparison will help the receiver identify the transmitters and where their symbols have started. In the same direction, [125] designed mLoRa protocol implementing Successive Interference Cancellation (SIC) to decode the received frames successfully. Through experiments performed using the USRP testbed, the proposed scheme showed his capability to decode three concurrent frames received simultaneously. Likewise, [126] presented a new LoRa receiver equipped with a commercialized LoRa chip able to deal with collided LoRa signals.

Capture effect, and SIC explored in [114] build robust LoRa based system against collision to support channel sensing enable to solve this issue due to GW wide coverage area. In this context, the SIC uses the sum of received signals to identify simultaneous transmission successfully. At the same time, capture effect allows demodulating at least one signal in the presence of multiple colliding signals successfully. Both methods are used to improve the overall throughput of LoRabased systems, although good results were obtained when the power difference of the received signals exceeded some threshold. Moreover, the LoRa-based system capacity limit was studied by analyzing the results of packet reception rate in function of the network size. A commercialized LoRa chip was employed to precess collision, which makes the proposed solution [115] more realistic and suitable for implementation in an already existing network to enhance spectral efficiency. The enhanced LoRa-Like receivers estimate the time shift between them from two received signals to enable processing the unsynchronized collided signals using their Fast Fourier transform (FFT) representations. Simulation results and the mathematical expressions provided in this work showed that the frame preamble could be used to identify the value of desynchronization between the two received LoRa signals.

In the same direction, multiple works focused on enhancing LoRa-Like Receiver [116], [117], [118] to successfully decode LoRa signals received simultaneously and using similar SFs. In [116] the legacy LoRa network capacity increased by 20 to support more EDs through designing a complete receiver, including an interference cancellation scheme, channel estimation, and packet detection models. Implementation issues arise as the major drawback of the proposed LoRa receiver. Another Uplink scheme was designed in [117] using both SIC, and the particular structure of the received superposed LoRa-like signals. The proposed schemes were implemented in the GWs due to their unlimited energy consumption. As a result, the energy consumption of EDs was reduced, and their spectral efficiency was enhanced due to the low number of re-transmitted packets. Differently, [118] designed a new multiuser detector to improve the downlink in LoRalike networks. This is due to the downlink's capability to limit the number of acknowledgments sent after successfully receiving packets, which directly influences the reliability of the LoRa-based network. The designed scheme was inspired by the Non-Orthogonal Multiple Access (NOMA) [127] that

TABLE V: A summary of interference cancellation schemes against LoRa scalability issues

Work	Successive Interference Cancellation	Frame Preamble	Propagation Losses	Capture Effect	Fourier Transform	Realistic Implementation
[106]	✓		✓			✓
[107]			✓	✓		
[113]	✓					
[114]	✓			✓		
[115]		✓			✓	✓
[116]	✓	✓			✓	
[117]		✓	✓		✓	
[118]	✓	✓			✓	
[119]	✓	✓			✓	
[120]	✓	✓	✓	✓	✓	✓
[121]	✓		✓		✓	✓
[122]		✓			✓	✓
[123]		✓			✓	✓
[124]	✓		✓			

reduces the impact of LoRa network sequential transmission as well as duty cycle, and half-duplex mode. Using the NOMA technique to build the proposed scheme allowed to overcome the interference cancellation issue, namely residual error, and reduced its complexity. Furthermore, NOMA was employed in [119] to enhance downlink for CSS communication combined with a SIC algorithm in the presence of concurrent CSS signals received simultaneously. The desynchronization time was managed to assign different powers into the transmitted packets.

LoRa receiver with SyNchronization and Cancellation (Lo-RaSyNc) designed in [120] to enhance LoRa network capacity limit. This is through extending the traditional demodulation procedures by synchronizing superposed signals and adding a clock tracking scheme to the frame reception procedure. Authors in [121] address LoRWAN stability by designing a SIC LoRa receiver. This two-user detector uses the bitinterleaved coded modulation to detect and cancel the strongest interfering signal, considering both soft-demodulator and a soft-decoder to attain acceptable error rates regarding the low SNR regime of LoRa communication. Online concurrent transmissions scheme for LoRa GW [122] consists of three steps: identifying the frame preamble, detection of start-offrame-delimiter, and packet decoding using only the legacy LoRa's (de)modulation. FTrack presented in [123] adopts a technique to distinguish between collided LoRa signals using their preamble and chirp characteristics. The model built in [124] resolves collided packets jointly considering SIC and a stochastic geometry model of LoRaWAN. Table V provides a summary of interference cancellation schemes proposed to alleviate LoRa signals interference using different approaches.

C. GW Densification

GW densification arises as an effective way to face the increased IoT EDs density in the target area due to the growing interest in IoT devices, especially in the city downtown's popular, crowded urban environment. So as LoRaWAN networks resorted to dense GWs deployment, this should be performed while avoiding the huge interference between the massive IoT ED and densely deployed GWs. New densification strategies should be designed since the existing ones suggested for cellular networks are unsuitable for the LoRaWAN use case. This is regarding the advanced coordination within and between cells to manage the radio resource, which is not the case for LoRaWAN [10]. A GW densification approach was suggested in [128] through analyzing the Multi-Cell LoRa Networks to scale the LoRa network. To this end, multiple GWs were deployed for free co-SF interference in dense networks. The proposed model considers the interaction between GWs and some specific properties of the LoRa technology. The coverage and scalability of the deployed LoRa GWs were analyzed mathematically, such as homogeneous Poisson point processes employed to uniformly and randomly distribute GWs and EDs in the target area. The network performance was evaluated based on the coverage probability derived from stochastic geometry tools [129] to unveil the positive impact of GW densification on the network coverage as well as its scalability.

Coverage probability of edge EDs using one rely on node distributed randomly through the network was deeply studied in [130] under different fading models. A closed-form expression coverage probability was calculated when considering the Rayleigh fading channel, while only an approximation was computed for Nakagami-m fading channel. This study concluded by suggesting the Intelligent Reflecting Surface and

an alternative of the legacy relay strategy for LoRa networks [131]. The coverage of LoRa links under the presence of multiple GWs studied in [132] considering the interference either coming from the LoRa network itself, which is called by co-SF interference. The coverage probability of ED under these interferences was expressed based on the stochastic geometry while considering the interference coming from underlying technologies (such as the common cellular communications) as impulsive noise [133] and modeled as an α -stable distribution. The study concluded that the existence of underlying technology in the neighborhood of the LoRa network drastically reduces its coverage probability, and this impact increases when considering space GWs deployment. An ADR mechanism suggested in [134] to manage the benefit from deploying multiple GWs and using FEC to enhance the reliability of the LoRaWAN network concerning its load. Thus, FEC is defined as the Frame Erasure Rate, which is the physical loss that occurred between an ED and a single GW without considering frame repetition showed a significant influence on defining the optimal operating point of LoRaWAN networks. The proposed scheme consists of adjusting the transmission parameters of the ED communicating through a channel modeled using experimental measurement over a public LoRaWAN network in the presence of multiple GWs and FEC. The data loss ratio between the EDs and the Application Server (AS) depicted by the data error rate was derived from the proposed channel model and used to evaluate the performance of the enhanced ADR scheme.

Network densification was suggested in [135] to support firmware updates in dense LoRaWAN networks. Knowing that the firmware update is necessary for EDs to accomplish their tasks efficiently allows upgrading the EDs firmware, enhancing their functionalities, and adding more security features. Although the firmware update expanded the network lifetime and improved its performance, it's considered a challenging task due to the huge number of EDs located in remote areas requiring periodic updates of their software. A new solution has been designed in [136] for this purpose, namely Firmware Update over the Air (FUOTA), which allows performing firmware updates remotely via the wireless medium. Planing and finding the minimum number of GWs and their optimal location to increase the number of EDs covered by the network will be essential for LoRa deployment in massive IoT. Due to the impact of GWs on defining the LoRa performance, authors in [137] designed a GWs planning scheme for hybrid LoRa networks. Moreover, the GW coverage determines the SNR values and consequently the DR of EDs under its control and the overall throughput. In hybrid LoRa networks [138], GWs work on opposite frequencies in downlink and uplink to cover S-EDs and D-EDs, which are respectively the EDs working with the same and different frequencies. Hybrid LoRa network suggested overcoming the self-interference appearing in the deployment of full-duplex commercial GWs [139].

Multiple GWs deployment was considered in [140] to evaluate the performance of LoRaWAN network in Industrial IoT (IIoT), where different classes of EDs were used to ensure low cost and efficient industrial process. The analyses were performed using realistic measurement based on [141] while

covering both confirmed and unconfirmed traffic as well as a non-standard channel plan. Through this study, LoRaWAN showed its power to perform 90% of packet success rate for HoT sensing applications. Authors in [142] modeled multi-GWs LoRa networks using the Matern Cluster Process to evaluate its uplink transmission based on a stochastic-geometry framework. The Laplace transformation of the intra and inter-cluster interference was analyzed regarding the multicell topology imperfect orthogonality between different SFs. Similarly, authors in [143] discussed the LoRaWAN scalability by using the stochastic geometry framework to analyze the impact of deployment of multiple LoRa GWs on increasing the number covered ED. NS-3 simulation showed in [144] that increasing the GWs density can not eliminate all the issues related the scalability since the duty cycle restriction remains applied for GW that restricts its downstream traffic.

IV. COLLISION AVOIDANCE MECHANISMS

This section discusses various solutions in the literature to avoid collision between concurrent transmissions. The aim is to enhance LoRaWAN capacity to cover more EDs and fit massive IoT requirements in terms of connectivity demands. To this end, some works leveraged LoRa features to design various logical and frequency channels allocation schemes, while others focused on scheduling LoRa transmission. Also, numerous works inspired from the traditional slotted MAC and carrier sensing medium access methods to design new ones suitable with LoRaWAN specifications. In the following, we discuss each of these schemes separately.

A. Windowing & Channel Allocation

The severe data collision occurring during the data collection process from LoRa EDs can be elevated using multiple communication channels. Thus, devices with different traffic loads may be assigned to different channels to tackle the propagation time-variance issue. An allocation scheme of the channel and backoff windows size was designed in [145] considering both homogeneous and heterogeneous LoRa networks. The objective is to enhance the overall throughput regarding the end-to-end latency for the two scenarios above. In the homogeneous LoRa network, a single channel is considered with the same traffic loads, which means identical arrival DR, while in the heterogeneous one, multiple channels are considered with various traffic loads. The formula to derive the LoRa network capacity corresponding to the optimal packet transmission probability was defined and validated through experiments and simulations. Their scheme showed high capability in assisting massive IoT networks through ensuring high throughput and low end-to-end latency compared to the legacy LoRa network and the existing enhancement.

LoRa offers users six SFs to employ to transmit their data which means a bounded number of virtual channels are available for a specific time duration. This limited number of virtual channels restrict the number of simultaneous uplink transmission to the GWs and define the network capacity such that a maximal number of devices can transmit correctly. Packet collisions frequently occur when exceeding the

network capacity, resulting in a drastic decrease in network performance. The game theory proposed [146] to model the trade-off between the network capacity and the virtual channel allocation. The aim was to restrict the use of each SF for a limited time duration while minimizing the waiting time of EDs. LoRa users' requirement has been considered in [147], such multi-channels were scheduled to avoid collision while satisfying constraint of duty cycle co-SF interference and the users' requirement. Authors assumed perfect SFs orthogonality to achieve efficient joint channels and SFs allocation that extend the communication range and significantly reduce the packets collision.

In general, LPWAN adopts asynchronous random-access protocols as pure ALOHA in the MAC layer. These protocols are known by their high packet collision probability, where multiple nodes may send their collected data simultaneously via a similar frequency channel. Carrier sensing and centralized resource management were suggested to deal with the packet collision issue. Although the large coverage area of LoRa networks makes the carrier sensing unfeasible, the high energy consumption of centralized schemes makes this solution unsuitable for LoRa networks. Authors [148] suggested the use of machine learning to automatically manage the transmission timing and avoid unnecessary, redundant packet transmission. The proposed scheme based on O-learning does not require additional signals to manage the transmission probability and timing to avoid packet collision effectively. In the first step, nodes detected a new event using Q-learning to determine its transmission timing. Multiple nodes may perform this step when simultaneously detecting the same event. Packet collision is avoided in this step by allowing transmission time shift of the same event. The additional step, define the event packet transmission as a probabilistic process to enable the correlation of the same event transmission, which reduces the uplink load and helps in avoiding packet collision.

Besides packet collision, windows mismatching is a severe issue facing LoRa concurrent transmission resulting in high ACK retransmission sent by the GWs to acknowledge the received packets, consequently draining the residual energy of the EDs. This issue does not appear when a single ED tries to transmit its data to the GWs and successfully acknowledges the reception by sending an ACK packet during its TX windows that match the RX windows of the sender. However, when multiple EDs concurrently send their data to the GW, in this case, the GW can only acknowledge the received data when the transmission through the uplink is completed. This ACK sent by the GW will miss the RX windows of EDs since the senders switch immediately from TX to RX windows after sending the collected data and wait for an acknowledgment from the GW. After a while, the sender closes its RX windows to save energy and retransmit its data. We can deduce that the throughput does not objectively evaluate the LoRa network from this scenario. For this, goodput should be considered for LoRa network evaluation since the throughput does not necessarily include only the goodput; duplicated packets may be transmitted, resulting in BW waste and unuseful energy consumption. An optimization solution designed in [149] to efficiently manage the RX windows to improve the goodput of LoRa concurrent transmission while considering the reception probability of downlink transmissions.

In [150] the authors' designed resource assignment schemes for different LoRa use cases such as smart homes, smart healthcare, smart metering, and smart agriculture to improve the network capacity. It leverages the SFs orthogonality and multi-channel structure. The space defined by channels and SFs is divided into multiple resource blocks used by EDs to transmit their data simultaneously without collision. Distributed scheduling was used for resource assignment while considering a realistic propagation model covering both indoor and outdoor environments (rural and urban). Logical channels modeled in [151] using both BW and SFs to reflect the SFs orthogonality and the bite rate difference. Each BW and SFs pair depict a logical channel with a different R_b due to the chirpiness. Furthermore, a logical channel assignment scheme inspired by the minimum weighted sum bin packing problem was suggested to reduce the energy consumption and response time for LoRa-based massive IoT networks. Authors in [152] described an adaptive LoRa sub-band allocation policy, which consists of assigning different adjacent channels of 125 kHz to the EDs located at the edge of SF regions-knowing that LoRa BW of 1 MHz can be splitter into eight different subband of 125 kHz considered in [152] as adjacent channels. The evaluation of this policy was performed statistically in terms of error, rate distribution, and power consumption for a LoRa network where EDs and GWs are deployed in the target area following the random Poisson Point Process [153], [154].

B. Beyond Star Topology

Traditional LoRa networks adopt start topology to connect EDs deployed around the GWs, restricting its coverage area and limiting its capacity for covering more EDs. Multihop communication can be considered based on the LoRa features to manage direct device-to-device links to cope with this issue. Such as, the SFs not only provide flexibility in terms of DR and sensitivity but also give another dimension to the channel multi-access. Using this new dimension, authors in [155] focused on improving the LoRa network capacity through adopting multi-hope communication where the data traffic is off-loaded into multiple subnetworks. In this scheme, paralleled transmission is realized by clustering EDs based on the SFs, such as each subnet uses separate SFs to communicate its data (Figure 9a). The clustering is performed taking into account the connectivity between subnets, keeping a balanced traffic load due to the SFs asymmetry, and finally minimizing the hop count to decrease the transmission airtime. The Bottom-up Breadth-First-Search algorithm was used to extract farthest nodes from the root and Top-down Breadth- First-Search to insert them into a new sub-tree [156].

Either by keeping the baseline star topology of LoRa, clustering was considered in [157] to build a reliable LoRa network with low energy consumption. Such as K-mean clustering scheme was proposed for SFs allocation in large-scale LoRa network using a single GW. Fairness was ensured in both performance, and SFs usage, such as minimal difference showed in the performance of the worst- and the best-case

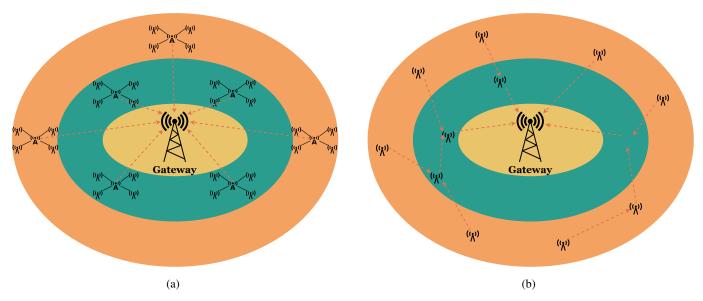


Fig. 9: Beyond star topology: (a) EDs grouped into cluster only the cluster head communication the collected data to the GW via LoRa communication link (b) EDs use multi-hop communication (instead of peer-to-peer communication adopted in legacy star topology) to extend their transmission range and transmit collected data to the GWs

nodes, which fairly distributed the energy consumption between nodes, consequently increasing the network lifetime. On the other side, SFs are equally used through the network. Different from the existing study where the SF areas were defined based on constant steps distance from the GW [100], [109], Distinct numbers of clusters with maximum range were adopted for used distinction. In [158] LoRaWAN packets were collected and processed for profiling and grouping IoT EDs to improve LoRa-based technology operation and ameliorate network anomalies detection. Specifically, the K-means algorithm was used for clustering the IoT EDs based on their behaviors and the operations performed over the networks. Machine learning tools were deployed to provide accurate profiling based on the collected data from EDs connected to the LoRaWAN network.

Based on the LoRa features, LoRaWAN coverage can be expanded at the expanse of low throughput and increased energy consumption. Multi-hop communication was used [159] to ensure simultaneously high throughput and large coverage (Figure 9b). LoRa modulation capabilities define the layers radius, where the network is partitioned into multiple layers; each layer is composed of multiple operational GWs. Since the traditional LoRaWAN network does not support layering, multiple messages should be defined to be exchanged between the GWs and EDs to incorporate the proposed functionalities. LoRa transmission parameters were clustered in [160] based on the QoS performance in terms of bit error rate, ToA, and RSSI to deal with the heterogeneity of IoT applications requirements. As such, a set of transmission settings providing similar QoS were grouped into the same cluster that can be used to adapt the wireless communication link regarding the IoT applications requirements in terms of the QoS metrics as mentioned earlier. To this end, a fuzzy C-Means clustering scheme was used to cluster random transmission settings. Priority scheduling technique [161] proposed to be implemented in LoRa GWs in order to group EDs based on the transmission priority. This scheme was built based on the unsupervised learning algorithms that allowed the GW to schedule the transmission of EDs regarding the corresponding cluster. The aim was to help scale up the network density by avoiding collision, consequently reducing the transmission delay and the energy consumption resulting from continuous retransmission attempts.

Fairness in terms of the throughput was sought in the clustering scheme of [162] where nodes are grouped based on the maximum served traffic using the two commons classification methods, namely K-means and FOREL. In addition, the throughput distribution in clusters was modeled to provide an accurate estimation of the real throughput capacity in each cluster. Knowing that the EDs communicate their data to all GWs among their ranges thus increases useless energy consumption resulting from the redundant transmission. The impact of the cluster range, EDs transmission range, as well as network density, was studied in [163]. Where the clustering was proposed to avoid redundant transmission in dense networks to reduce the energy consumption and increase the network lifetime. The proposed seek the shortest multipath route that connects the EDs to the GW and consequently to the cluster head. LoRa multi-hope network suggested previously in [164] to enable concurrent transmission and build robust and efficient LoRaWAN network while considering the LoRa physical-layer standard. Network slicing alongside softwaredefined networking was combined [165] for enhanced network configuration for large-scale scenarios, where LoRa parameters are tuned to provide for each virtual network slice an optimized QoS threshold. LoRaWAN adopting slicing architecture showed promising results through NS-3 simulation in terms of reliability with respect to the QoS thresholds in dense networks. Hybrid deployment was also used to enhance the LoRaWAN network capacity [166], [55]. In [166]

ANT technology [167] was enabled alongside the LoRa to enable short-range and ultra-low power communication for data gathering in ultra-dense LoRaWAN networks. At the same time, Interleaved Chirp Spreading LoRa based modulation was introduced in [55] to work in parallel with the standard LoRa modulation.

C. Carrier Sensing

The ease deployment of LoRaWAN networks as specified in [60] aim to ensure the coexistence of multiple networks as well as thousands of EDs based on the features provided by the LoRa physical layer, such as multiple logical channels and the SFs orthogonality. Although, regarding the set of features, LoRaWAN remain in the category of ALOHA protocols which are well known by their limitation as shown [168]. Moreover, long-range communications are known for their low throughput (about 100bps- 30kbps), and the large time-on-air transmission of the transmitted messages. Thus, play a key role in increasing the collision probability between concurrent transmission in addition to the limitation of the duty cycle regulation imposed on the LoRa communication. Low-cost LoRa testbed experiments were performed in [169] to analyze the impact of using the carrier sense mechanism on reducing collision between simultaneous transmissions. The comparison between the real-world testbed measurement and simulation results obtained by the NS-3 simulator showed that the use of CSMA to enhance LoRaWAN in terms of collision avoidance paid in the increase of energy consumption [170]. However, in dense network deployment, the legacy LoRa network presents significant energy consumption compared to CSMA while this latter increases the overall throughput taking advantage of the limited European Telecommunications Standards Institute duty cycle restriction [171].

Authors in [172] investigated the use of a listen-beforetalk mechanism to enhance LoRaWAN channel utilization and efficiency due to its ability on deciding whether the channel is idle or used, which reduces the collision between simultaneous transmission using the same SF and transmitting via the same channel. Modified versions were designed for this purpose, namely the Binary Exponential Back-off (BEB), Binary Exponential Delay, and Binary Exponential Hybrid, which combine the two previous algorithms. These algorithms were used to model the interaction between the channel activity detection scheme and the data transmission. Numerical results showed that BEB has the minimum energy consumption during the channel activity detection process and significantly decreases the collision rate. An advanced CSMA/CA variant was suggested [173] to ameliorate LoRa IoT network experience in the context of smart city applications. It includes some specifications of this kind of application, and a per cent of hidden nodes was considered, which showed promising results regarding various sensing ranges. This can help with LoRa based IoT deployment by anticipating the CSMA performance under the considered environment conditions.

Practical viability of carrier sensing has been provided in [174] for the LoRa-based wildlife monitoring network. By evaluating the proposed channel activity detection scheme

considering both laboratory and field conditions, the authors observed that the payload symbols and the preamble remain detectable until 4 km away from GW. Moreover, performing the channel activity detection eight times during payload frame time can ensure a clear channel assessment, reducing the collision rate. Hybride MAC protocol based on slot scheduling and multiple listen-before-talk (mLBT) is designed [3] to deal with data loss resulting from collision and signal suppression. The aim was to cope with these issues facing efficient deployment of LoRa-based industrial systems. Knowing the reference LoRaWAN architecture composed of EDs collecting data and the GW is playing the role of relaying node between the EDs and the application server. In the proposed scheduling scheme, EDs transmit their data during the data acquisition cycle times, also referred to by frames composed of multiple time slots. A logical slot index was assigned to each time slot in the frame to facilitate the scheduling task and help EDs to respect their data transmission time constraint. Distinct SF and frequency channels were assigned to different sets of EDs that are grouped regarding the signal attenuation degree to remove interference between them. In addition, mLBT was used to help avoid transmission via a busy channel by performing multiple times the channel activity detection during the same time slot. Packet delivery rates superiority of the proposed scheme regarding the existing approaches was shown analytically and experimentally.

A cognitive model was suggested in [175] to ensure efficient multiple access in LoRa-based IoT networks, where the interaction related the parameters of the user traffic to the quality of network operation was modeled analytically. To this end, the heterogeneous users' conditions were considered when tuning the network parameters regarding bit error probability. Authors in [176] performed extensive real-world experiments to design a reliable, clear channel assessment procedure which is an essential component of the CSMA mechanisms. Experiments were performed to understand the concurrent transmission mechanism at the MAC layers for LoRaWAN dense configuration and leverage the capture effect and channel activity detection properties. Cognitive radio was considered in [177] to assist LoRa based IoT applications where EDs cooperate with each other to reach a decision on the primary user status with the help of a fusion centre and performing the spectrum sensing. Additional energy will be consumed during the spectrum sensing and reporting to efficiently monitor the primary user status, which requires the development of a new scheme to manage the data exchange between these EDs. This motivates the authors in [177] to design a new protocol that defines the nodes that are eligible to perform the spectrum sensing efficiently based on their residual energy.

D. Slotted MAC

Multiple solutions were discussed above to enable decoding collided LoRa signals either by using the channel allocation or the carrier sensing. These solutions were proposed as alternatives to the pure ALOHA medium access mechanism adopted by LoRaWAN, which suffers in terms of scalability. Frequency or logical channel allocation mechanism was suggested to

avoid collision between concurrent transmission such as each EDs use a different frequency channel to transmit its data or either by using the logical channel defined by the combination of LoRa features such as the SFs, BW and so on. This solution solved the problem of concurrent transmission in dense configure in terms of energy efficiency, end-to-end delay, and packet delivery rate. Due to the limited frequency and logical channel possibilities, this solution performs well for a LoRaWAN network capacity under a threshold related to the number of allowed channels. Carrier sensing was also proposed to allow the EDs to sense the medium before transmitting their data, which helped reduce collided transmission. However, additional energy will be consumed to perform sensing, which is not beneficial for the LPWAN network composed of batterypowered EDs. In this section, we will discuss another solution to overcome the issues of LoRaWAN scalability, which is the slotted MAC protocols.

Authors in [178] propose an analytical model to evaluate the performance of pure ALOHA alternatives such as slotted ALOHA (S-ALOHA) and non-persistent carrier-sense multiple access in terms of throughput and energy efficiency while capturing the LoRa physical layers characteristics. The aim was to emphasize the impact of these random access mechanisms to improve the throughput of LoRaWAN networks regarding the energy consumption and LoRa modulation properties in the existence of interference. Thus, the proposed model can be used to design a random access mechanism for different LoRa network scenarios. A method to decode superposed LoRa signals was suggested and integrated into the MAC protocol [179] that allows retrieving the entire frame from desynchronized signals without any loss. Beacons and slotted MAC were used to alleviate the issue of desynchronization and allow multiple EDs to transmit simultaneously using the assigned slots. In the case where the proposed method cannot decode some LoRa signal frames, a CRC decoding scheme was used to cope with that issue.

Even though slotted MAC protocols have been broadly investigated in the literature for decades and many real-world applications depend on them, the distinctive characteristics of LoRa PHY layer characteristics, as well as the duty cycle restrictions imposed in sub-GHz ISM bands, render the design of new Time-Slotted MAC layers suitable for LoRa networks a difficult problem. Authors in [180] discuss the specific LoRa characteristics that should be taken into account when designing time-slotted MAC protocols, and they summarize the current enhancement in this field. A timeslot scheduling scheme that captures the requirement of LoRaWAN-based machine-type communications was presented in [181] for massive deployment to increase the number of EDs that can transmit over a single GWs. The proposed scheme does not require additional downlink transmissions and the synchronization between the EDs and the GW while considering the particular characteristics of the network such as multichannel diversity, quasi-orthogonal DRs, and the periodicity of traffic. A new decoding scheme was incorporated into the slotted MAC protocol [182] which allowed decoding symbols of multiple colliding frames. This decoding scheme compares symbols at each subslot (instead of each symbols' end), increasing its ability to decode collided frames. Besides the decoding scheme, the proposed slotted MAC protocol includes retransmission management.

The use of time-slotted MAC protocols results in the overhead of synchronizing and scheduling the transmission, which can be easily afforded regarding the duty-cycle restrictions imposed on LoRaWAN and the availability of downlink communications. To deal with these overheads, authors in [183] suggested that EDs autonomously manage their transmission and self-organize the position of their slot in the frame. Moreover, a single slot in each frame is reserved to ensure synchronization and acknowledgments. The aim in [184] was to equalize the success probability over the EDs distributed in the network using a S-ALOHA mechanism to transmit their data regardless of the used SF and the location of the source node. In order to efficiently manage resources of uplink communications in slotted MAC protocols, LoRa EDs synchronization was proposed in [185] using the out-ofband time-dissemination. The experimental approach in [186] was based on a central entity to assign slots and ensure the synchronization between EDs. Such as, the slot length in the frame was determined using the real-world measurements of the clock drift.

Authors in [187] showed that S-ALOHA could be deployed on top of the traditional LoRaWAN without the need for any changes using a new distributed synchronization approach. An adaptive medium access scheme was designed in [188] to ensure the best link quality between the EDs and GWs. This is through adapting LoRa physical layer parameters and leveraging the coordination ability of beacons regarding the duty-cycle restrictions for both EDs and GWs. A new MAC protocol was designed in [189] to enhance collision avoidance between concurrent transmission and leverage fairness through adopting GWs that periodically broadcast beacon frames to synchronize and coordinate between nodes. For reliable networks, the proposed protocol allow EDs to transmit randomly over a specific available channel using different DF value based on the scheduling information included in the beacon frame. Due to the limited EDs-GWs connectivity time availability of GWs and the limited number of GWs in the networks, transmission of collected data should be scheduled to capture the windows availability of GWs. A time-slotted transmission scheduling scheme was designed in [190] to efficiently optimize the data transmission time regarding the issues mentioned above related to the LoRaWAN architecture.

V. USE CASES/APPLICATIONS OF LORAWAN

Due to its power in enabling long-range communication with low power consumption LoRa communication systems have been widely considered for diverse applications related to IoT devices. It allows establishing a smart system as a smart building, smart grid based on battery powred IoT devices requiring a low DR operating with low computation capability. In addition, it is considered for space to ground communication purposes due to its long communication range and its immunity to different signal propagation drawbacks as the doppler effect and path loss. In this section, we

survey the latest use cases of LoRa communication systems, such as applications domains are distinguished into four categories: LoRa-Based localization systems, Smart-to-ground LoRa- based communication, smart building, and environmental monitoring.

A. Space-to-ground communications

LoRa has been proposed in the last few years as a leading technology enabling wireless network service in space due to its power in providing long-range communication and the great interest of the research community to establish Low Earth Orbit (LEO) satellites (Table 10). Unlike the enormous traditional satellites, nanosatellites weighing only 1–50 kg can be launched on the LEO around 2000 km from the ground. The number of these nanosatellites launched to LEO has known a considerable increase recently due to the achieved advancement in computer and electronics technologies. Instead of developing their satellite communication (considering all the protocols settings and the RF modulation used to enable robust space to ground communication), LoRa has been deployed to build wireless network service in space to allow easy and low-cost management of these nanosatellites. In [191] authors designed a high-quality wireless network in space to connect ad manage these nanosatellites from the ground via internet connection. The study provided in [192] analyzes the performance of the newly launched 3U Cubsat called by Satish Dhawan Satellite that carries a LoRa transceiver in terms of resistance to Doppler shift packet loss.

The adaptability of LoRa for LEO satellite Internet of Things deployment is analyzed in [193], according to its characteristics, including LoRaWAN architecture, the activation mode of LoRa nodes, the mechanism to access the communication channel as well as the used BW. In addition, some enhancements were proposed to deal with these inapplicable characteristics. Doppler effect on the LoRa modulation adopted for ground-to-space communication was presented as a major issue facing the advancement of the CubeSat industry. Multiple works deal with this issue [194], [195], [192], Authors in [195] identified the doppler frequency shift resulting from the high speed of these nanosatellites passing over the ground station. This study consists of a laboratory experiment of the LoRa modulation under similar conditions to Cubsat flaying in LEO to ground communication. The aim is to study the immunity of LoRa modulation against the Doppler effect in such conditions. Simulations in [196] obtained that the maximum Doppler frequency shift that occurs in LoRa communication in LEO Cubsat is about 22kHz, while the maximum Doppler rate can go until 270Hz/s. Another fact was obtained, 100% packet error rate was reached when using a SF of 9, whereas Doppler-rate significantly increases.

In the same way, additional outdoor experiments were conducted in [194] to study the usefulness of LoRa communication technology in LEO CubeSat radio communication systems. These CubeSats flaying 550 km orbits endure satellite-to-Earth radio channel destruction due to rapid change of the Doppler effect frequency shift. This destruction appears clearly when the nanosatellite located directly above



Fig. 10: An example of LEO satellite used as GW for LoRabased smart farming, where EDs deployed in the target area transmit their collected data using LoRa communication into a CubeSat flaying in low earth orbit.

the ground station uses a spreading faction of 12. The orbit altitude greatly influences the communication session duration, as concluded by this study. As explained previously, GWs are one of the critical components of a LoRaWAN network; in this context, authors in [197] suggested the use of ZYNQ SOC to build a space GW for space-based IoT communications to fit the non-operating system requirements of the nanosatellite, knowing that this chip serves as software, hardware, and I/O programmability. Different LoRa device configurations were evaluated in [198] to identify the most suitable one that meets the space-to-earth channel requirements. Moreover, Software-Defined Radio experiments were conducted to evaluate the performance of LoRa modulation under such harsh conditions regarding the ionospheric scintillation effect.

A set of IoT devices may be under the coverage of a satellite constellation which imposes the need for designing efficient access methods to the ground-to-space channel. To this end, an intelligent strategy has been designed in [199] named Intelligent traffic load distribution. Erasure probabilities employed in this strategy enhance the overall throughput of the system through managing the traffic load allocation for different LEO constellation positions regarding the IoT clusters. As studied in [200] access strategies to LoRa multi-channel should deal with the Doppler effect CubeSat radio communication. In this work, LoRa immunity against the Doppler effect has been studied through both simulation and laboratory experiments to

identify the applicability of LoRa modulation under such harsh conditions. Sparse satellite constellation allowed in [201] using some specific LoRa configurations as maximum clock drift feature of LoRa devices, in order to reduce direct-to-stellite IoT communications. Another point that should be considered when focusing on the communication between IoT devices and GW on satellites is the security and preservation of the privacy of transmitted data, especially when we know that most use cases of this system rely on critical infrastructure. A security scheme suggested in [202] based on the Advanced Encryption Standard (AES) to secure the transmitted data into the private LoRaWAN-server via satellite GWs.

LoRa receiver designed [203] for IoT devices in remote areas such as islands or mountains transmitting and receiving data from CubeSat; the receiver is equipped with SX1276 chip used to process the received passband signals. Low R_b allowed using SF 7 and 12, respectively, equal 5468.750 and 292.969 bps. Due to the insufficient space allowed by the CubeSat geometry to embed a LoRa antenna, with respect to the dependency between wavelengths and the antenna size, authors proposed in [204] planar antennas. In this latter, both the meander line and the ground plane are placed on the same side. Authors in [205] suggested benefiting from rocket debris of various Polar Satellite Launch Vehicle (PSLV) that are revolving in different space orbits in order to build a low-cost and flexible software-defined networking platform. Instead of destroying the PSLV rocket and throwing it into the ocean, PS4 PSLV Stage 4 keeps this debris in its initial orbits, weighing around a tonne. This work aims to enable inter-PS4 and ground-to-PS4 communication through LoRa technology. Performed simulations showed the feasibility of the proposed network to ensure high connectivity besides the enhanced throughput. LoRa-based CubeSate design and challenges were the focus of [206], [207], [208], such as in [206] radiomeTry and vegetation Analysis (RITA) payload with a customizer LoRa transceiver were integrated to 3U satellite. While in [207] authors analyze the NORBY CubeSat nanosatellite launched into LEO on 28 September 2020. The Internet of Space Things (IoST) based on CubeSats to enable low-cost global connectivity was introduced in detail for the first time in [208].

B. LoRa-based localization systems

An experimental study was conducted in [209] to evaluate the efficiency of different wireless communication techniques to perform indoor localization. This study covers Bluetooth Low Energy (BLE), Wi-Fi, and LoRa considered the most suitable communication technique for indoor locations due to low energy consumption. However, an efficient localization system should be robust and cost-effective and provide a real-time and accurate localization decision. Based on the outcome of this study which used the RSSI to calculate the coordinates of nodes, Wi-Fi is the best technique to provide an accurate localization, while BLE is the worst one. Between them, we find LoRa communication systems that localize devices with an average error of 0.62 m. The RSSI-based localization system faces many problems in providing accurate localization

in the outdoor environment, such as signal fading related to the land-cover types or labor-intensive. To face this, authors in [210] used satellite images with high resolution to manage path loss by identifying different land-cover types using collected images of the target area. By profiling the environmental parameters, SateLoc allows the cooperation of multiple GWs to provide a highly accurate outdoor localization with an error of 47.1 m. All the localization schemes discussed in this section are summarized and classified in Table VI.

Localization algorithms can be categorized into two categories as explained in [211], the first is range-based algorithms where the RSSI value received from the GW can be converted to a distance using a specific path loss model. The combination of ED distances from GWs help in calculating its localization. Second, fingerprint-based algorithms in this category location of ED is approximated by comparing the current RSSI values of the device and the previously collected RSSI values of known locations. This approximation can be provided using some machine learning models trained on labeled RSSI datasets as shown in [211]. In a rangebased localization algorithm, several methods can be deployed to provide an accurate location of devices as proposed in [212] where time difference and Angle of Arrival (AoA) are combined for time-based localization. The first one relies on propagation time to determine the coordinates of devices, while the other uses the RSSI values received from multiple GWs and calculates the corresponding angles of arrivals to provide a location estimation of the ED. As demonstrated in this paper, the combination of these two methods requires only the use of two GWs to achieve an efficient location with a mean estimation error of 339m for Line of Sight (LoS) signals and 159m for a Non-Line of Sight (NLoS). On the other hand, filtering algorithms such as Bayesian and Kalman filters can be deployed to build an efficient, stable, and accurate localization system. These filters can aide-localization system in providing a more accurate location by solving LoRa indoor localization problems as the ranging error caused by multipath as discussed in [216] where a new particle filter was designed to cope with Lora pseudo-range fitting. The authors in this paper provide a fingerprint of ED using a real LoRa round-trip time (RTT) measurement and adopt the cumulative distribution function (CDF) criteria to calculate the quality of the estimated location by comparing it with the ground truth. The AoA of the received signals has been estimated in a real-life urban environment by developing a complete system composed of hardware and software solutions [217]. This work aims to estimate the AoA from the received signals, which are highly correlated using a space alternating generalized expectation-maximization algorithm. This system estimates the AoA of the received signal for both LoS and NLoS with an average error respectively of 2° and 10°. LoPy and FiPy are two low-cost LoRa devices used in [218] to build a low-cost local positioning system based on the RSSI to fit some IoT applications requirements that are not allowed by the Global Positioning System (GPS). These applications require the deployment of multiple small resource-constrained devices. The proposed system benefits from Pycome radio frequency capabilities were evaluated in an outdoor rural

TABLE VI: Performance comparison of the recent LoRa-based localization systems

Paper	Year	Environment	Technique	Performance	Evaluation	Advantages	Drawbacks
[209]	2021	Indoor	RSSI range- based	Wi-Fi, error = 0.54m BLE, error = 0.82m LoRa, error = 0.62m	Experiment	Provides a comparative of LoRa, Wi-Fi and BLE-based localization systems	Unfair comparison since the use case of each one should be considered
[210]	2020	Outdoor	Satellite images, fingerprint	Error = 47.1m	Dataset [213]	High potential on performing large-scale tracking	Needs more real-world evaluations
[211]	2020	Outdoor	RSSI, range based and fingerprint	Range-based error = 700m Fingerprin- based error = 340m	Dataset [214]	Efficient GWs selection strategy	Localization in a predefined area
[212]	2020	Outdoor	TDoA, AoA range-based	LoS error 339m, NLoS error 159m	Simulation [215]	Combaning TDoA with AoA using only two GWs	Should include more synchronized GWs
[216]	2021	Indoor	Round- Trip Time, fingerprint	LoS error = 1m	Experiment	Use of particle filter to deign a LoS and CDF to evaluate its performance	Should focuse on pseudorange correction for NLoS
[217]	2021	Outdoor	AoA range- based	LoS error = 2°, NLoS error = 10°	Simulation	Provide an accurate esti- mation of the AoA in an intensive multipath en- vironment for LoS and NLoS	Restricted study to LoRy systems
[218]	2020	Outdoor	RSSI Range- based	LoS error = 7% of max distance	Simulation	Use of LoRa Pycom RF capabilities	Study restricted to LoPy and FiPy devices
[219]	2020	Outdoor	RSSI range- based	Error about 40-60m	simulations	Operate also in indoor environments (playgrounds, or shopping malls)	Machine Learning can help on improving system performance
[220]	2020	Outdoor	RSS, PL range-based	Error ≤ 90m	OMNeT++	Enhance emergency request deliverance using multi-hop communication	Phone dependency. Simula- tion always shows optimistic results, need for some exper- iment
[221]	2020	Outdoor	PL, range- based	Error ≤ 60m	measurements assessed by simulation	Design PL model for a challenging environment	The low number of devices monitored simultaneously
[222]	2021	ndoor	RSSI range- based	Wi-Fi, max error = 1.12m LoRa, max error = 4.63m	Experiment	Suggest PL model for indoor environment	The study focused on particular indoor environment
[223]	2021	indoor	LoRa Backscatters	Accuracy = 89.7%	Simulation	provide 3D localization	Real data can improve
[224]	2019	Indoor, outdoor	RSSI	Error = 70.41m	simulation, real experiments	Proposed model cover indoor and outdoor	Adopt basic localization algorithm

environment and showed an average error of the estimated position around 7% of the maximum distance between ED.

LoRa-based localization systems can be designed for critical applications such as Search And Rescue (SAR) operations which require fast localization of persons involved in accidents in a harsh environment. Some standards exist for SAR missions in snowy environments such as ARVA and RECCO, though these standards suffered from their limited radio range. Their limited performance motivated the research community for seeking an alternative that offers a long communication range with an extended lifetime. For this purpose, multiple research works have been published in the last few years. Authors in [219] proposed to analyze the behavior of the

LoRaWAN channel while using trilateration methods and the RSSI values to provide the localization of the target person in the concerned area with an error average between 40–60 m. The author in [220] focused their efforts on the mobile emergency management system that allows people to send emergency requests from their own mobile to rescue teams. Although the pervasiveness of these devices, LoRabased localization is needed to support the effectiveness of mobile-based rescue systems in critical scenarios. Emergency requests sent from mobile can be forwarded by multiple peers equipped with LoRa transceivers using BLE until reaching the rescue teams. This process increased the probability that a request message was successfully received at its destination,

taking advantage of LoRa interference immunity and long communication range. This model implements the LoRa-based trilateration technique and uses path loss measurements to provide an accurate GPS-free localization with an average error of less than 90m. A radio path loss model has been developed in [221] based on real path loss measurements in a harsh mountain environment in order to estimate the coordinates of a lost hiker either in the bottom of a canyon or on the top of a snowy mountain. This study showed that localization systems based LoRa path loss estimation outperform the existing ones in this field, namely ARVA, by achieving a five times longer radio range.

The exact location of objects is not always required, especially in some indoor localization systems. In this kind of application, we need only to know in which place, room, or hall the object is present, which tolerates a considerable estimated error range. In this direction, the author in [222] suggested a 2-phase cell localization algorithm based on the LoRa trilateration algorithm, which consists of finding out the cell location in which the target object lies. The first phase begins with the analysis of the path loss exponent of all the anchor nodes using the received RSSI value, while the second phase consists of devising the target space into virtual cells to determine the cell where the object is present. Two wireless channels are considered in this study, Wi-Fi and LoRa, where the proposed method showed a mean error of 1.12m and 4.63m. A LoRa Backscatters-based room level localization system was designed in [223]. It uses LoRa transceivers to transmit an RF signal by modulating the received one. This system comprises multiple LoRa receivers deployed in different rooms, a LoRa transmitter in a central point (reference point), and the backscatter device carried by the object. In order to determine the position of the LoRa backscatter devices, the RSS values are compared between all the receivers, while machine learning is used to enhance the system's performance. Based on the linear discriminant analysis, this system achieved a localization accuracy of 89.7% in a real-life scenario. Multiple algorithms of localization based on the LoRa RSSI values are proposed in [224], in order to face the issue of Gaussian and non-Gaussian noises by reducing their impact on the localization accuracy. Through simulation and real experiments, this model showed its ability to perform well either in the indoor or outdoor environment.

C. Smart building

Smart building is the newest application field of LoRa communication systems to enable efficient IoT devices connectivity inside crowded buildings. Supported by its interference immunity, low cost, and easy deployment, LoRa is becoming the leading technology in this field. A comparison study provided in [225] showed the high capabilities of LoRa to enable school monitoring compared to IEEE 802.15.4 wireless technology. Besides the low-cost IoT deployment, LoRa was implemented on Arduino-based hardware to build robust and reliable monitoring systems due to its low energy and random MAC protocol. The authors in this work provided a rich dataset produced from 6 different school buildings

using 49 devices. LoRa communication technology has already been proposed as a part of smart healthcare systems [226]. It enables patient tracking inside a hospital composed of multiple buildings connected via underground tunnels. Intrahospital transport of patients, especially those accepted in intensive care units, is one of the major challenges facing the efficient deployment of the internet of medical things. Patients, in this case, require periodic transportation between different units inside the hospital buildings for diagnostic reasons. Consequently, knowing their location is a major key for efficient transportation and coordination between units evermore a challenging task at huge hospital infrastructures.

Advanced meter infrastructures make our building more intelligent; it helps design smart buildings throughout, allowing efficient and intelligent electricity power consumption. Authors in [227] designed a LoRa-based architecture to manage the electricity power intelligently inside a residential grid and evaluated their system regarding different factors such as energy efficiency, packet delivery ratio, and throughput. This architecture is based on the ADR features of the LoRaWAN network to face the system's dynamic behaviour and get benefits from a scalable LoRa network. The study consist of knowing the right place to put GWs for cost-effective and efficient deployment. LoRaWAN is used in [228] as a low-cost infrastructure for electric vehicles to gride communications in smart cities. It is proposed in this kind of application due to its long communication range and its ability to reduce power consumption either by allowing efficient coordination between the electric vehicles and the corresponding aggregators or by enabling low-cost communications between different nodes.

LoRaWAN network has been suggested to develop highly critical applications, namely indoor air quality [229]. Precisely it is integrated into Radon Risk Management in public buildings with high density knowing that Radon is a natural radioactive gas classified by the World Health Organization (WHO) as the most dangerous gas that can cause lung cancer. The Radon gas naturally occurs and accumulates inside the indoor environment as the school, which makes LoRaWAN plays a crucial role in reducing public health risks associated with this pollutant. Another critical use case of the LoRa communication system is monitoring Elderly People and following up on their health conditions, especially those isolated for Covid-19 infection. The proposed system in [230] integrates low-cost devices for data processing and communication, connected to the IoT network via LoRa communication. Various sensors are incorporated into this system to collect critical data that allow the authorized entities to have real-time information of system users' health and their urgent needs. In addition, sensor networks can be employed to monitor Elderly people using LoRa GWs for cost efficiency.

D. Environmental monitoring

LoRa technology is often used for monitoring harsh environmental conditions as part of smart cities systems, taking advantage of its large coverage and low transmission rates (low energy consumption). Furthermore, it adapts its SF and DRs to fit the communication environment conditions, consequently

dynamically managing the link quality. Authors in [231] used RSSI, Signal to Noise Ratio (SNR), and packet delivery ratio to study the propagation of LoRa signals in urban, suburban, and forest environments for a mobile node scenario. Monitoring the wildlife and integrating it into smart agriculture are the recent use cases of the LoRa communication system [232]. A design of wildlife monitoring system was provided in [232] for IoT animal repelling devices; the aim is to overcome the issues appearing when incorporating cellular and shortrange wireless technologies for this kind of application. In this study, RSSI values, SNR, and packet delivery ratio are used to characterize the communication link to evaluate the performance of the proposed solution.

Environmental radiation monitoring system designed in [233] is composed of LoRa devices deployed in CERN sites that periodically measure the radiation levels and send this data to a LoRaWAN server via LoRa GWs. This allows to automatize the control of the radio-activities level in the conventional waste containers and provide a real-time warning of potential radiation release. Likewise, authors in [234] proposed to integrate of LoRaWAN network in Carbon Monoxide Measurement System. That is proposed within the context of smart cities to monitor the emission of Carbon Monoxide with a costeffective and increased lifetime of the system. Safety is the aim of the LoRa-based use case in [235], where LoRa devices were deployed alongside the high-voltage transmission lines for real-time temperature monitoring. LoRa technology was used in this scenario as an alternative to the legacy monitoring systems as manual or drone-based inspection and the shortrange wireless technologies for its long communication range. Moreover, multi-hope communication was adopted in order to allow broader coverage for data transmission between adjacent nodes.

LoRaWAN network has been suggested in [236] to manage groundwater resources by providing real-time information on groundwater levels. Supported by its low cost and low power consumption LoRa-based groundwater management system was revealed as the most suitable technology to deploy in regions under development. The usability of LoRa technology to monitor underground activities was provided in [237], such as the study focused on discussing the ability of both the LoRa physical layer and LoRaWAN to communicate data from underground sources to the aboveground base station. The analyses were performed considering three different soils (gravel, sand, and clay) under 50 cm depth acquiring SNR and RSSI value to evaluate the transmission's performance. LoRa Through-wall Sensing also explored in [4] aim discovering new sensing opportunities using LoRa transceivers. Recently proposed in the military context, LoRa helped in building IoT applications responsible for decision-making through collecting data from the battlefield [238]. LoRa communication role in this application provides resilience and survivability for the military network, benefiting from preinstalled IoT devices and their capacities.

VI. DISCUSSION & FUTURE RESEARCH DIRECTIONS

The existing research showed that massive IoT requirements in terms of connectivity exceed the legacy of LoRaWAN

capabilities due to its limited features such SFs (7-12), BWs (125; 250; and 500 kHz), and CR (4/5 4/6 4/7 4/8). Also, the overpassed standard ADR to manage the massive connectivity demands and the low impact of the CSS modulation to ensure efficient wireless communication in ultra-dense deployment is challenging. This resulted in LoRa signals interference and collision between concurrent transmissions, which drastically reduced the network's performance and rendered the deployment of LoRaWAN in this scenario unsuitable in its traditional version. This motivated the research community to propose various enhancements of the LoRaWAN schemes to ensure a reliable and scalable LoRaWAN network. Nevertheless, various open research challenges still need to be further investigated.

A. Joint Scheduling and SF Assignment

SF is a parameter that allows the EDs to adapt their TP, transmission range regarding the used frequency, and BW. The SFs may be assigned randomly, just like the legacy LoRaWAN or based on the distance of the EDs from the GW, such as the EDs nearest to the GWs using the lowest SF to transmit their data. In contrast, the faraway one uses the most giant SF that is SF 12 (Figure 8). Other methods assign a single SF to a set of EDs based on their communication link quality or requirement regarding the collected data type. All these methods showed encouraging results to solve the issue of LoRa signals interference and enhance the network scalability. Although, the limited SF combination restricts the enhancement of LoRaWAN capacity to efficiently connect a high number of EDs in the massive IoT deployment. Therefore, the SF assignment may join the transmission scheduling in a crosslayer protocol that involves the link between the LoRa physical layer characteristics and LoRaWAN MAC layer capabilities.

B. Efficient Interference Cancellation Schemes

Interference cancellation is implemented either on the EDs or on the GWs to help decode multiple superposed LoRa signals transmitted using different SFs. Various signal processing methods can distinguish between interfered signals, such as FFT and Discrete Fourier Transform. Also, the capture effect may also be considered where only the strongest signal is decoded. Furthermore, frame preambles are identified from the received signal to decode the received signals effectively. Additional information should be exchanged, including the SF and CR used to transmit the data, which means extra energy consumption. These time-consuming methods will not be suitable when dealing with time-sensitive information and increase the cost of receivers not allowed in LPWAN networks suggested for low-cost and long-range communication. Therefore, a tradeoff between the cost and the network performance in terms of received packet rate should be considered when implementing this solution to cope with interfered LoRa signals.

C. Novel Densification Techniques

Cellular networks may inspire researchers to design new densification strategies for LoRaWAN networks concerning its restriction, such as the duty-cycle and low throughput. This is a traditional solution to the increased demand for connectivity in a crowded urban environment like the city downtown. Joining the GWs densification with the previous solution mentioned in this work can significantly increase the capacity of LoRaWAN to connect more EDs. However, some architectural changes may be required to adapt the legacy LoRaWAN with its new enhancement, which requires specific attention when designing a densification strategy to facilitate the coordination within and between the cells and avoid additional collision between concurrent GWs transmission.

D. Optimized Windowing & Channel Allocation

The resource management schemes are employed mainly to fit the TX windows of EDs with the RX windows of the GWs. Knowing that RX windows of GWs are not always open since TX should be opened to acknowledge the received data. Also, EDs can not keep their TX and RX windows always open due to energy efficiency requirements. Therefore, this mismatch should be solved while considering the network density, which restricts the impact of these methods to enhance the LoRaWAN capacity. Thus logical and frequency channels were managed in such a way to allow simultaneously concurrent transmission of multiple EDs. Promising results showed in this context using smart resource assignment schemes. Furthermore, mathematical tools as the game theory can be used to manage resources through modeling the interaction between the EDs and GWs leveraging the various game type depending on the target scenarios. Alternatively, reinforcement learning can also be deployed as an optimization tool.

E. Relaying and Routing

Conventional LoRaWAN adopts star topology to connect EDs into the network through peer-to-peer connection with the GWs. The EDs deployed either randomly or following a specific strategy using a TP and an SF to transmit their collected data via a frequency channel. Massive direct connection to the GWs results in the appearance of collision between concurrent transmission as well drastically decrease in the network performance either in terms of received packets rate or in the communication latency due to multiple retransmissions of collided data. Hence, multihop communication can be adapted to deal with these issues where EDs far from the GW can rely on intermediate EDs to transmit their data. Otherwise, the new topology may be designed to seek fairness between EDs in terms of link quality, used SFs, or energy efficiency to increase the network lifetime. Consequently, new routing protocols should be designed to assist this enhancement which can be performed conjointly to the GW densification for efficient network topology design. Furthermore, a set of EDs with low residual energy can rely on a cluster head with high residual energy and ensure the forwarding task between the cluster members and the GW.

F. Energy-Efficient Carrier Sensing

The Listen-before talk mechanism is leveraged to enhance the LoRaWAN channel utilization and efficiency. Since the EDs can sense the medium and decide whether the channel is idle or occupied by another transmission using the same SF and signal characteristics. Carrier sensing is an energyconsuming process that raises the interest in carefully utilizing this method, especially when dealing with the battery power of EDs. However, due to the large time-on-air of long-range communication that decreases the performance of carrier sensing methods, multiple channel sensing may be required to benefit from its advantage efficiently. Moreover, data transmission via multi-hop communication should be enabled in the subsequent medium access protocols. Adapted CSMA/CA protocols were suggested in this direction while considering a portion of hidden nodes that showed promising results in terms of collision avoidance regarding various sensing ranges. Despite provided efforts, energy consumption remains the main issue facing the efficient deployment of CSMA methods in LoRaWAN networks.

G. Machine Learning for MAC

Slotted MAC protocols are suggested as an alternate of pure ALOHA-like protocols adapted by LoRaWAN networks due to their limited scalability. Nevertheless, designing an efficient time-slotted MAC protocol faces severe challenges due to the specific characteristics of LoRa and the duty cycle restrictions imposed in sub-GHz ISM bands. Also, the decoding schemes such as CRC may be incorporated to help decode symbols of multiple colliding frames. As a result, an overhead of synchronizing and scheduling the transmissions was raised due to the duty-cycle restrictions imposed on LoRaWAN and the sparse availability of downlink communications. To overcome that, autonomous and distributed scheduling schemes were considered such that EDs collaborate to self-organize their transmission and avoid collisions regarding each node's requirement and communication conditions. To this end, distributed machine learning may be suggested as a new research direction to solve this issue. In addition, slots can be shared between the EDs based on the previous transmission history to ensure a low collision probability.

VII. CONCLUSION

Although LoRa is a promising technology for massive IoT networks for providing reliable long-range communication, it suffers from signals interference and concurrent transmission collisions. Therefore, this survey examines the scalability challenges facing the deployment of LoRaWAN in ultra-dense IoT networks where massive LoRa connectivity is required. Moreover, we reviewed the state-of-the-art solutions in both the PHY and MAC layers to cope with the scalability challenges. We discuss the literature to assist LoRaWAN deployment for the massive IoT connectivity requirements, where modulation, channel characteristics, interference, collision etc., are the major issues. Most of the existing solutions to tackle these challenges leverage LoRa features to extend the capacity, while others designed new relaying/routing protocols or relied on signal processing techniques to cancel the interference. Moreover, CSMA and S-MAC are employed at the MAC layer to cope with concurrent transmission collisions. However, more efforts are needed towards developing reliable and scalable LoRa-based massive IoT systems. Therefore, this survey also presented some enticing research directions to assist researchers in designing efficient and scalable LoRaWAN systems.

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