Performance Determinants in LoRa Networks: A Literature Review

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***Abstract*—The LoRa radio technology is one of the most prominent choices in the Internet of Things Low-Power Wide Area Networks (LPWANs) industry due to its versatile and robust technical characteristics along with its ability to achieve long communication ranges combined with low energy consumption and reduced cost. One of the main issues in LoRa networks is how many end-devices can be reporting efficiently while meeting the requirements set by the application they support. This is known as the capacity metric and it is affected by many network parameters and various factors. A literature overview is presented in this work, studying works on LoRa-based networks, outlining their behavior and categorizing them based on their technological breakthroughs. Throughout this survey, a number of performance determinants that stand out are highlighted. These factors span five main categories that encompass physical layer characteristics, deployment and hardware features, end device transmission settings, LoRa MAC protocols, and application requirements. Discussion follows the presentation of each of the factors pinpointing the relevant research, and describing the impact of each one of them on the achieved network efficiency focusing especially on the capacity metric. Open issues and research directions are also highlighted for each of the five identified categories.**

***Index Terms*—Internet of Things, communication networks, access protocols.**

I. Introduction

Low POWER Wide Area Networks (LPWANs) fill a void in the Internet of Things (IoT) booming industry. These technologies came with a promise to answer how low cost, long range, and low power communications with usually low data transmission rates and with no particular latency requirements can be achieved. Cellular networks, while offering similar range technologies, fail to meet the most important factors of low cost and low power consumption [1]. The LoRa technology (PHY layer) [2] supported or not by the LoRaWAN specification (MAC & link layers) [3], seems to be capable of addressing the LPWANs' promises regarding cost, power, and range. Due to their characteristics, LoRa-based networks have been adopted in numerous cases. According to the relevant literature, prominent areas where LoRa technology can be implemented can be summarized as follows:

- Smart cities and environment, where services as street lighting, parking spaces, waste management, air quality, pollution monitoring, and detection of forest fires can utilize LoRa technology [4]–[11].
- Smart homes and buildings, where issues like home security, home automation and buildings safety are addressed [12]–[14].
- Industrial and enterprise applications, where issues like smart sensors, asset localization and tracking, shipping and transportation, leak detection and smart metering are dealt using LoRa implementations [15]–[20].
- Healthcare where health monitoring and health management are addressed [21]–[26]. LoRa-based networks have also come to aid the battle against Covid-19 [27], [28].
- Smart agriculture, where farm monitoring, livestock management and irrigation control are also example application areas [29]–[32].

In the last few years, a number of research papers have examined various internal critical functionalities, features, and capabilities of the LoRa-based networks. A number of factors have been identified that affect – positively or negatively – the performance of these networks. While the complexity and the intricacies of these factors have been investigated in the past, the need of having a descriptive metric for measuring the performance of these networks is imperative. Since the IoT networks target to support hundreds or even thousands of devices, the LoRa networks' capacity comes to the fore. A question that defines the term capacity of a LoRa cell would be, "what is the achievable number of supported End Devices (EDs) serving an application with specific requirements while complying with defined Quality of Services (QoS) metrics?" [33]. From this point on, the term "LoRa capacity" will refer to this definition. However, as pointed in [34], the calculation of capacity in LoRa networks is not a trivial task because there are a host of factors that cause significant network capacity fluctuations. Thus, the purpose of this work is to identify these factors, categorize them, and discuss their impact, mainly on the network capacity, but since capacity is linked with other performance factors such as the throughput and the energy consumption, several performance trade-offs between capacity and other factors will also be highlighted.

A rather quick overview of some of the factors that impact the LoRa capacity is given in [35], where capacity is described from the perspective of a LoRa gateway. According to [35] the gateway must have the capability to receive messages from a

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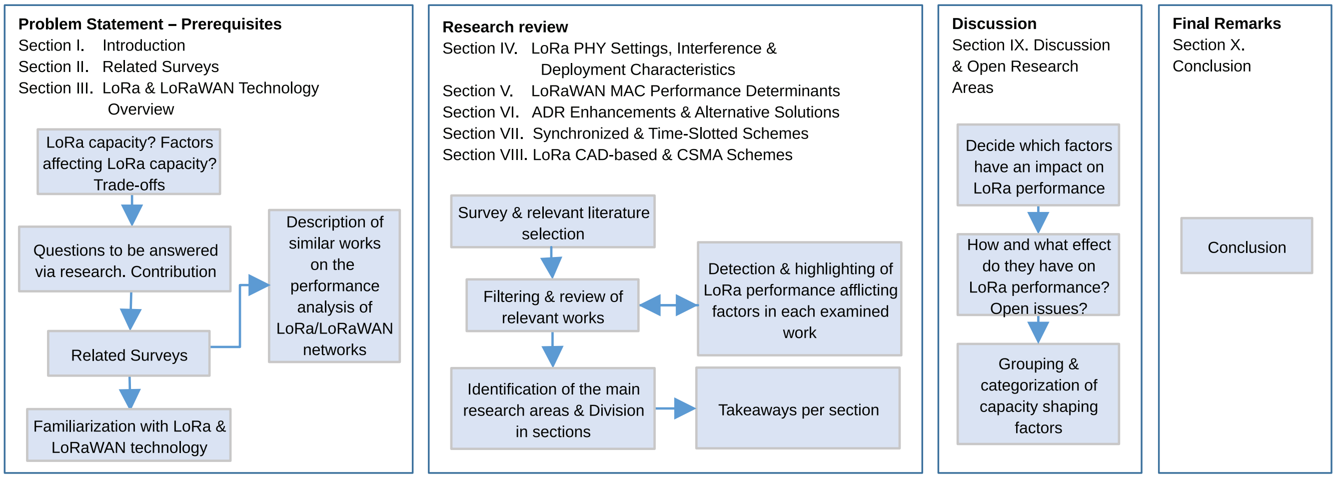

Fig. 1. Section names and workflow of the main components of the conducted work.

very high number of nodes. It is also underlined that a high capacity in a LoRaWAN network can be achieved by utilizing an Adaptive Data Rate (ADR) mechanism and by using a multi-channel modem transceiver at the gateway. Additional critical factors that affect the capacity include the number of concurrent channels, the data rates, the payload length, and the transmission rates. Apart from that, the configuration of some LoRa settings, such as the Spreading Factor (SF), which is discussed in Section IV, can also improve the network capacity and performance. Thus, application driven characteristics as well as physical layer phenomena and capabilities of the LoRa technology considerably affect the network performance.

Besides the above characteristics, the way of accessing the common medium plays a significant role in the achieved overall network capacity. As in popular wired and wireless networks, the use of protocols that arbitrate the medium access is of high importance in the overall network efficiency of LoRa-based networks. In LoRaWAN networks, an Aloha-like medium access procedure is adopted, i.e., every node transmits whenever it has something to transmit. The only limiting factor in this way of accessing the channel is the imposed regional radio duty cycle, that restricts the duration of the allowed transmission time. All of the above factors as well as the fact that LoRaWAN is an open not obligatory layer for the proprietary Semtech's[1] LoRa, have attracted considerable attention and research interest on LoRaWAN MAC and link layers behavior. Moreover, channel-sensing approaches as well as synchronized solutions have been recently proposed promising an increased LoRa performance over or beyond the functionalities of the LoRaWAN specification.

Contribution: In this paper, LoRa networks are examined through a thorough study of the relevant literature so as to answer questions about their behavior and especially their capability to serve crowded deployments efficiently. The contributing points of this work are:

- The thorough examination of the LoRa literature while pinpointing efficiency-related factors. This examination spans in five sections (as described in Structure).
- The underlining of LoRa capacity determinants in the examined works. Highlighting points that seem to have an effect on the network capacity and on the overall network performance are presented as takeaways for each of the five sections.
- The final categorization of these capacity deciding factors into:
  - PHY characteristics & Phenomena
  - Deployment features & Hardware selection
  - EDs transmission settings & Features
  - LoRa MAC protocols
  - Application requirements & Policies
- The pinpointing of open research areas.

Structure: The overall structure of the current survey is illustrated in Fig. 1. This introduction section contains paragraphs raising questions on performance-affecting factors of LoRa-based networks, along with the contribution of this work (Section I). A section mentioning related surveys – and briefly comparing them – comes after (Section II). A LoRa and LoRaWAN technology overview section follows (Section III). All the above sections form the Problem Statement part of this work. The Research part sections come next where a categorization of the cited works takes place (Sections IV–VIII) after examining the content of each research paper. The main LoRa PHY and deployment characteristics that can affect capacity are highlighted in Section IV. Section V describes works about the LoRaWAN MAC performance, while Section VI is dedicated to ADR enhancements and to alternative to ADR solutions. Section VII deals with Synchronized and Time-Slotted schemes and Section VIII with LoRa CAD-based and CSMA schemes. Factors afflicting the performance are filtered out and presented in each of these sections (Takeaways). In the Discussion part that follows, a grouping into categories of the factors impacting the performance takes place based on the previously examined research sections. Corresponding discussion subsections and open issues are also presented (Section IX). The Conclusion section (Section X) ends this

[1]In 2012 Semtech acquired Cycleo that initially invented the LoRa PHY layer back in 2009. Semtech further improved the technology and the chips for end devices and gateways supporting LoRa.

TABLE I
ABBREVIATIONS AND THEIR MEANING

Abbreviation	Meaning
ED	End Device
ADR	Adaptive Data Rate
BER	Bit Error Rate
BW	Channel Bandwidth
CAD	Channel Activity Detection
CF	Central Frequency
CR	Coding Rate
CSMA	Channel Sensing Multiple Access
CSS	Chirp Spread Spectrum
DER	Data Extraction Rate
DR	Date Rate
FEC	Forward Error Correction
FSK	Frequency Shift Keying
GW	Gateway
UL / DL	Uplink / Downlink
LoS	Line of Sight
MAC	Medium Access Control
PDR	Packet Delivery Ratio
PER	Packet Error Rate
PHY	Physical layer
PRR	Packet Reception Ratio
RSSI	Received Signal Strength Indicator
RW1/2	Receive Window 1/2
SF	Spreading Factor
SNR	Signal to Noise Ratio
TDMA	Time Division Multiple Access
ToA	Time on Air (transmission time)

work by showing the main concluding points of this work and how these points can become useful. To facilitate the reading of the paper, Table I summarizes the main abbreviations that are used across the paper.

II. Related Surveys

The strengths and the weaknesses of LoRa networks as well as open research issues have been the focus of several works. Haxhibeqiri *et al.* [36] provide a comprehensive overview of previous works focusing on various aspects of LoRaWAN, such as the security mechanisms, possible applications, and the performance of the LoRa physical and MAC layers. Advantages and disadvantages are also presented. Sundaram *et al.* [37] focus on the technical challenges of deploying LoRa networks as well as on possible solutions. The authors propose a taxonomy of the LoRa research challenges based on how energy consumption, MAC layer, and security issues are addressed. They also highlight a number of solutions for each of the identified categories and conclude their work with some open issues. A short overview of LoRa networks challenges are also described in [38]. Network scalability, capacity, and interference management are the main issues addressed in this work. The authors mainly focus on the complexity of dealing with the issues detected in the examined works since there exist multiple interacting factors that impact the performance and the capacity of LoRa(WAN) networks. Works describing the performance of this technology under different scenarios constitute the main focus in [39]. Through the examination of a number of works, a categorization of research papers along with the current research trends are derived by Saari *et al.* [40]. Similarly a paper categorization is proposed in [41] based on the key-points of each highlighted work. Additionally, an extensive overview of the LoRa PHY and of the LoRaWAN MAC is offered.

Link budget and energy consumption capabilities of LPWAN technologies, including LoRa, are examined in [42]. The authors focus on the comparison of these technologies and mainly on their achieved coverage rather than on aspects related to scalability, interference, and capacity.

Beltramelli *et al.* [43] investigate a number of alternative ways of accessing the medium other than the Aloha-based approaches of LoRaWAN. The authors also develop a theoretical model in order to compute the probability of packet delivery as well as the throughput in slotted-Aloha and in CSMA schemes. This model is based on an interference model and a number of parameters derived from experimental and numerical observations.

Marais *et al.*'s work [44] focuses on the LoRaWAN confirmed traffic. The authors do a literature review on the confirmed traffic and highlight the main issues that could lead to performance degradation in LoRaWAN at the presence of confirmed transmissions. These issues include the duty cycle restrictions at the gateways, the use of spreading factor 12 for RW2, the allowed maximum number of re-transmissions, and the policy used in the re-transmissions back-off interval. Some of these factors are also highlighted by Capuzzo *et al.* [45].

Kufakunesu *et al.* [46] do a literature review of ADR approaches. They focus not only to works related to LoRaWAN's ADR but also to those that present optimization approaches to improve throughput, energy efficiency, and scalability. The authors discuss possible advantage and disadvantages.

Most of the above works, take a wide view on the LoRa networks research field. Table II briefly presents the research works mentioned above. Despite some necessary overlaps, the differentiating point of the current study is that we focus on an important network efficiency determinant, namely the capacity of LoRa and LoRaWAN networks. To this end, we extensively survey the existing literature starting from physical layer aspects and continuing to alternative MAC layer options, while also addressing LoRa transmission and application layer settings. After having defined the exact nature of the concept to be surveyed, a categorization of the selected works is provided and features affecting the capacity are highlighted along with the presented proposed solutions and open issues.

III. LoRa & LoRaWAN Technology Overview

A. LoRa

At the physical level, Semtech's LoRa [47] uses a modulation derivative of the Chirp Spread Spectrum (CSS). CSS makes it capable to cover long ranges and achieve resilience against interference, fading, and Doppler effects. Frequency Shift Keying (FSK) modulation can be used as well. While FSK achieves low power communication it does not achieve the communication range of the LoRa CSS. In most cases in which the CSS modulation is used, the information carrying

TABLE II
SUMMARY OF RELATED SURVEYS AND COMPARATIVE WORKS, THEIR EXAMINED AREAS, AND THEIR CONCLUSIONS

Ref.	Type Of Paper - References	Paper Categorization – Areas Examined	Areas examined not signified by the previous column	Short Description - Conclusions
[36]	Literature review - 132 references up to 2018. Target theme: LoRa PHY and LoRaWAN MAC.	Based on paper content: (i) physical layer aspects (ii) network layer aspects, (iii) possible improvements, (iv) extensions to the standard.	Applications and deployments, Network level simulators for LoRaWAN and deployed test-beds, power usage and security related studies.	Strengths and weaknesses of proposed improvements. Research opportunities and LoRa and LoRaWAN challenges. Strengths, weaknesses, opportunities and threats analysis of LoRaWAN.
[37]	Literature review - 137 ref. up to 2019. Target theme: LoRa PHY and LoRaWAN MAC.	Based on research challenges: (i) Energy Consumption, (ii) Commu-nun. Range, (iii) Multiple Access, (iv) Error Correction, (v) Security.	Existing LoRa Deployments.	Based on the research challenges, performance measurements, current solutions, key insights and open issues are discussed.
[38]	Literature review - 33 ref. up to 2019. Target theme: LoRa PHY and LoRaWAN MAC.	No paper categorization takes place. The authors review 13 papers regarding the challenges they are dealing with and the proposed solutions.	-	Challenges and solutions as well as research opportunities.
[40]	Literature review - 40 references up to 2017. Target theme: LoRa PHY and LoRaWAN MAC.	Based on paper content: (i) Analysis, Survey, Factual Discussion, (ii) Performance, Technical Evaluation, (iii) Real Deployments, Experimental, Prototype Implementations, (iv) Simulation, Modeling, Networking Stack, Software, (v) Applications	-	The authors mention key-points of the research papers related to LoRa on a variety of research themes, objectives, and methodologies. A paper classification, research trends, and practical applications are derived.
[39]	Literature review - 35 ref. up to 2018. Target theme: LoRa PHY and LoRaWAN MAC.	Mainly performance analysis works of LoRa technology networks are mentioned here along with the conclusions derived from each one.	-	An overview of LoRa technology is presented accompanied with works pertinent to the network performance under different scenarios.
[41]	Literature review - 157 references up to 2019. Target theme: LoRa PHY and LoRaWAN MAC.	Based on paper content: (i) PHY Layer (Coverage, Interference, Optimization) (ii) MAC Layer (Energy, Mesh, Security) (iii) Applications.	LoRaWAN specification versions overview. LoRaWAN Netw. Server implementations are mentioned. A simulation showing PSR/#no of nodes.	An extensive description of LoRa PHY and LoRaWAN MAC is offered along with key points of numerous works pertinent to the proposed categorization. Possible research directions.
[42]	Comparative Study - 76 references up to 2018. Target theme: (LPWAN technologies) Sigfox, LoRaWAN, WavIoT, RPMA, NB-IoT, and LTE-M are considered.	The comparative analyses presented in this paper are based on available data sheets and on simulation results. The related papers are categorized based on the area of focus (technology).	Per LPWAN technology: Signal propagation (Fresnel Clearance and Path Loss), Network performance analysis (Coverage, Sensitivity Analysis, Network Optimization, Transmission Delay, Energy).	The comparative performance of the examined LP-WAN technologies, including design choices and their implications.
[43]	Experiments & analysis paper, 26 references up to 2020. Target theme: LoRaWAN MAC methods.	The related papers are categorized based on channel access enhancements: (i) slotted ALOHA (S-ALOHA), (ii) CSMA, (iii) Scheduled MAC.	Success and Coverage Probability, Energy Efficiency, Channel Throughput of pure ALOHA (P-ALOHA), S-ALOHA and non-persistent carrier-sense multiple access (NP-CSMA).	The development of a unified analytical model for the performance analysis under three basic random access mechanisms. Experiments & conclusions are presented comparing the MAC methods examined.
[44]	Literature review - 73 references up to 2019. Target theme: LoRaWAN Confirmed traffic.	Based on the aspect of the impact of the confirmed traffic: the impact of (i) retransmissions, (ii) confirmed traffic ratios, (iii) SFs, (iv) receive windows, (v) multi-gateway networks.	IoT use cases that require confirmed traffic, new proposed ACK methods.	A survey on the LoRaWAN confirmed traffic literature to identify common themes, open challenges and potential solutions. Potential solutions categories are presented: (a) Indicating Network Congestion and Reply Urgency, (b) Grouping Traffic and ACK aggregation, (c) Competitive Space (d) Other Challenges.
[45]	Experiments and Analysis Paper - 13 references up to 2017. Target theme: LoRaWAN Confirmed traffic.	Examination of Packet Success Rate caused by three factors: (i) confirmed to unconfirmed traffic ratio, (ii) number of retransmissions, and (iii) number of devices.	Factors causing packet losses, ADR effect on confirmed traffic, Random backoff intervals, EDs locking on uplink packets, Sensitivities asymmetry, Sub-band prioritization.	A simulation analysis using confirmed traffic in LoRaWAN networks is presented. Critical points and insights gained are discussed along with possible approaches to alleviate some of the revealed issues.
This work	Literature review - 150 references up to 2020.Target theme: LoRa PHY and LoRaWAN MAC	Based on paper content: (i) LoRa PHY settings, Interference, and Deployment characteristics, (ii) LoRaWAN MAC Performance Determinants, (iii) ADR Enhancements and Alternative Solutions, (iv) Synchronized and Time Slotted Schemes, (v) LoRa CAD-Based and CSMA Schemes.	Key factors per category and their impact on performance/capacity for (i) and (ii) as well as potential mitigation solutions. Review of solutions proposed in (iii), (iv) and (v).	A literature study on the performance and the behavior of these networks along with attempts of improving and even substituting some critical functionalities. A discussion along with a categorization of the capacity deciding factors and open issues takes place: (a) PHY characteristics and Phenomena, (b) Deployment features and Hardware selection, (c) EDs transmission settings and Features (d) LoRa MAC protocols and (e) Application requirements and Policies.

signal after having gone through a Forward Error Correction (FEC) mechanism is modulated in the form of a sequence of chirp pulses before being sent. A chirp pulse is a linearly increasing frequency signal that cycles the channel bandwidth (BW) of a central frequency (CF) (see Fig. 2). LoRa CSS signals of a certain BW can also utilize different spreading

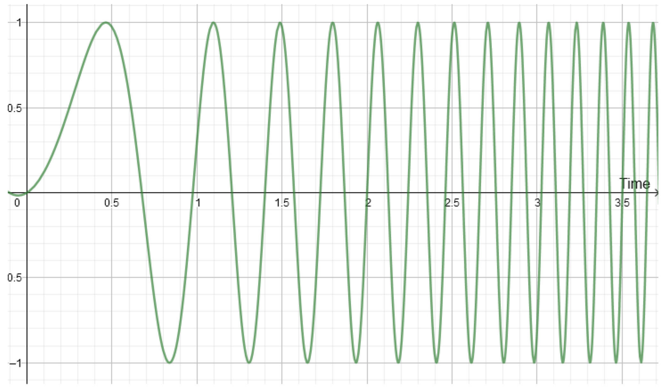

Fig. 2. A linear chirp waveform; a sinusoidal wave that increases in frequency linearly over time.

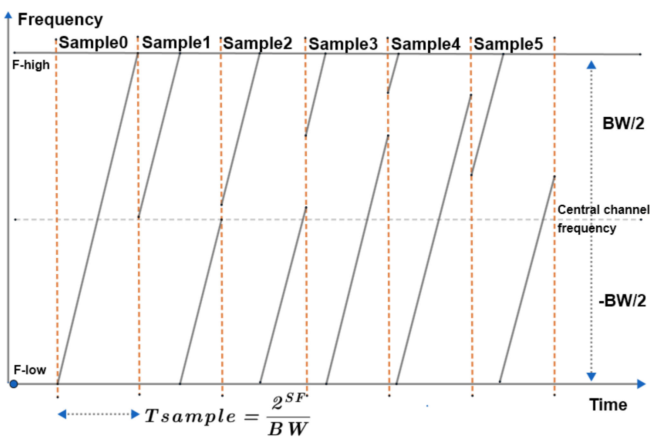

Fig. 3. LoRa modulated signal.

factors (SF) achieving different processing gains $(N = 2^{SF})$ and spectral efficiencies.

In the same channel frequency of a certain BW, each chirp (or commonly known as sample) is differentiated from another chirp of the same SF by the starting frequency of the signal as shown in Fig. 3. The rate of increase is defined by the used SF, the value of which ranges from 6 to 12 [48], however, SF6 is not practically used [47]. Lower SFs sweep through the channel's BW faster than higher ones, thus leading to higher data rates but also to higher susceptibility to noise and interference, and to smaller coverage. Thus, data can be encoded by combining the selected channel bandwidth and spreading factor, and can be modulated over the selected channel's central frequency.

A chirp signal encodes a number of SF bits with 2^{SF} possible chirp states within a chirp duration, which allows LoRa to achieve several data rates. The chirp duration T_s can be computed using the following equation:

$$T_s = \frac{2^{SF}}{BW}. \tag{1}$$

Considering also the FEC added information, noted as Coding Rate (CR), with typical values of 4/5, 4/6, 4/7 and 4/8, the bit rate of a transmission R_b, can be calculated as follows:

$$R_b = SF\frac{BW}{2^{SF}}CR. \tag{2}$$

A smaller CR (e.g., 4/8) results in a better transmission reliability in a badly conditioned channel but with a larger overhead in the overall transmitted bits than a larger CR (e.g., 4/5).

In addition, larger SF values achieve larger distances (due to better receiver sensitivity) and provide more robust signals. However, they result in lower transmission rates and longer time on air (ToA) for packets with the same payload. Moreover, by using larger BW channels better transmission rates can be achieved but within a smaller distance. Another setting that can be tweaked is the transmission power whose adjustment can improve the achievable range and the survivability probability against possible channel losses [49]. Concurrent uplink transmissions (uplinks) from multiple EDs on the same channel but with different SFs (i.e., orthogonality) can co-exist and be decoded simultaneously at a multi-channel gateway. Different combinations of SF as well as of channels can be used to ensure successful concurrent uplink transmissions. However, signals of different SFs are not perfectly orthogonal (quasi-orthogonal) allowing overlapping signals to survive given a minimum SINR among signals (Table V). Multi-channel LoRa gateways can decode up to eight concurrent quasi-orthogonal uplink transmissions [50]. It should be noted that since both the LoRa gateways and the end-nodes are half-duplex they cannot receive and transmit at the same time. Various works exist analysing the CSS modulation technique and verifying its traits such as robustness to interference and quasi-orthogonality [51] as well as proposals of achieving perfect orthogonality, higher spectral efficiency and BER performance [52].

Moreover, regional-specific guidelines, that should be followed by LoRa network designers, define how and which sub-GHz ISM bands can be used in LoRa deployments. The purpose of these regulations is to increase the levels of fairness between devices. In Europe, duty cycle restrictions are imposed per frequency band, as depicted in Table III. The duty cycle period is calculated in a per hour basis which practically means that within an hour a device has 36 seconds available transmission time assuming a 1% duty cycle. The rule can be bypassed if a listen before talk (LBT) method is used. In the U.S., the duty cycle restriction is per channel rather than per band. More specifically, the duty cycle is 2% if the channel bandwidth is less than 250KHz and 4% if it is lower than 500KHz but higher than 250KHz. The duty cycle period is

TABLE III
TRANSMIT POWER AND DUTY CYCLE REGULATIONS PER SUB-BAND FOR THE EU868 BAND [56]

Frequency	Transmit Power	Duty Cycle
863 – 865 MHz	25 mW ERP	$\leq$ 0.1% or LBT
865 – 868 MHz	25 mW ERP	$\leq$ 1% or LBT
868 – 868.6 MHz	25 mW ERP	$\leq$ 1% or LBT
868.7 – 869.2 MHz	25 mW ERP	$\leq$ 0.1% or LBT
869.4 – 869.65 MHz	500 mW ERP	$\leq$ 10% or LBT
869.7 – 870 MHz	5 mW ERP	No requirement
869.7 – 870 MHz	25 mW ERP	$\leq$ 1% or LBT

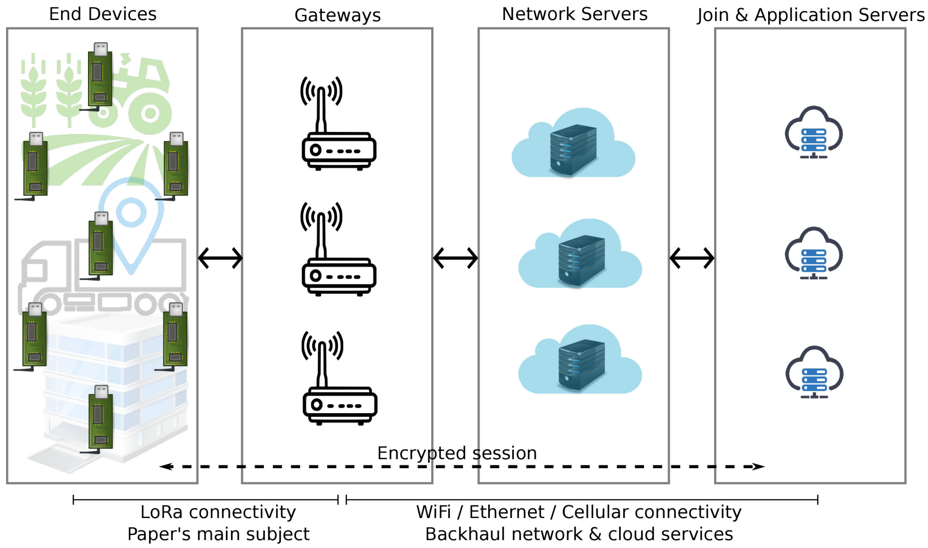

Fig. 4. The LoRaWAN architecture consisting of end-devices, gateways as well as network, join, and application servers.

20 and 40 seconds for these two cases respectively. The number of channels is up to 64 (up to 8 in Europe). It must also be noted that the maximum allowed transmit power is higher in the U.S. (30dBm for channel numbers >50 and 24dBm otherwise). Similar rules are imposed by regulation organizations in Asia, Australia, and South America [53]. The network designers or administrators must select an appropriate channel plan that dictates besides the channel frequencies and bandwidths, the duty cycle restrictions as well as the maximum allowed transmission power in each selected channel. Finally, it must be noted that the present work focuses on sub-GHz LoRa, however, several aspects and outcomes are valid for the recently announced 2.4GHz LoRa as well where no duty cycle restrictions are applied [54], [55].

B. LoRaWAN Overview

LoRaWAN defines the MAC and link layers that are used on top of the LoRa PHY layer and it is maintained by the LoRa Alliance. It is the only standard currently developed for LoRa-enabled devices. The latest version of the standard is v1.0.4 [57]. In order to give a complete picture of LoRaWAN, we present some insights on its architecture [57]. As seen in Fig. 4 the involved devices-roles are (a) the EDs that send in uplinks the sensor data, (b) the Gateways (GWs) that receive the uplinks and pass them through a backhaul network to the Network Server (NS), (c) the Network server that handles all the required network functionality and the interactions with the end-devices and the gateways, and (d) the Application server (AS) where the data from the end-devices are evaluated and the downlink data (downlinks) is sent back if necessary. Apparently, this paper deals only with the research challenges that arise between (a) and (b). Research topics related to the backhaul network are out of the scope of this paper. The creation of an IoT solution with LoRa EDs (sensors or actuators) based on the LoRaWAN specification can be realized in a number of ways. Such a network that makes use of the collected data in various use-cases can choose one or a combination of the following ways:

- The utilization of a commercial network of LoRa GWs of a Public Operator in a specific area can usually be chosen offering a high quality of service. However, the choice of such a solution is dependent on the operator's policies regarding the cost and the implementation.
- A Private Network creation can also be chosen, i.e., the installation of private GWs covering selected areas or buildings. Beside the deployed LoRa EDs and GWs, private network servers and application servers must also be configured and deployed. The NS(s) and AS(s) that control, maintain and offer the collected data are privately managed by the creators of the network. Operator independence is the main advantage of this solution.
- An intermediate solution is the usage of a Community Network (e.g., The Things Network)[2] where the GWs of the network are offered and maintained by multiple independent individuals choosing to connect their equipment in such a network while sharing a common cloud-based platform (i.e., NS and AS services). An individual or a company choosing such a solution can simply connect its EDs and possibly its GWs to the network and utilize the offered services in a data-secure way. These community networks span from small to vast areas (covered by usually the numerous GWs offered by the community) offering their services free or in a more cost-effective way than the commercial networks.

In the LoRaWAN specification, the specified data rates (DR0-DR7) indicate the allowed combinations of BW and SF as depicted in Table IV. LoRaWAN also specifies the ADR mechanism which allows a dynamic assignment of the transmission settings (i.e., SF, transmission power, and radio channel) to the end-nodes. The role of the ADR is to suggest to the EDs to use less energy-consuming DRs and transmit

[2]The Things Network, commonly known as TTN, is an open source infrastructure aiming at providing a free LoRaWAN network cover.

TABLE IV
LoRaWAN Data Rates (DR) in Europe for the Lowest and the Highest Coding Rate (CR)

DR	Configuration	Bitrate (bit/s) CR=4/5	Bitrate (bit/s) CR=4/8
0	LoRa: SF12 / 125 kHz	293	183
1	LoRa: SF11 / 125 kHz	537	336
2	LoRa: SF10 / 125 kHz	977	610
3	LoRa: SF9 / 125 kHz	1758	1099
4	LoRa: SF8 / 125 kHz	3125	1953
5	LoRa: SF7 / 125 kHz	5469	3418
6	LoRa: SF7 / 250 kHz	10937.5	6836
7	FSK: 50 kbps	50000	

TABLE V
Interference Thresholds Per SF (*dBm*) [62], [63]

Ref. \ Int.	SF7	SF8	SF9	SF10	SF11	SF12
SF7	1	−8	−9	−9	−9	−9
SF8	−11	1	−11	−12	−13	−13
SF9	−15	−13	1	−13	−14	−15
SF10	−19	−18	−17	1	−17	−18
SF11	−22	−22	−21	−20	1	−20
SF12	−25	−25	−25	−24	−23	1

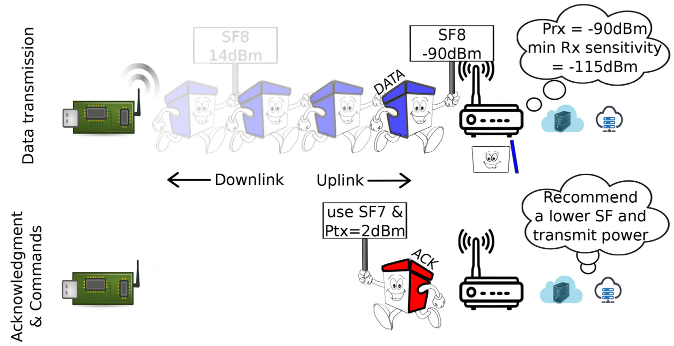

Fig. 5. A simple representation of the Adaptive Data Rate in LoRaWAN. A data packet is transmitted with SF8 and 14 dB of power. The packet is received by the gateway with a much higher power (−90dBm) than the minimum required threshold sensitivity for SF7 (−115dBm). The gateway suggests to the ED to use less energy consuming settings in future transmissions (i.e., SF7 and 2dBm transmit power). The ADR commands are encapsulated into the ACK packet.

power to reliably reach the GW. To do so, the NS checks how much above the sensitivity threshold the received power of the incoming packet is, and estimates the best settings in terms of energy costs. A simplified description of ADR is given by The Things Network in [35]. ADR consists of two parts; the ED-side and the Network Server side algorithm. Its logic can be summarily described as follows. The ED communicates initially with the GW at a random SF and at a random transmission power and if this is not possible it increases the SF value. After succeeding, it waits instructions from the Network Server to configure more efficiently its transmissions parameters (i.e., SF and power). The NS keeps track of each ED's maximum SNR among its last 20 uplinks and based on that it decides the more efficient ToA-wise and energy-wise configuration for each ED's future transmissions (i.e., by decreasing the SF and adjusting the transmission power). At the first downlink opportunity, NS tries to instruct the ED to act accordingly. The ADR information is usually encapsulated in acknowledgments in the form of commands (as it is depicted in Fig. 5) or it is sent in a separate downlink packet through one of the gateways.

LoRaWAN distinguishes three modes of operation for the end-node devices. The class A mode is the one mostly used as it is the most energy efficient. In class A, an uplink may be followed by one or two downlink receive windows (RW1 and RW2), after specified intervals and in specified SFs and channels (i.e., confirmed uplinks). The two downlink windows are used for acknowledgments and LoRaWAN commands (e.g., ADR control packets). If an ACK is received during the first window, the second window does not open. The ED is allowed to transmit again after a successful reception during the first window (ACK in RW1) or at the end of the second window if the duty cycle limit permits it. If the ED does not receive any ACK during RW1 or RW2, it can re-transmit for a predefined number of times after some random time from the last transmission. However, the re-transmission can be skipped if the new transmission cycle has arrived or if a new event has triggered data generation and transmission. All this process also depends on the implementation followed by the user and by the manufacturer. There also exist the mutually exclusive class B and C modes that are supported along with the class A mode. The synchronized class B devices open extra downlink windows at on-demand scheduled times using gateway beacons. Class C devices always listen for downlink activity except from the times when uplink transmissions take place.

IV. LoRa PHY Settings, Interference, & Deployment Characteristics

A multitude of research works on LoRa and LoRaWAN networks study how the various LoRa PHY characteristics affect the overall network performance and resulting capacity. Some of these works are summarily presented below along with selected key-points.

A. *LoRa PHY Selection Parameters*

As mentioned by Bor and Roedig [58], there are 1152 combinations of LoRa and LoRaWAN settings that can lead to various levels of performance. Nevertheless, the PHY parameters that affect the network capacity are mainly those that affect the data transmission time. These parameters are the SF, the channel bandwidth, and the CR.

The transmission time increases when higher SFs, narrower channel bandwidths, and lower coding rates are used. If an Aloha-based MAC layer is adopted (e.g., LoRaWAN), the proper selection of the SF and the CR among/by the nodes is critical for the total achievable network capacity [59]–[61]. However, most of the times the lowest (higher) possible SF (DR) is selected to achieve the lowest possible energy consumption. Moreover, the selection of the channel bandwidth (whenever this is possible) also plays an important role on the overall capacity; LoRa transmissions are delivered much quicker over wider channels than over narrower

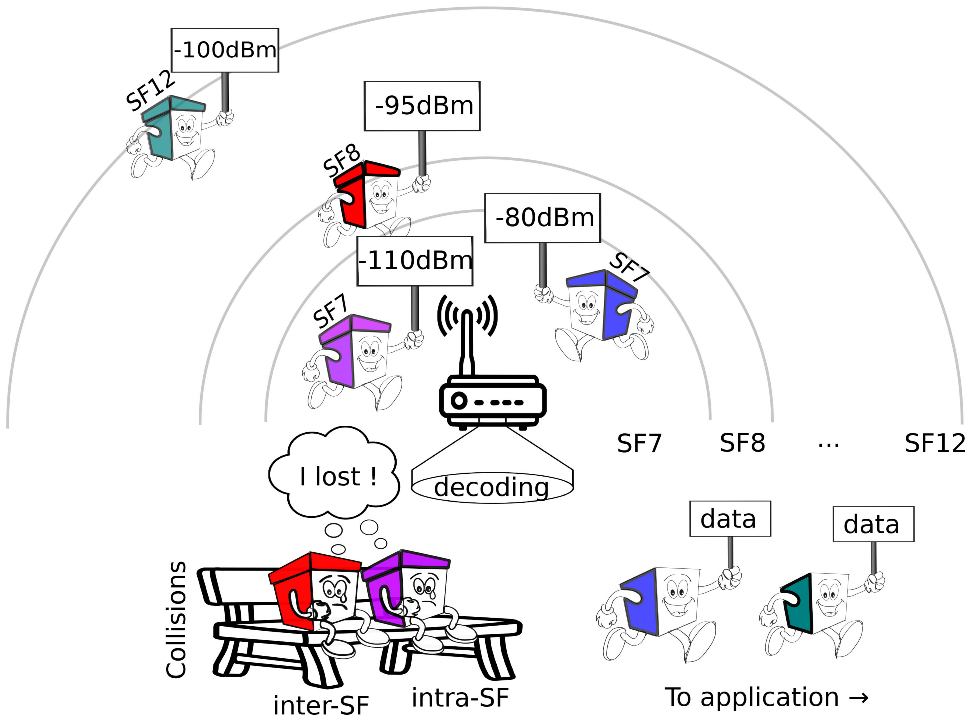

Fig. 6. Example of intra- (or co-) and inter-SF collisions in LoRa. It is assumed that all the 4 packets overlap in time. Two packets collide due to the co-SF interference in SF7 and due to the imperfect orthogonality of SFs (SF7 with SF8) when the received powers at the gateway (node signs) are beyond the isolation thresholds so the strongest signal wins (see Table V). The other packets are successfully decoded.

ones. However, as with the SF, on one hand this has a negative effect on coverage while it has a positive effect on energy consumption on the other hand [47]. How all these parameters impact the network performance and capacity when they are collectively assigned to the network nodes is the subject of many studies in the literature that will be presented separately in Section VI.

B. LoRa Susceptibility to Interference

Another factor affecting a LoRa network's performance is interference. Interference may be caused by other LoRa networks as well as by LoRa signals inside the same LoRa network, denoted as inter-LoRa and intra-LoRa interference, respectively. Intra-LoRa interference is divided into two categories; intra- and inter-SF interference (see Fig. 6). Intra-SF interference is caused when two or more packets overlap in time and have the same SF, while inter-SF interference is caused due to the imperfect orthogonality of the SFs. As it will be discussed later in this subsection, the probability of different-SF signals interfering with each other is considerably lower (i.e., it happens more rarely) compared to the one of the same-SF signals.

Interference may also be caused by non-LoRa signals. This kind of interference has been investigated [64] in the presence of IEEE802.15.4g transmissions. It is shown, through a series of experiments, that due to the nature of the two different modulations used (GFSK and CSS), the effect of the GFSK transmissions on the LoRa's CSS performance is not high. The lower the SF and the higher the BW of the LoRa signal, the higher the effect of the interference caused by IEEE802.15.4g transmissions for overlapping 868 MHz channels. In [65], it is mentioned that interference of non-LoRa signals on LoRa signals comprising of tone pulses less than 5 dB above the desired signal for SF7 (and less than 19.5 dB for SF12) with an error correcting scheme of 4/6, is not a problem.

In [66], an experimental evaluation of the susceptibility to inter- and intra-SF interference of LoRa signals is performed in an isolated testbed. Experiments using 3 interfering EDs show several interesting results and lead to the following conclusions that coincide with observations made by other studies. Firstly, LoRa transmissions with different data rates in the same frequency channel negatively affect each other (inter-SF interference). The packets sent with high DRs suffer more from inter-SF interference than the ones sent with low DRs. In the case in which the interfering signal uses the same DR as the target device, there is still a probability of receiving the desired packet correctly. This success depends both on the difference in the power levels of the two signals and on the used DR. Namely for signals of the same DR, about 1/3 and more than 90% of the packets are delivered successfully for respectively 0 dB and 3 dB stronger target signals than the interfering one. For cases above 6 dB, the desired signal will almost surely be received correctly. Furthermore, if the interfering signal is transmitted at a different DR and is less than 6 dB stronger than the target signal, both signals will be encoded. If the different DR interfering signal is more than 6 dB stronger, only the interfering signal will be received, and most likely, not the interfered one (with even lower probabilities as the DR of the interfered signal gets larger). Similarly, a Gaussian Frequency Shift Keying (GFSK) interfering signal can prevent the reception of a LoRa-modulated signal if the first is more than 6 dB stronger.

Similar experiments have been recorded in Croce *et al.* [62] where the interference that LoRa signals induce to each other in a LoRa channel is examined. This is done by investigating what happens when two signals coincide temporally and use the same SF or/and different SFs (using the same BW and CR). During each of the previous cases, the difference between the power of the desired signal and the interfering signal, in the form of signal to interference ratio (SIR), varies in the range of −30 dB to 5 dB. The Bit Error Rate (BER) of an overlapped by interference reference signal is studied while the SIR changes. No channel noise is assumed. The experimental evaluation took place by employing software defined radios (SDRs) that were generating the LoRa interfered signals, with varying SIR, while checking their reception at a commercial transceiver and logging the BER of the desired signal. Line of sight (LoS) propagation is considered. Both the simulations and the experiments displayed similar results regarding the co-channel interference rejection (CIR) values. For the same-SF signals collision cases, the desired signal will be most likely received correctly (Packet Error Rate - PER lower than 2%), if it is 3 dB higher than the interference. For different-SF coinciding signals, the desired signal most likely will not be correctly received if it is weaker than a threshold value. The average co-channel rejection threshold shown experimentally is −16 dB with values ranging from −8 dB to −25 dB (depending on the SFs of the desired and interfering signal). The above evaluations showed, once again, that different-SF transmissions are far from perfectly orthogonal.

The LoRa receivers' performance under co-technology interference is also examined in [67] via simulations and experiments. Specifically, in the context of creating a multi-hop LoRa network, an examination of intra-SF and different SFs interference takes place yielding useful results. Firstly, to study intra-SF interference a simulation takes place using all the SF values with varying timing offsets, carrier frequency offsets, phase offsets, power offsets and a fixed bandwidth with no use of an error correcting code. The results provide a detailed picture regarding the behavior of signals in each SF in case of intra-SF interference. More specifically, it is shown and that in case of the 3 dB power offset, all SFs exhibit a behavior similar to the collision-free case. During the simulation of studying the interference between different SFs, a transmitter/receiver pair was setup using different SFs. All possible combinations were tested for a fixed wanted signal and a varying power level of an interfering one, thus achieving a varying SIR. Once again, besides the imperfect orthogonality, the results showed the higher tolerance of larger SFs to the under-study case of interference as the SIR thresholds derived were lower than those of the lower SFs. It was also observed that lower interfering SFs were impacting to a greater extent the desired signal. The corresponding experimental results were similar to the ones of the simulation. During both these evaluations, a signal of any SF with SIR greater than 3 dB is very likely to be received correctly under any type of interference. In the case of inter-SF interference, a more thorough examination should happen, taking into consideration the SFs of the interfering signals and the respective SIR to decide if the interfered packets will be received with a specific packet reception rate. Indicatively, during the experiments (simulations), the lowest SIR to achieve a PPR of 90%, in the case of interfered SF7 and interfering SF8, was almost −6 dB (−12 dB) while in the case of SF12/SF11 it was almost at −31 dB (−25 dB).

C. Deployment Characteristics

The LoRa networks' performance may be heavily affected by a number of characteristics related to the hardware selection, the topology, and the environment of the deployment. This subsection surveys works dealing with these characteristics and identifies the most critical factors that affect the network's performance.

Some earlier works focused on evaluating the maximum coverage limits of LoRa networks by doing real life measurements at different areas. For example, in [68], measurements that took place in a coastal city with medium height buildings and a harbor are presented. The measurements showed that on the ground, for distances up to 5 km the amount of successfully delivered packets exceeds 80%. Up to 67% of the packets were received successfully at distances of 5 to 10 km. At distances exceeding 10 km, the majority of the packets sent (74%) were lost. On the water, an almost 30 km communication range was examined with an average of 68% packet success ratio. Two channel attenuation models were created (i.e., path loss exponent, intercept and shadow fading effect values were derived) that can be used for estimating the communication distances for the LoRa technology at areas similar to those of this experiment.

In [69], the coverage of LoRa in indoors environments was studied. The results showed a packet success ratio of well above 94% in all cases measured in a campus spanning a 320x570m area. In a similar environment in [59], a channel path loss model was deduced for up to 100m after a series of indoor measurements. This model was categorized as a built-up environment describing model. A more realistic path loss model appropriate for long distances that also considers the gateway's antenna elevation (0–50m) is used in [70] for high density urban environments and buildings of approximately uniform height, as described in [71]. A log-normally distributed shadowing with a standard deviation of 10dB is added to the final path loss calculation. Moreover, accounting for building penetration losses and for correlated shadowing such as in the Manhattan layout model this path model is used for simulating a single gateway LoRa cell of a radius of 7.5km. The simulation scenarios showed that the gateway height (i.e., at 50m instead of 15m) affects the packet success ratios because it mitigates the effect of propagation loses in not so favorable channels. A similar improvement is noticed in [72] when larger antenna gains are used since they lead, as before, in the possibility of a more favorable ED distribution per SF.

Voigt *et al.* [73] study the effect of employing directional antennas at the nodes' side and the alternative of using multiple gateways to deal with interference issues. LoRaSim (a LoRa network simulator developed in a previous work [59]) was extended to include the functionality of the directional antennas, and was used as a simulation environment. During the simulations, one of the first conclusions is that as the number of interfering LoRa networks increases and as the distances among them decreases the network performance in terms of the Data Extraction Rate (DER) decreases. The adoption of directional antennas only by the nodes in the interfered network results in a slight improvement of the interfered network's DER. This is attributed to the capture effect at the interfered network's gateway, resulting more often than before in favor of the nodes in the interfered network that are transmitting with the installed antennas. The installation of more gateways in the interfered network also results in a DER improvement that clearly outperforms the alternative proposal. The positioning of the gateways also seems to play an important role in the achieved network performance. In addition, it is observed that using three gateways in the interfered networks outperforms even the case of the one gateway with no interference. Thus, it is shown that to achieve a high DER, independently of the existence of inter-LoRa interference, it is more efficient to deploy multiple gateways than to use directional antennas.

In [74], a series of experiments is used to model the path-loss and intra-Lora interference of the LoRa signals in several use cases. A series of simulations with single-GW small range LoRa cells (where small SFs are assigned to EDs), larger area cells (larger SFs are assigned), and multi-GW LoRa networks (smaller SFs are assigned) were conducted. The use of multiple GWs considerably improved the Packet Delivery Ratio (PDR) and the capacity metrics in the simulated use cases.

Mikhaylov *et al.* [75] computed the optimal spatial distribution of the nodes (according to the calculated best possible throughput capacity) per DR for specific application requirements scenarios. Indicatively, in all scenarios studying the capacity of LoRa networks that serve specific applications, it is shown that for achieving the maximum capacity, most of the deployed EDs should be close to the gateway. Similarly, Duda and Heusse [76] examine non-homogeneous spatial distributions of devices around a gateway to keep the PDR level above a certain value. As with [75], it is shown by mathematical analysis that the placement of nodes closer to the gateway helps to achieve higher capacity values.

Finally, the performance of LoRa networks under the Doppler effect has also been assessed [77]. Experimental measurements are employed to exhibit the impact of the Doppler Effect on LoRa packets. It is shown that when the ED's velocity is above 40 km/h (SF12 is considered), the performance deteriorates rapidly. The packet success ratio exhibited for an ED with a speed of about 26 km/h, 40 km/h, and above was 84%, 50%, and down to a value of 30-40%, respectively.

D. Takeaways

Several observations can be made after examining the above works. Key points derived from the works examined are presented here and highlighted in Table VI.

The LoRa device features and the deployment decisions considerably affect the network performance. LoRa PHY gives the flexibility of several transmission settings to be adjusted [58]. The SF, the BW, and the CR are the three main factors that affect the transmission time, and, thus, the overall network capacity.

Many works highlight the capability of LoRa transceivers to simultaneously decode more than one signal at the presence of one or more SFs [59], [78]. As far as intra-LoRa interference is concerned, several works, using different approaches, exhibited converging results. Namely, it is shown that even a 1 dB stronger signal can survive and can be received correctly if it starts not later than 3 symbols after the start of the weaker same-SF coinciding one [78]. Besides, using a temporal analysis, most works showed by means of simulations and/or experiments the high potential of the capture effect. If the desired signal is 6 dB stronger than the co-SF interference (and any kind of interference), it will be received almost certainly [62], [65]–[67]. In the same case for only 3 dB stronger signals, a successful reception is also very likely [66], [67].

Regarding the interference among different SFs, it has been shown that different SF signals affect each other in cases of a large power difference between the stronger interfering signal and the weaker interfered one. In all relevant works it is shown that smaller SFs are more susceptible to inter-SF interference than larger ones. Thus, inter-SF interference can somehow be tackled by adjusting the transmit power levels of the nodes. However, this is not always a safe solution because of the very likely changes in the environmental conditions, the appearance of obstacles, and node mobility. In addition, interfering signals with neighboring SF values to the SF of the interfered signal influence it more than non-neighboring SFs [62], [67].

Furthermore, the same or different SF signals colliding in the same LoRa network (intra-SF or inter-SF interference) and other types of interference on LoRa networks are also underlined [65], [73]. These include interference from non-LoRa signals and inter-LoRa interference from other neighboring LoRa networks. Some studies pinpoint that the non-LoRa networks interference does not cause a significant damage to LoRa networks [64], [65]. More specifically, interference from external sources is not a problem as long as it is no more than 3 and 89 times stronger when coinciding with LoRa signals that use SF7 and SF12 respectively [65]. Inter-LoRa interference is getting weaker as the distance between the interfering LoRa cells gets larger and as their number gets smaller [73]. Directional antennas at the EDs can be used to mitigate inter-LoRa interference [61], [73].

In LoRa range studies, the network coverage depends on its innate features and the environment that it is deployed in. The deployment environment can vary, as it may be densely built urban, suburban, rural, on the sea or in generally LoS capable areas. Different propagation losses and fading occur in each of the above cases [59], [68]–[70] that influence the packet successful reception levels and degrade or improve the network performance in combination with many other network features. Moreover, the node mobility influences the packet reception probability as it is considerably influenced by the speed of the transmitting ED [77].

TABLE VI
LoRa PHY Selection Characteristics & Deployment Parameters Along With Their Corresponding Effects on the Network Performance

Characteristic	Negative effects on Performance	Positive effects on Performance	Importance	References
SF selection	Higher values reduce the capacity because of the higher transmission times. Transmissions with the same SF (and the same channel) are subject to intra-SF interference when they overlap in time. Inter-SF interference may appear between transmissions with different SFs.	Parallel transmissions with different SFs are mostly orthogonal to each other. Thus, multiple SFs considerably increase capacity.	High	[58], [59], [61], [62], [65]–[67], [70], [74], [78]–[80]
BW selection	Transmissions with the same or different BWs may collide with each other depending on their SF and on the received power. Higher BWs are more vulnerable to non-LoRa GFSK interference.	Higher values increase capacity (at the expense of lower coverage ranges) because of the shorter transmission times.	Low	[59], [64], [66]
CR selection	There is a trade-off between reliability and transmission time which can lead to lower or to higher performance. In general, lower values (e.g., 4/8) reduce the capacity because of the higher transmission times. However, the communication becomes more resilient to errors.	Higher values (e.g., 4/5) increase capacity because of the lower transmission times. However, the communication becomes less resilient to errors.	Low	[59], [64], [66] [58], [59]
Transmit power	Signals with a low transmit power are in general more vulnerable (i.e. to path loss, shadowing and to interference) than stronger signals. However, the received power at the gateway plays a dominant role on the survival of a signal.	The transmit power can be adjusted to achieve longer ranges or better energy consumption. However, it can be also used (under some circumstances) to control the received power at the gateway and take advantage of the capture effect. Imperfect SF orthogonality can also be tackled by properly adjusting the transmit power.	Medium	[58], [62], [65]–[67], [80]
Channel selection	Transmissions on the same channel are subject to intra- and inter-SF interference. In LoRaWAN, downlink transmissions in RW1 may collide with each other or with uplink transmissions on the same channel. In RW2, only downlink transmissions can collide with each other.	The more the channels, the higher the maximum network capacity. However, the load must appropriately be balanced among all channels to get the maximum benefit.	High	[59], [79]
Number of GWs	Single-gateway networks may suffer from low performance, especially in the presence of downlink traffic.	The use of multiple gateways is the most efficient way to increase the probability of packet delivery, and, thus, the network capacity in Aloha-based protocols such as LoRaWAN.	Very high	[58], [61], [74], [80]
Node distribution	Over-crowed areas may decrease performance due to the high number of nodes using the same SF (The problem is connected to the SF-assignment problem presented in Section VI-C).	The performance improves when most of the nodes are located closer to the gateway.	High	[75], [76]
GW position & elevation	Low elevation antennas or indoor antennas dramatically decrease the probability of packet reception.	Positions that minimise the average RSSI and allow access via multiple and lower SFs provide better performance. LoS and higher elevations (up to some point) also improve performance.	High	[61], [69], [70], [74], [80]
Directional antennas	Two devices can communicate only if their disk sectors intersect.	The use of directional antennas can mitigate the interference coming from neighboring LoRa networks and increase the achievable range.	Low	[73]
Capture effect	-	The capture effect considerably increases the network capacity of an Aloha-based LoRa network. 6 dB is an efficient threshold to successfully decode concurrent signals.	Medium	[59], [62], [65]–[67], [79], [81]
Path-loss & other effects	Phenomena such as path-loss, and shadowing negatively affect the LoRa performance and may limit the network coverage. They have an impact on network capacity since they affect the SF assignment and network metrics such as PDR. The Doppler effect may also have a negative impact on performance.	Favorable channel conditions increase the possibility of assigning smaller SFs to EDs, thus allowing the possibility of a larger cell capacity.	Medium to high	[59], [68]–[70], [74], [77], [80]

It has also been observed that deployment characteristics such as multiple gateways and ED antenna gains [72], [73] as well as the elevation of their respective antennas [70] most likely alleviate path-losses, increase successful packet ratios and improve a LoRa cell's capacity. In addition, a certain number of gateways with a specific area deployment can be used to achieve a desired coverage probability of a given LoRa network [61] and also increase the packet success ratios in case of external interference [61], [73]. The exclusion of the SF12-assigned EDs seems to also improve the overall cell throughput at the expense of a slightly shorter coverage [61].

In conclusion, LoRa PHY layer provides a high level of interference resistance when competing with other radio technologies. In Aloha-based networks, the number of deployed gateways plays a critical role for the capacity of the network. The selection of PHY layer settings and the transmit power also considerably affect the overall performance because they can increase or decrease the number of collisions. This selection is further discussed in Section VI. Finally, the distribution of the nodes around the gateway also affects the overall capacity of the network.

V. LoRaWAN MAC Performance Determinants

This section surveys studies related to the performance and the capacity of the LoRaWAN MAC layer. The role of factors such as the Aloha medium access, the downlink activity, the radio duty cycle, and the uplink traffic generation patterns are examined. Works proposing mathematical models to reproduce the LoRaWAN's behavior and works estimating its performance and capacity using computer simulations are also presented.

A. *LoRaWAN MAC Assessment*

Several works examine in depth the capabilities as well as the limits of the LoRaWAN MAC layer. In [75], the focus is on the performance analysis of LoRaWAN networks in terms of scalability and capacity. Firstly, the potential throughput of a LoRa node when using LoRaWAN is estimated. Transmission settings such as data rates and maximum packet sizes [57] as well as the presence or not of downlink traffic are considered. Thus, the maximum potential throughput, at the application and MAC levels, in each possible case is calculated. Furthermore, considering the imposed duty cycle restrictions, the maximum feasible application level throughput is calculated per DR and per duty cycle value. Given the above results and also considering the channels used for transmissions, the possibility of different SF concurrent transmissions per channel and the specific application requirements (i.e., transmission rate and message size) the maximum theoretical capacity (i.e., number of nodes when perfect synchronization and scheduling are assumed) and the best possible capacity for LoRaWAN networks (and optimal for Pure-Aloha) are calculated. A similar and more inclusive work is presented in [77]. The longest and shortest uplink packet duration per physical channel are calculated as in [75]. Using the latter and considering the duty cycle restrictions, the maximum application throughput for non-confirmed transmissions per channel and per duty cycle value is presented. Specific application loads and channel configurations are considered and the maximum number of nodes under perfect synchronization and scheduling for future reference as well as the real optimal throughput are presented. In addition, based on the best feasible throughput and two different scenarios, i.e., urban and suburban, the coverage (i.e., radius) and the average node densities are reported. They are shown to be dependent on the transmission rate and the number of available channels.

Similarly, Adelantado *et al.* [82] show the relationship between the throughput and the load of a network. Assuming the minimum of three-channel LoRaWAN networks with perfect SF orthogonality and no capture effect, it is shown that as the load increases (i.e., increasing number of nodes and transmission rates), after a specific point, the throughput rapidly decreases due to the increasing number of collisions, with only the duty cycle restriction holding back a little bit this decline. It is observed that, although the duty cycle limit was introduced to achieve collision reduction and access fairness to the medium, it also acts as a throughput-limiting factor for low load networks. Thus, in a cell with a small number of EDs the limiting factor of the number of received packets per node is the duty cycle whereas in a large cell the prominent limiting factor are the presented collisions. Alternatively, it can be said that despite the many advantages of LoRa's physical-layer and the agility of its MAC-layer, the nodes' Aloha-like access to the medium is an important performance-limiting factor.

Georgiou and Raza [83] model the innate PHY characteristics and the behavior of the LoRaWAN networks by means of Stochastic Geometry. The respective probabilities of packet failure, due to the low SNR received signal (below the acceptable levels at the receiver's side) and/or the intra-SF interference are modeled. During this analysis, transmission with Rayleigh fading is considered. The path-loss attenuation functions are considered according to the Friis equation (using a path loss exponent values of $\eta \geq 2$ and, more specifically, equal to 2.7 in sub-urban environments). The mathematical model and the simulations show that SNR is only affected by the distance while the intra-SF interference is affected mostly by the increasing number of nodes. An exponential decay with a larger number of end-devices is observed.

Waret *et al.* [84] present a theoretical analysis of the throughput of a LoRa network stressing the importance of the imperfect orthogonality of the SFs. Two cases are examined; a cell where the nodes are randomly (with equal probability) assigned to each SF and a cell where the nodes are assigned to an SF based on their distance from the gateway. Simulation and analytical results show the significant impact of the inter-SF interference on the network throughput. However, the authors agree that the main scalability factor of LoRaWAN seems to be the intra-SF interference when two or more packets overlap in time. Finally, as with other studies, the need of a more scalable SF allocation algorithm than the distance-based one in order to improve capacity in LoRaWAN is stressed.

In [79], a packet level, event-based model for LoRaWAN was developed using the Riverbed Modeler. The path-loss model used is based on the Hata Rural model. The BER model was created with MATLAB simulations where the BER curves were obtained for varying S(I)NR for all SFs in an additive white Gaussian noise channel and a coding rate of 4/5. For calculating the BER of a packet in case of no collisions the SNR at the GW of the desired packet is used. In the simulated scenarios, the impact of the considered collision model, of the number of channels, of the applied duty cycle restriction, and of the application generated traffic on the performance of a LoRaWAN cell are studied. In single ED scenarios the

PDR per SF as the distance increases is shown to validate the simulator functionality. More importantly, the effect of the duty cycle restriction is showcased with the stabilization of the transmitted traffic above a limit of the generated traffic. Moreover, with the addition of channels of different sub-bands an almost linear increase of the transmitted traffic is shown.

B. Effect of Downlink Traffic

There are many studies in the literature that stress the significant impact of the downlink traffic on the LoRaWAN performance. The works of Bankov *et al.* [60], [81] focus on that impact taking into account the presence or lack of presence of the capture effect. A mathematical model is created which calculates the PER as a function of the network load. The analysis shows that the effect of the re-transmissions cannot be ignored when estimating the PER of a network. A PER 50% higher when re-transmissions are considered was observed. In addition, a simulation is used and similar results are shown until the point where a maximum load is reached. In the case of the capture effect, the performance is substantially improved, showing once more that it is a factor that must not be ignored when modelling a LoRaWAN network. In their latest work [85], the authors also take into account the transmission failures due to channel noise. These failures seem to be a dominant performance degradation factor for low traffic loads.

The negative effect of the downlink activity is also stressed in many other works [70], [72], [79], [86]. Varsier and Schwoerer [72] show that the QoS and PER metrics deteriorate faster if downlink traffic is present compared to the case when there is no downlink traffic as the number of nodes increases. The same impact is observed by Markkula *et al.* [79]; when confirmed traffic is required. The GW seems to be having trouble acknowledging all the uplinks in the RW1 or in the RW2 slots as the transmitted traffic increases.

As Pop *et al.* [86] mention, this happens due to the imposed duty cycle that is valid for the GW transmissions as well, along with the increased demands to serve the downlink traffic on the GW. The 1% or 10% usage of the channels (in Europe) is getting narrower as the network grows larger and the GW starts having trouble sending the needed ACKs for the uplinks along with the downlink data. The latter leads to unacknowledged uplink and downlink data with limited chances of being delivered. Moreover, it is noted that it is not often wise for EDs to change to a higher SF in case of consecutive failures to receive ACKs, as it is described in the LoRaWAN specification in order to overcome problems of poor link quality. That is because, this might occur due to the exhaustion of the GW's duty cycle permitted transmission time or due to the increased probability of collisions. Changing to a larger SF will only exacerbate the problem. Based on the above, special care should be given to the number of re-transmissions allowed in the case of confirmed uplinks. While in unsaturated cells, only a small number (i.e., one or two) of re-transmissions is necessary, in more loaded networks a value of up to four re-transmission attempts is needed to achieve over 90% of successfully acknowledged frames. For saturated networks higher values of re-transmission attempts are necessary. However, in the latter cases, the network goodput drops and the energy consumption increases significantly highlighting the need of deciding the re-transmissions properly and/or of alternative strategies instead of re-transmissions for having reliable LoRaWAN networks.

Similarly, in [87] a study on the impact of the confirmed uplinks, coined as high priority traffic – in contrast to the low priority unconfirmed ones – takes place. A simulation environment (MATLAB) is used to observe the impact of a varying ratio of confirmed-to-unconfirmed traffic on the network throughput and on the outage probabilities metrics per traffic case. Capture effects are not considered and perfect SF orthogonality is assumed. It was shown, as expected, that as the confirmed-to-unconfirmed traffic ratio increases, the total network throughput decreases more drastically than in the case of a decreasing traffic ratio. Moreover, as with [86], the authors stress the need of setting an adaptive number of re-transmission attempts for the confirmed uplinks. In addition, it is mentioned that the number of channels used and the gateways deployed help overcome the duty cycle restrictions applied on the EDs' and on the gateways' transmissions. Similarly, different sub-band channels can be used to achieve a higher ToA availability since the duty cycle limits are only shared among channels of the same sub-band (in Europe).

An interesting observation is made by Van den Abeele *et al.* [88]. By simulating the effect of confirmed traffic on the network performance, they discovered that in medium load cells a fixed number of transmissions of unconfirmed packets is a more efficient and reliable choice to finally deliver a packet than the choice of confirmed packets in medium load cells. Also, when downlink traffic besides ACKs is required, in the worst case the PDR of the uplink traffic is only slightly affected, mostly due to the DL-traffic's rarity.

Centenaro and Vangelista [89], [90] propose improvements on the gateways' hardware as well as on the LoRaWAN functionality of the confirmed uplinks in LoRa networks. This comes as a continuation of the observations made in their previous work [87] where the negative effects of the increasing confirmed uplink traffic on the LoRa networks performance were observed. They propose the decoupling between uplink and downlink traffic, using exclusively only one channel in the h1.6 band (869.4–869.65 MHz) for all downlink traffic. As it was explained in Section III, this channel is used only for the RW2 of the class-A confirmed uplinks and implements a duty cycle of 10%, with an allowed ToA of up to 360 seconds per hour, and a maximum transmission power of 27 dB. They also stress that the use of all the available channels in the spectrum (compared to the minimum 3 of LoRaWAN specification) considerably improves the performance. They also argue that if it was possible for the LoRa transceivers to transmit at different SFs at the same time, the performance would greatly improve. Also a varying transmit power (19-27 dB) is proposed during the parallel downlinks to leverage the higher allowed transmission power, achieving higher power budgets per SF than then one achieved during uplinks. The above proposal is tested against a network applying the LoRaWAN specification and

TABLE VII
LoRaWAN Network Performance- and Capacity-Shaping Factors

Factor	Effect on Performance/Capacity	Importance	Mitigation	References
Aloha-based MAC	All studies stress a performance limit because of the unregulated medium access. As the load increases (i.e. the number of nodes and the transmission rate) and after a specific point, the throughput rapidly decreases, due to the increasing number of collisions.	Critical	Deployment of multiple-gateways at different positions, optimized node area distribution and node density (when this is possible), packet creation and transmission control.	[75], [77], [82], [83], [95] [60], [70], [72], [79], [81], [85]–[87], [89], [90] [91], [93]
Radio duty cycle	Regional duty cycle restrictions have been imposed to increase fairness. However, several studies showed that these restrictions also positively affect the network capacity because they limit the number of collisions in saturated channels. Nevertheless, the duty cycle has a high negative impact on the gateways and on the confirmed traffic.	High	Good scheduling of uplink confirmed data can mitigate the problem of limited downlink time of the gateways. However, the deployment of multiple gateways is the only reliable solution.	[75], [77], [82] [70], [79], [86], [87], [89], [90] [93]
Downlink traffic	There is no provision in LoRaWAN to support high loads of confirmed traffic. As a consequence, high downlink demands can easily slow down the performance of the network. This comes in combination with the limited radio duty cycle.	High	Deploying additional gateways is the only major mitigation solution with the current version of the protocol. Proper scheduling of acknowledgements on the network server can increase fairness among all nodes.	[75], [77] [60], [70], [72], [79], [81], [85]–[87], [89], [90]
Downlink channels	The available downlink channels may not be enough to accommodate all the downlink traffic. This leads to a downlink traffic bottleneck, re-transmissions, and reduced capacity.	Medium	Currently the protocol does not support the addition of extra dedicated downlink channels but only uplink ones that can also be used for downlink.	[75], [77] [60], [70], [72], [79], [81], [85]–[87], [89], [90]
Downlink windows	If a gateway is not available for downlink traffic in 2 seconds interval after the uplink transmission, re-transmissions occur leading in increased traffic and low performance.	Medium	The protocol does not support a way to add extra receive windows. Manipulation of re-transmissions before dropping a packet may be used to alleviate collisions.	[75], [77] [60], [79], [81], [85]–[87], [89], [90]
Traffic pattern	The examined studies show that bursts in traffic cause a higher number of collisions due to the channel saturation but also due to the unavailability of the gateway especially in confirmed traffic which causes re-transmissions. In periodic traffic, the performance is smoother but still degrades at the presence of high traffic and at the presence of a small number of gateways.	Medium	Adding more gateways and changing the transmission settings are the two solutions proposed.	[91], [93]

conventional GW hardware using simulations. While varying the network load and the ratio of confirmed-to-unconfirmed uplinks, higher overall network throughput values and lower outage probabilities are observed in comparison to the ones of the conventional LoRaWAN functionality.

C. Effect of Uplink Traffic Generation Pattern

In [91], an evaluation of the LoRaWAN performance in the presence of different traffic generation models is presented. An extended version of LoRaSim is created and used as presented in [92]. This version of LoRaSim is able to simulate cells in which traffic is generated not only exponentially but also periodically and randomly distributed. In addition, it is also possible to simulate LoRa cells in which there exist groups of EDs that generate packets using different traffic generation models at the same time. Thus, the simulation of a LoRa cell with multiple concurrent IoT applications is possible. Several unconfirmed traffic generation cases are tested such as periodic, event based, hybrid, and exponential, where each of them corresponds to specific real-world applications. Three transmission settings scenarios are considered; SN1 with SF12, BW125, CR4/8, and one channel, the same as the SN1 but in this case using three channels (SN2), and one with randomly selected transmission settings from all available value ranges of SF, BW and CR (SN3). The simulation results show that an increasing number of EDs in exponential, periodic and event-based traffic cases can be reliably supported when SN3 is employed. The same holds in cases of SN2 in multiple-GW cells. Better results are exhibited in the hybrid traffic case where it seems that SN2 and SN3 single-GW cells can be supported besides multi-GWs scenarios.

In another work [93], the LoRaWAN's performance behavior is evaluated during a periodic and during an event-generated traffic. In the specific case under study, events (e.g., a fire) that trigger uplinks when they are detected are considered. These events may trigger multiple neighboring EDs (that are spatially correlated) after a specific time. For modelling this kind of traffic, a Coupled Modulated Markov Poisson Process [94] is used in which the traffic is described as a Poisson process modulated by a Markov chain. To study the traffic described above a 3-channel LoRaWAN network with class A unconfirmed uplinks and a gateway in the center of a 2500m radius deployment area are simulated. An urban area is assumed and the respective Hata path-loss model is used considering possible building penetration losses as well. Moreover, intra-SF and inter-SF interference as well as duty cycle limits were considered. EDs used four regular periodic traffic patterns with different probabilities and a Pareto distributed payload value. Using a series of simulations, it is concluded that a gateway might be able to handle a large number of EDs under average loads that is not the case when there occur propagating events via triggering neighboring EDs.

D. Takeaways

The LoRaWAN performance heavily depends on its adopted Aloha MAC layer. Table VII summarizes the top factors that affect LoRaWAN's performance at the MAC layer. Additional factors such as the radio duty cycle restriction and the downlink channels are considered. A number of solutions – as proposed by the studies – to improve performance are also listed.

The majority of the papers show how LoRaWAN networks scale with increasing traffic demands [59], [60], [72], [75], [79], [82]. While in low traffic cases LoRaWAN cells seem able to service a large number of EDs, in high traffic cases they become unable to service the required number of EDs efficiently. The unregulated access to the medium is characterized by most studies as the most critical factor of limiting the LoRaWAN capacity. Capacity baselines for assessment and comparison with other MAC redesigning efforts can be estimated as in [75], [77], [82] for specific IoT traffic cases. In efforts of modelling LoRaWAN cells, the successful transmission of packets is examined and the main factors that can prevent it are modelled analytically [81], [83]–[85], [95], [96]. These works employ mathematical tools to analyze LoRaWAN's Aloha-like performance given a series of LoRa PHY characteristics such as those were described in the previous section.

Duty cycle restrictions have been imposed for sub-GHz ISM bands in the EU (or per channel in the U.S.) to achieve fairness in the time to access the shared network medium avoiding cases of EDs monopolizing it. Moreover, imposing a duty cycle restriction seems to achieve stabilization of the network uplink throughput after a certain network load value since it lowers the number of collisions. However, it acts as a throughput limiting factor given a low network load [79], [82]. In the case of confirmed uplink traffic and/or of downlink data, the duty cycle restriction that is also valid for GWs becomes a bottleneck, since GWs start suffocating due to the lack of enough available transmission time so as to both acknowledge uplink data and to send downlink data (e.g., commands) [44], [45], [79], [86]–[90]. This fact soon leads to a channel saturation problem due to the high number of packet re-transmission cases that lead to more traffic that in turn leads to more collisions.

Improvements on the above described impact of confirmed uplinks and of downlink traffic are achieved with the increase of the number of deployed gateways as discussed in Section IV. The increase of the number of available channels from 3 (minimum required) to more has also a positive effect [87], [88]. An alternative proposal is presented by Centenaro and Vangelista [89], [90] that also highlights the above problems. LoRa hardware and LoRaWAN protocol improvements are proposed to overcome mainly the GW side limitations, dealing with the available duty cycle limited transmission time and the possibility of multiple parallel GW transmissions. A fixed number of repetitions of unconfirmed uplinks as an alternative to confirmed transmissions is also proposed since according to a study yields better PDRs [88]. Finally, many researchers bring up the issue of a better re-transmission policy than the one currently used in LoRaWAN [86]–[88]. For instance, the number of retransmissions can be adapted to the current traffic load in the cell. However, how the nodes can massively get aware of this information raises a new problem. Indeed, the gateways could easily run out of resources if a large number of EDs needs to get the traffic load status in regular time intervals.

VI. ADR Enhancements & Alternative Solutions

As it was mentioned in previous sections, the assignment of SFs is critical to the system performance and to the overall cell capacity. Thus, a number of approaches proposing ways to improve the performance of the ADR mechanism of LoRaWAN cells are presented in this section. The works presented below are described as enhancements or as alternatives to LoRaWAN's ADR mechanism.

A. ADR Analysis & Enhancements

Slabicki *et al.* [97] propose an improvement over LoRaWAN's ADR for environments with high variance in path-loss (e.g., with mobile EDs). The ADR mechanism as outlined in [35] and described in Section III is simulated and examined. The authors observe that choosing the maximum SNR value (of the last 20 uplink transmissions) as a link quality indicator leads to an overestimation of the channel quality. To tackle the above problem, a new improved ADR link-based algorithm, called ADR+, is proposed. This algorithm consider as an SF assignment indicator the mean value of the last 20 uplinks SNR values received by the GW and not the maximum SNR value. The simulation results comparing ADR and ADR+ based networks in OMNET++, showed a significant PDR improvement in environments with medium or high variability in path-loss (i.e., badly conditioned channels with a shadowing standard deviation of $\sigma > 2.25$dB). Similar improvements are exhibited in the energy consumption per successful transmission. A network-centric approach is also proposed that assigns SFs based on an equal intra-SF collision probability as in [98]. The evaluation results showed that ADR+ and the network-aware approach exhibit comparable results for a small number of EDs. The performance changes as the number of EDs increases with the network-centric approach showing better delivery ratio values.

Hauser and Hégr [99] also study the ADR implementation of the TTN. The authors highlight three possible improvements and present interesting simulation results. The first improvement is related to the received signals with an SNR close to the threshold of being able to be received. This causes the transmission settings imposed by the ADR (since there is a downlink message every now and then) to be most of the time sub-optimal and oscillating (depending on the SNR received) between neighboring transmit power settings (in the same DR).

The improvement proposed here is to choose the next larger SF (smaller DR) before increasing the transmit power (which is the only thing the ADR does when the SNR of the transmission decreases). The second improvement is that instead of taking the maximum SNR of the last 20 received transmissions of an ED to calculate the appropriate transmission settings (first the DR and then the transmit power), to take an SNR calculated by a function of an exponentially decaying weighted average of the past N averages. This approach avoids possible SNR outliers and calculates an average that favors the most recent SNR values over the older ones. The outcome here is a better starting point for the algorithm in the case of badly conditioned channels. The third improvement is to decrease the granularity by which the steps are taken when the calculated margin of the received signal SNR is positive (i.e., the transmission is received with a very high probability) in order to decide the optimal transmission settings (increasing DR and/or decreasing transmit power). According to the authors' recommendation, the above should be happening in smaller steps (e.g., increasing DR3 to DR4 instead of DR5 and decreasing the transmit power similarly) thus avoiding possible oscillations. These oscillations occur when the calculated link margin of a received signal lies approximately at the midpoint between two "decision levels" of the algorithm. The evaluation of the previous proposals was conducted in MATLAB and showed considerable performance gains in terms of PDR especially by applying a combination of the first two proposals.

B. ADR Alternatives & Settings Allocation Solutions

The works in this subsection propose a number of SF assignment solutions (sometimes in combination with other settings) in order to reduce the number of occurring collisions and, thus, improve the network capacity. These solutions can be considered as alternatives to the LoRaWAN ADR mechanism.

Farhad *et al.* [70], [100] present two alternative ways of assigning SF to EDs with the aim of improving the packet success rates and the overall LoRaWAN network behavior. The first proposal (Channel-Adaptive SF Recovery Algorithm at the ED side) improves the original functionality of EDs as described in the LoRaWAN specification, where if an ED fails to receive an ACK after two confirmed ULs, it changes to the next larger SF. The authors consider that an ACK reception failure does not always occur due to path-loss but it might also occur due to interference. Thus, the action of resorting to higher SF, means that a higher ToA will only exacerbate the problem of receiving ACKs due to increased collisions. The authors' proposal is to keep track of the number of received ACKs, denoting a series of reliable transmissions in the current SF. If a limit is reached the ED will revert back to the next lower SF given that an SF change to a larger SF has taken place in a previous step. The second proposal (Proposed Distance-Based SF Assignment Algorithm-ED Sensitivity) is based on the power of received transmission signals of the ED at the GW. The latter is communicated to the ED by the receiving GW. Given this, an SF assignment takes place based on the ED sensitivity SF thresholds, which are decided based on the chip used at the EDs. The lower SF possible is assigned to address the required sensitivity and minimize the ToA along with the probability of collisions. These SF sensitivity thresholds of the EDs' chip are usually higher than the GW's respective ones. ADR uses the GW's sensitivity thresholds for assigning the proper SF to the EDs, an action that might lead to successful uplink transmissions but not to the successful reception of the required respective downlink-ACKs. This drawback is being dealt with the above proposal, assuming of course similar chips (i.e., sensitivity levels) are used at all EDs. Simulations are used for validating the presented proposals. The results showed that the first proposal exhibits an improvement of the packet success ratios of almost 7.5% as well as of the average delay metrics (delays of start transmitting and finish receiving a packet, and of a firstly transmitted packet till the final ACK reception). The second algorithm also exhibits packet success ratio improvements in comparison to ADR as the distances in the cell get larger.

Sorensen *et al.* [95] show the importance of the SF allocation strategy on the number of occurring collisions and, thus, on the network capacity. MATLAB simulations are used for validating the analytical capacity results in three different SF allocation schemes in eight-channel cells. The SF allocation schemes are as follows; uniform allocation, where the available nodes are randomly assigned among the six SFs; distance-based allocation that assigns the uniformly distributed nodes based on the required per SF GW sensitivity; equivalent load allocation per SF, assuming greater ED density near the GW, that assigns nodes at SFs while keeping an equivalent network load at each SF (i.e., by assigning EDs equivalently to SFs based on the total ToA of packets per SF). The results show that frames of higher SFs exhibit lower PRR values as the traffic increases, which happens because of their longer ToA values that make the case of experiencing interference more likely. The equivalent load approach exhibits the best results in terms of PRR due to the allocation of more EDs to lower SFs and the equally distributed traffic load among SFs resulting to a smaller number of network packet collisions. The distribution towards smaller SFs also leads to smaller times of occupying the GW's demodulation/receive paths which in turn mean a smaller probability for each transmitted packet of not being able to be demodulated at the GW.

Two SF allocation approaches are proposed by Cuomo *et al.* [101]. The first algorithm, named EXPLoRa-SF, besides using the distance/RSSI information, also tries to allocate an equal number of EDs in each SF group. The second algorithm, named EXPLoRa-AT, is a more sophisticated one as it tries to allocate EDs to SF groups having as a goal the equal total ToA of the allocated EDs in each SF group (see Fig. 7). The simulations, which are conducted in LoRaSim, show a better PRR for the two proposals in comparison with ADR as the packet rate gets higher. The EXPLoRa-AT algorithm achieves the most significant improvement. Moreover, both algorithms performed better than ADR in small cells (radius $<$100 m), while as the cell size becomes larger, the PRRs tend to become equal because in larger areas reachability is the dominant factor. Finally, another set of simulations showed that by increasing the number of EDs in the area close to the gateway, EXPLoRa-SF along with

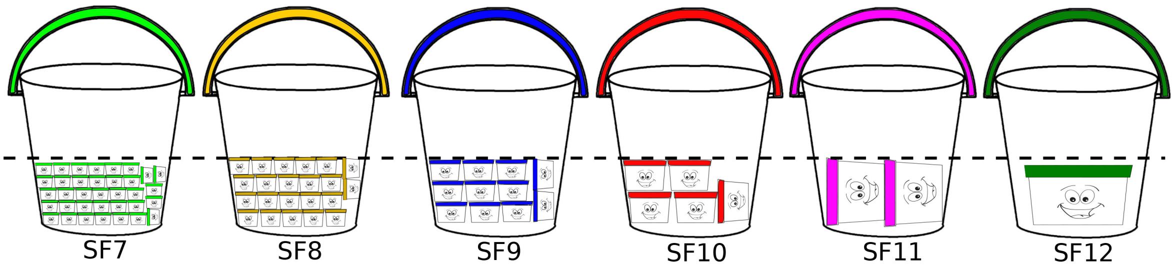

Fig. 7. SF-assignment based on the equalization of the total transmission time per SF [101], [102]. In this example, an equal payload per SF is assumed; bigger packet sizes correspond to higher transmission times because of the higher SFs.

ADR reach their maximum PRR with the same number of EDs, while EXPLoRa-AT reaches its maximum at higher ED numbers (∼40% increase). Both of these algorithms achieve almost all the time larger PRRs and throughput. It should be also mentioned, that after their maximum PRR points, the two algorithms show almost constant values in terms of PRR and throughput which is not the case with ADR. Both algorithms as the number of EDs increases exhibit better channel utilization in small radius cells than the ADR algorithms. However, no results are presented regarding the consequences of the new SF assignment method on energy consumption. The authors extend their work in [102] by mitigating the effect of collisions in areas with clustered same-SF nodes. They propose an algorithm similar to EXPLoRa-AT (namely the EXPLoRa-TS) that also considers nodes using different payloads and transmit rates. Some further improvements are achieved compared to the previous proposals.

The authors of [103] deal with an SF optimization problem. Given a minimum required average probability of packet delivery, they compute the optimal number of nodes per SF that can achieve this requirement in a small cell. Based on their previous work [104], they take into consideration the intra-SF collisions and the capture effect. The analytical results show that the percentages of nodes assigned to SF7··· SF12 are 46%, 26%, 14%, 8%, 4%, and 2%, respectively. Simulation and experimental results validate the analytical results. Moreover, when testing experimentally the PDR metric in a cell with the proposed optimal SF ratios and in one with the ADR (all EDs use SF7 because of the small cell), the results showed a better performance for the first case for a variable number of nodes. However, on average the energy consumption increases because some nodes switch to a higher SF.

A similar theoretical framework for maximizing the capacity of a LoRaWAN network is proposed by Caillouet *et al.* [105]. The capacity is maximized by optimally selecting the SF assigned to each ED considering the intra- and the inter-SF interference while at the same time a minimum probability of successfully being served is assured for each ED in the network. The authors also present a variation of the problem in order to increase network fairness [106]. To achieve this, they compute the probability for a successful frame transmission in a Pure-Aloha manner, given a specific transmission rate (within the duty cycle limits) and a certain number of likely interfering devices when using a specific SF. An optimization problem is formulated as an integer linear program; i.e., find the optimal SF assignments, favorably weighted towards small SFs, that maximizes the number of EDs in the network. Given the SNR thresholds per SF, the channel fading, and a required minimum 66% probability of successful reception, the following distribution of EDs within each SF area was obtained for the 6 SFs; 33%, 15%, 21%, 22%, 8%, 1%. As it is shown, higher capacities can be achieved for lower serving probabilities. Similarly, a larger number of EDs can be served efficiently when the minimum required probability of the successfully transmitted packets is low enough. The positive impact of the capture effect on the number of the served EDs is also exhibited. In addition, the inter-SF interference seems to negatively influence the capacity in unsaturated networks whereas this is not the case near the maximum network capacity. Since the model can also consider cases with more than one GW, significant improvement in capacity is exhibited in such cases. That is because of the increased probability of a transmission being received successfully above the required SNR and the overcoming of collisions with other concurrent transmissions due to the higher GWs' availability.

In El-Aasser *et al.*'s work [107], the goal is the improvement of the overall network success probability. To achieve that, the authors propose two heuristic algorithms, named "SensitivitySFAllocation" and "AssignmentSFAllocation". These algorithms attempt to maximize the throughput per spreading factor by assigning to the nodes combinations of SF and CR. In their first heuristic, the authors base their algorithm on the adjustment of the receiver sensitivity which can be achieved by considering different SFs and custom CRs (non-native LoRa) [108]. In fact, the algorithm assigns lower SFs and higher CRs to nodes closer to the GW and the opposite for more distant nodes with the goal of approximating the optimal network load per SF. The second algorithm comes to the aid of the first one, if the process of setting different CRs per SF has not accurately approximated the desired optimal load, by further fine tuning the SF assignment to EDs (i.e., moving some EDs to higher SFs). The simulation results show performance gains of over 10% in high load scenarios compared to ADR, however, there are no results on how the proposed approaches affect the energy consumption.

The work of Reynders *et al.* [98] studies a similar problem while taking into account node fairness. As with some previous works, the authors compute the optimal distribution ratios of

EDs among SFs to achieve equal intra-SF collision probabilities for each SF. Apart from that, they propose a scheme to distribute spreading factors and discrete power settings to the nodes. The goal of this scheme is to improve the PER for nodes far from the base station which leads to unfairness because of the capture effect. This paper is different in the sense that the goal of the proposed optimization is not throughput but PER fairness. This is achieved by utilizing an estimated path-loss (EDs' received power minus the transmit power) for each node. This information is used to sort the nodes in ascending order and divide them in K equal groups (K is the number of available channels). Then, the EDs in each group are assigned in SFs based on the optimal distribution of the EDs' ratios calculated in the first step of the approach. Afterwards, the EDs in each group are assigned the appropriate transmit power (by taking into consideration the sum of the CIR-co-channel interference rejection [65] and the received power information from each node) in order to reduce the PER of the higher SF assigned EDs (which implies higher PER for smaller SF EDs) and an overall reduced PER for the channel. As it is implicitly understood, the ideal functionality of the proposed solution is achieved when the cell is relatively small (so that the algorithm has no limits regarding the receiver sensitivity levels). The NS-3 simulation results showed an overall fairer behavior by means of the PER metric for the furthest EDs in comparison to the analysis of Georgiou and Raza [83]. An increase was noticed in PER for the EDs in the low SFs, while the opposite was observed for the higher SFs.

The issue of fairness among the nodes is also studied by Abdelfadeel *et al.* [49], [109]. The authors present an algorithm named FADR to achieve a fair PRR among all nodes while at the same time avoid excessively high transmission powers. As it is intuitively understood, fairness decreases drastically with the increasing network size. Even without the capture effect and with perfectly orthogonal spreading codes, fairness decreases due to the different collision probabilities of the SFs. The first step of the authors' approach is to optimally allocate the EDs in the SFs as in [98]. However, this fair collision probability allocation is not applied to the entire network as in [98] but to regions. The nodes are first ordered based on their RSSI and divided into groups. The optimal SF distribution is applied to each group of nodes. The second step is to run the FADR algorithm which takes care of the transmit power levels allocation. The algorithm allocates the lowest possible transmission power that can reduce the difference in RSSI below the CIR threshold to mitigate the capture effect and the imperfect orthogonality of the spreading factors. The simulation results in a modified version of LoRaSim showed that FADR surpasses Reynders' approach in terms of fairness and energy consumption, without sacrificing the PRR. Moreover, FADR achieves roughly the same PRR for a larger proportion of the network than what is achieved in [98], in which high variation is also experienced by nodes with SF7 and high path-loss.

The rest of the studies in this subsection, leverage machine learning techniques in their attempts to compute optimal or near-to-optimal configurations. Ta *et al.* [110] propose a method where the nodes autonomously decide the most efficient transmission settings leveraging machine learning. More specifically, the authors employed the Multi-Armed Bandit approach to formulate the problem and the reinforcement learning based algorithm (called EXP3) on the nodes. Each device is considered as an intelligent agent, capable of selecting the best combination of SF, channel, and transmit power (i.e., action) based on locally available information. Each transmitted packet using a combination of transmission settings gets back an ACK or not, which is considered as a reward of 1 or 0, respectively. Thus, each ED transmission is evaluated by the same ED, altering along the way the initially uniform distribution of the available equal weighted strategies-actions. The key concept here is to explore the available choices (actions) so as to accumulate knowledge (rewards) while at the same time the already accumulated knowledge is exploited by making appropriate decisions. A time horizon of 10^7 iterations during experimentation is chosen and a learning rate, calculated based on the time horizon and the number available strategies at each experiment, is used. EXP3 is tested against uniform and random resource allocation cases. The results exhibit significant improvements on the PRR and on the average energy consumption per packet when using EXP3. However, long convergence times are observed that as noted by the authors are acceptable in static setting cases that are common in wide area IoT scenarios. Also to this end, they propose combining EXP3 with an initial distance-based resource allocation or with getting help from the GW which has a global network view.

Learning approaches to obtain optimal configuration settings are also proposed in [111], [112], and [113]. In [111], Sandoval *et al.* focus on optimizing throughput while dealing with an event-based data generation pattern with certain priorities per packet. A Markov Decision Process (MDP) system is proposed to maximize the number of reported events (prioritized by their importance) while still complying with the duty cycle regulations. The mathematical model was designed having in mind the possible states of a LoRa node (SF/CR combinations), the remaining time to transmit again (i.e., due to the duty cycle), and the priority of the event to be transmitted. The possible actions that a node can take are defined as the transmission settings combination (i.e., only SF and CR were considered since BW is constant). Moreover, each action has a cost and the reward obtained when reporting a generated event is defined as the product of the priority of the event and the theoretical packet reception rate (PRR) under the employed configuration (i.e., the action). Finally, to be able to calculate the reward (for every possible action), the future actions are decided also considering past transmission experiences of each ED (in the simulation the past was based on the last 50 sensing cycles). Thus, the action of a node that has an event of a specific priority to send is decided based on the policy which is computed synchronously at each ED (i.e., to transmit or not in order to achieve the maximization of the expected total future reward). The authors opted for modeling the optimal action-derivation problem as an infinite horizon, discounted reward MDP. A set of possible actions is defined (not sending a packet plus the 12 different combinations of SF and CR) in a state-space of reporting events of different importance (0-2) and 41 cases of available DC times (i.e., 41x3 states totally). To analyze and judge the obtained performance, the proposed MDP-based transmission policy is implemented on a number of nodes in Python-based simulations. The proposed MDP solution was compared to LoRaWAN's ADR with two different transmission policies; the always transmit when an event occurs and the Transmit High-Importance Events Only if the duty cycle permits it. In these scenarios, the average reward values at various transmission rates of normal and high priority events are obtained. The results show the superiority of the MDP solution as they achieve almost 1.5 to 3 times better average rewards. Furthermore, the authors' confident view is that the proposed solution is computationally fitted for the resource-constrained LoRa nodes since such MDP-solving cases run in polynomial time and are suitable for memory-limited devices. Thus, this method is well-fitted for time critical applications as in industrial scenarios. In [112], the authors use the same mathematical model to formulate a similar optimization problem. The optimal transmission policies are computed while each individual node is not allowed to exceed a certain energy consumption.

Similarly to the previous approach, the same authors maximize the network throughput by computing the optimal configuration settings (i.e., SF/CR combination) per node [113], using a GW-based maximization approach in a polynomial time. These optimal settings are analytically computed by the GW and transferred to each ED via one of the downlink windows. The authors underline that the update of the nodes should happen in a way that maximizes the accumulated average throughput per node obtained during this process. Thus, an optimal updating policy derivation that allows or not the transfer of the optimal settings to each ED is proposed. They propose the usage of a prior created and pre-trained artificial neural network (ANN) at the GW side which will be deciding the updating or not of each ED. The ANN takes as input the state of the network at a specific time (i.e., the sets of updated and not updated nodes), the active receiving windows of the nodes (open or not), and the remaining duty cycle time of the gateway. Furthermore, the ANN is trained by a genetic algorithm after there has been a dimensionality reduction by mapping the original input (that scales rapidly as network size grows) to a new low-dimensional, fixed size one, regardless of the number of EDs in the network. Thus, this low dimensional input is fed into the already trained ANN policy network every time the gateway has to make a timely decision on whether to update a certain nodes, or not. During the implementation for the derivation of the optimal settings table for the network's EDs by the GW, the Sequential Least Squares programming (SQP) method was used. Moreover, the authors note that the gateways can also offload the computation to cloud-based servers. Regarding the updating policy derivation (i.e., training of the ANN), a population of 101 ANNs evolved for 1000 iterations. Each iteration simulated a twelve-hour process in 128 different randomly-generated varying-sized IoT networks with a particular ANN-based updating policy. A learning rate of 0.01 was used and the total time was 58 hours with an 8-core Intel Xeon server. However, as the authors note, this process needs to be carried out only once in the lifetime of a IoT network rendering the training duration of the ANN not critical. This selective update policy was compared to an always update policy and to the LoRaWAN's ADR. The results showed that the combination of optimal configurations and selective updates offers high performance gains in terms of throughput.

Finally, a game-theoretic approach to decrease the overall network interference and to potentially lead to a higher overall probability of packet delivery is proposed by Kumari *et al.* [114]. The authors propose a follower-leader model and analyze the Nash Equilibrium among EDs and the Stackelberg Equilibrium between the GW and the EDs, respectively, and then they assign SFs to the nodes. They also propose a scheduling algorithm to minimize the overall waiting time; that is the time a node has to wait until a transmission performed on the same SF has finished (so that there are no collisions). The whole process takes place at the GW which has an overview of the whole network and can deal with the complexity of the calculations involved. Simulation results, conducted on NS-3, indicate an over 80% throughput improvement compared to distance-based SF allocations. A small number of EDs was used in a small LoRa cell to assess the solution proposed. Convergence during simulations occurred after a relatively small number of iterations of the Nash and Stackelberg equilibrium algorithms and it was dependent on the selected precision thresholds in each algorithm besides the number EDs in the network. However, it should be noted that certain practical LoRa performance-shaping features, such as the capture effect and the imperfect SF orthogonality, have been neglected. No results are given regarding energy consumption.

C. Takeaways

After the outlining of the characteristics, behaviors, and restrictions of the LoRa PHY and the LoRaWAN MAC layers in the previous sections, several works in this section are dedicated to how to improve or develop new settings assignment solutions. Table VIII summarizes the main takeaways of these works pinpointing advantages and disadvantages.

Many works focus on improving the way the transmission settings of EDs are decided and assigned to them. LoRaWAN's proposal is the ADR mechanism [35], [99], [115]. If ADR is enabled a number of settings are suggested to the nodes, such as the least SF with which the ED can reliably reach the gateway based on the ED's RSSI perceived by the gateway. An ED gets informed of the SF assignment as well as of the recommended power settings using downlink data encapsulated in acknowledgments or sent separately. In fact, ADR operates over a sequence of ED-gateway interactions utilizing control commands at both the uplink and the downlink levels [57].

Some works deal with the very same ADR algorithm and the decisions that are taken while assigning SF and transmit power values at devices, resulting in faster and more precise decisions that improve the quality of transmission, and achieve

TABLE VIII
ADR ENHANCEMENTS & SETTINGS ASSIGNMENT APPROACHES

Approach	Description	SF assignment	Advantages	Disadvantages	Experimentally Validated?
[97]	ADR improvements in the presence of varying channel conditions.	RSSI-based	Improved reliability, scalability, and energy consumption.	Inter-SF interference is not considered.	No
[99]	ADR stability improvements	RSSI-based	Reduced PER	Higher energy consumption compared to native ADR	No
[70], [100]	An ED-based ADR system is proposed	RSSI-based	Improved PDR.	The GW has to always send out information about the RSSI back to the nodes, high implementation complexity due to different sensitivity thresholds of possibly different LoRa transceivers.	No
[101]	SF assignment solutions are proposed with the aim to equalize the number of transmission or the total transmission time per SF.	Based on transmission time equalization.	Better PDRs can be achieved since the number of collisions is minimized.	Energy consumption is increased in low network loads.	No
[102]	Detecting areas of clustered nodes of the same SF so as to decrease load, and SF assignment solution for equalizing the total transmission time per SF.	Based on the equalization of the transmitted symbols' weight ed number.	Better PDRs are achieved, collisions in the clustered area are minimized, able to handle heterogeneous traffic.	It is assumed that the EDs' positions are known. Increased energy consumption in low loads is observed.	No
[103], [104]	Optimizing SFs for a given small cell satisfying a minimum average success probability.	Static (optimized)	Optimized PDR.	Energy consumption increases as more nodes are switched to higher SFs.	Yes for [103]
[105], [106]	Optimizing SF settings achieving a minimum success probability per node [105], and fairness. [106]	Static (optimized)	Optimized PDR (Multiple GWs can also be considered).	Increased energy consumption compared to ADR.	No
[107]	Assignment of SF/CR combinations to achieve a better BER.	RSSI- and sensitivity-based	Improved PDR by alternating the CR per SF.	Higher CRs imply a higher energy consumption.	No
[98]	Improvement of fairness in LoRa cells by considering the available channels, optimally distributing EDs among SFs and adjusting the transmit power of nodes.	Static (optimized)	Improvement of the PER for nodes far from the base station (a result of the capture effect).	Higher PER than before applying the proposal for nodes close to the GW.	No
[49], [109]	Improvement of fairness for distant nodes by assigning EDs to similar EDs' RSSI regions, in which the EDs are being optimally distributed among SFs and, furthermore, by adjusting their transmit power.	RSSI-based	Improved PER for distant nodes	In a dynamic environment the transmit power adjustment may be problematic.	No
[110]	ED-based. Machine learning is leveraged so that each node selects the best combination of SF, channel, and transmit power based on local information.	Learning-based	Improved PRR and energy consumption.	Learning mechanisms work only in the confirmed LoRaWAN.	No
[111], [112]	ED-based assignment of SF/CR combinations for event- and priority-based traffic.	Learning-based	PRR gains compared to ADR.	Complex. Confirmed transmissions are required.	No
[113]	GW-based assignment of SF/CR combinations for event- and priority-based traffic.	Learning-based	Throughput gains for the examined traffic scenarios.	Some info from the GW has to be piggybacked in the downlink packets.	No
[114]	GW-based SF assignment based on game theory.	Game-theoretic	Throughput gains for the examined traffic scenarios.	The GW must constantly know the number and the status of the EDs in the network and update their status accordingly. Simplistic collision model.	No

less signaling back and forth between the device and the gateway and higher scalability [97], [99], [100]. Indicatively, the decision of assigning a specific SF is proposed to be based on the ED's signal SNR value, i.e., the mean or the weighted average at the GW and GW receiver sensitivity values. Alternatively, Farhad *et al.* [100] suggest that these decisions be taken based on the ED's receiver sensitivity levels. Moreover, local decisions of when the SF needs to be increased or not, after two confirmed uplink ACK reception failures are proposed, highlighting the fact that non-received ACKs might be due to collisions and not due to path loss related issues [86], [100].

A huge amount of research effort is related to the ADR-alternative transmission settings management. Some works – assuming a small enough network – optimally assign SFs to EDs in order to improve metrics such as network reliability, network throughput, network utilization, and capacity. This happens usually by improving the initial EDs distribution ratios at the SF level, such as to improve the required metric under study [101], [102], [104], [105]. Some studies try to solve on-the-field problems [103] like faster collection times from a known number of devices while achieving a minimum level of average packet success rate by deciding the optimal distribution of SFs ratios to EDs. There are cases where besides SF assignment CR tweaking is suggested as well, as in [107] where a CR adjustment per SF takes place. The goal by this CR adjustment is a similar one as above that is to achieve a near-to-optimal network load per SF and, thus, improve the achievable throughput.

Fairness among the cell devices' transmissions is the main objective of many works [49], [98], [109] – fairness is being defined as equal probability of success of every transmitting ED. Similarly as above, the optimal SF assignment ratios regarding fairness of co-SF collision probabilities are calculated in these works. Secondly, separate groups of similar RSSI EDs are assigned in different channels [98] or in the same channel [49]. In every group the previously optimal SF ratios are applied and specialized algorithms take over by adjusting the transmit power values in order to minimize the network unfairness in terms of PER or of DER.

Machine learning approaches are also proposed to deal with same challenge. In [113], [114] GW-side algorithms are employed to decide the optimal SF assignments achieving improvements on the network performance. The authors of [113] employ a pre-trained ANN to communicate efficiently the calculated optimal transmission settings to EDs. In [114], game theory techniques come into action to calculate the optimal SF assignments that maximize the utility perceived by the GW and by the EDs of the network. However, in both works it seems that there are convergence related issues that might undermine their effectiveness in some IoT use cases. Most of the above works are designed to be network-side centered approaches, which means that the decisions of assigning specific transmission settings happen at a central point that has an overall picture of the network. However, a number of machine learning approaches have recently been proposed to calculate sub-optimal settings and alleviate the overhead cost of the centralized approach. EDs-side suitable approaches are proposed in [110]–[112], where each ED, based on local information autonomously decides the best possible transmission settings combination. These techniques, at the same time, improve network metrics such as PRR, network throughput and energy consumption.

In general, the proposed machine learning and game-theoretic approaches seem to significantly improve performance, even though the findings are based on pure simulation results and none of the approaches has been tested in practice. Nevertheless, according to the authors and the data provided, low computation and memory capabilities are required at least for the ED-side approaches which are based on reinforcement learning. Convergence times are not very clearly discussed in the studies, especially in the case of a dynamic system where the number of EDs and their settings changes rapidly. Finally, a known identified issue in machine learning is that some tweaks on the objective function may be needed to achieve a domain-specific goal [116]. No information whether and how this "tweaking" can be done is given in the proposed approaches.

VII. Synchronized & Time Slotted Schemes

This section presents a number of time-slotted LoRa solutions aiming at improving the network performance by reducing or eliminating collisions. Each solution proposes its own way of accessing the medium, working hand-by-hand or in some times replacing the Aloha-based MAC of LoRaWAN.

A. Slotted-Aloha Schemes

Polonelli *et al.* [118] present a Slotted-Aloha MAC-access method to replace the Pure Aloha approach used by LoRaWAN as illustrated in Fig. 8. The necessary functions, such as the synchronization and the selection of the appropriate slot length, take place as an overlay above the already existing LoRaWAN layers. Firstly, synchronization is implemented as a service at the application server and as a function call at the end-node side; thus, synchronization is transparent to any version of the LoRaWAN stack used. Secondly, the slot size takes into consideration the packet transmission time, the LoRaWAN protocol time overhead and an extra padding interval, which is needed to compensate for the clock drift. In this study, the authors considered a specific scenario where the packet payload is 200B with 6 symbols of preamble; the SF is 9 with a bandwidth of 250 KHz that generates a ToA of about 546 ms. An experimental setup was used to evaluate this proposal against the LoRaWAN simple Aloha MAC layer. The results show a 2 times throughput improvement and a more than 3 times reduction in packet collisions.

In an extended version of their previous work [119], the authors give a more detailed presentation of their S-Aloha proposed solution. Specifically, the new parts of this work are the added functionality of the software component of the overlay realizing the S-Aloha, the experimental calculation of the tolerance interval added in the slot duration to account for clock drift in the nodes, and the further experimental verification of the proposal's superiority over LoRaWAN Aloha-like networks. In addition, it is shown that an S-Aloha deployment of the proposal on LoRaWAN networks achieves similar performance improvement as it does in general wireless deployments (i.e., doubling the maximum Aloha throughput for twice the traffic load). A restrictive factor of the effective throughput, which can be achieved in this S-Aloha proposal is the duration of the tolerance interval that increases the slot duration decreasing at the same time the effective throughput. The slot duration should be proportional to the node's clock drift and inversely proportional to the transmission rate periodicity. Besides, it is stressed that the overlay imposed functionality of transmitting at the beginning of synchronized slots, significantly reduces the collision rate, thus, achieving better network throughput (in comparison to the classic LoRaWAN) even in high traffic scenarios.

Chasserat *et al.* [117] highlight the shortcomings of LoRaWAN adopted way of accessing the channel as well as the advantages of Time Division Multiple Access (TDMA) ways of accessing the channel in terms of capacity and energy

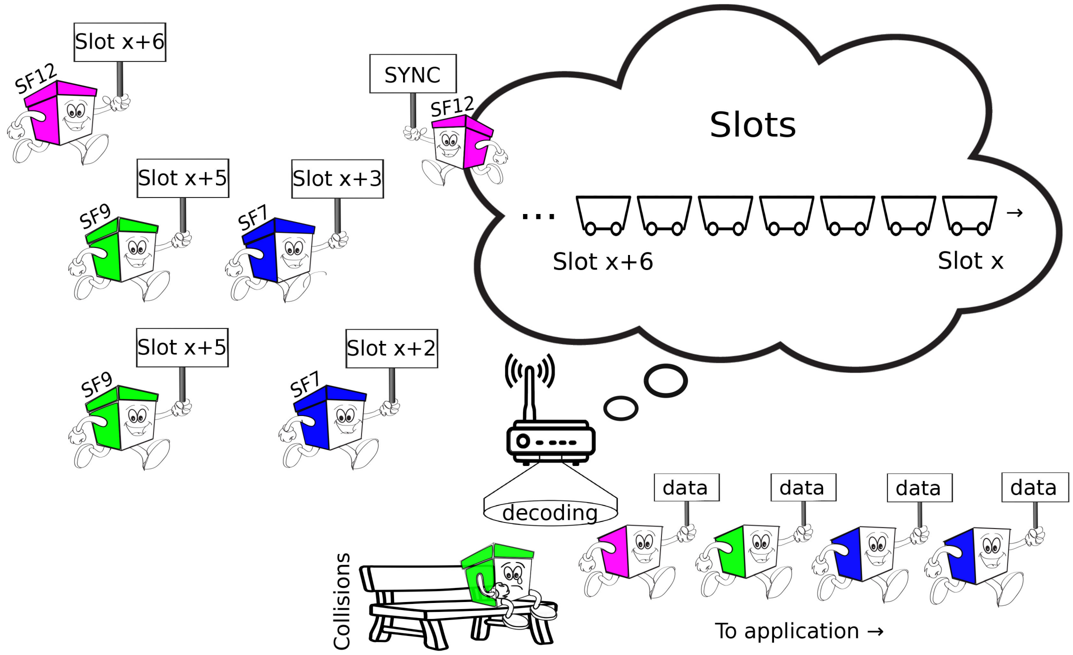

Fig. 8. A variation of the Slotted-Aloha scheme [117] with fixed slot lengths according to the highest SF in the system (synchronization beacons are sent every a while over SF12).

consumption. They stress the fact that Pure-Aloha used by transmitting class-A devices is efficient enough for small cells with rare transmissions, however, for larger LoRa networks the achievable capacity with Pure-Aloha and the rising energy consumption justify the use of synchronized techniques. They describe an abstract way of creating an S-Aloha-like scheme for LoRaWAN unconfirmed uplinks leveraging the class-B beacon-synchronization functionality. Between the GWs beacons, the timeslots are set large enough to accommodate the longest uplink packets of the selected LoRaWAN data rate. In these timeslots, uplinks or even downlinks can be accommodated. Sensing for possible downlinks takes place before the uplink transmission in each slot. The LoRaWAN class-A functionality is compared with the described one, denoted as Class S, in terms of achievable throughput, number of served nodes and energy efficiency. The class S functionality results in nearly doubling the throughput for twice the number of EDs, in comparison with the class-A functionality. However, the energy efficiency metric for class S is worse in all the tested cases. This disadvantage can be overcome if the EDs skip sensing all the beacons and hear only, for example, one beacon per five or ten beacons, thus lowering the energy consumed for sensing beacons. This, of course, should be carefully selected according to the clock drift exhibited in the nodes. Thus, class S after a specific number of transmitting nodes exhibits better energy efficiency than the LoRaWAN class-A functionality. Hence, the authors underline the fact that there is need for a seamless switch between the two modes in order to achieve an overall better network performance in all LoRa networks sizes.

In [120], the design, analysis, and evaluation of a more advanced scheduling technique is proposed. A low overhead synchronization and scheduling scheme for LoRaWAN networks was created, where the timing and the number of transmissions of EDs is dictated by a central entity that resides in the network, preferably at the Network Server. This entity schedules the transmissions of the EDs by sending a list of time slot indices when they are allowed to transmit. These indices are encoded in a probabilistic data structure using Bloom filters to reduce the size of the messages that are needed to perform the synchronization and the scheduling. At each ED's side, a synchronization component is responsible for generating synchronization requests and for processing synchronization replies. Inside a synchronization request, the node includes information such as the requested uplink traffic periodicity, the clock accuracy and/or the resynchronization periodicity. The time slot assignment is based on the availability of time slots, the information that is included in the synchronization request, the SNR and the channel at which the synchronization request has been received. The logic is that a time slot is assigned to an ED only if the time slot in the channel (on which the node made the request) is available and the incurred interference from this allocation results in acceptable SNRs for the already assigned in different channels nodes. The evaluation of the proposed approach is made by means of simulation in NS-3. Two scenarios with in-band and out-of-band synchronization against non-synchronized networks were evaluated; in both of them, the synchronized method outperforms the non-synchronized communication in terms of PDR and of the total amount of delivered data packets. In saturated synchronized and non-synchronized networks, the differences in PDR become more profound as the nodes in the first case are only scheduled as long as they can be accommodated given the remaining capacity of the network while in the second one this is not the case resulting in massive collisions as the number of nodes increases.

In [121], a new MAC-layer for LoRa networks is proposed, which exhibits improvements in terms of reliability and scalability in comparison with LoRaWAN MAC-layer networks by employing a two-step lightweight scheduling (RS-LoRa). The gateway transmits beacons that define a frame-time. Every frame is further divided into sub-frames. Each sub-frame comprises one synchronous slot where a downlink transmission of a beacon occurs and several asynchronous uplink/downlink slots where EDs' confirmed or unconfirmed uplink transmissions are generated in an Aloha-like way. To minimize the beacon loss probability, beacons are transmitted in every channel using every SF in a cyclic manner at the start of any frame and sub-frame. Beacons are used for two purposes in RS-LoRa. Firstly, for synchronizing the nodes (nodes listen to the first beacon once they wake up and then adapt their clocks to the gateway) and, secondly, for carrying downlink information (i.e., each beacon carries information about how to use the uplink/downlink slots in that corresponding sub-frame) which the EDs use later to select the channel and the SF for transmission. The second step of the proposed lightweight scheduling is performed at each ED in a distributed manner. In RS-LoRa, each node uses the information carried by beacons to determine its transmission parameters, namely the channel, the SF, and the transmission power. An algorithm is used to determine the transmission parameters at each node based on alleviating the capture effect and on reducing the probability of packet collisions. The simulations for evaluating this work took place in NS-3. The Okunura-Hata model for urban areas together with Rayleigh fading as the path loss model were used during the simulations. The nodes are distributed around the gateway following a Poisson distribution. Three channels were simulated. In all the scenarios, the comparison took place between RS-LoRa and the legacy LoRaWAN. The results showed that RS-LoRa achieves better PER than LoRaWAN as the number of EDs and the distance increase. The network throughput and the achieved fairness are also better. It was noticed that at close distance the PER values were larger with RS-LoRa than those with LoRaWAN. This happens because of an increase in collisions since all nodes close to the gateway are using the same channel (according to the internal workings of the algorithm in the proposed solution), while in LoRaWAN, they could choose from three different channels. Nevertheless, it seems that RS-LoRa improves the overall network performance considerably compared to the legacy LoRaWAN. Similar results were displayed in a simulated scenario with multiple gateways.

B. Collision-Free Schemes

This subsection describes a number of studies that propose collision-free time-slotted methods. This is achieved by allocating nodes to unique timeslots or channels. An example of such an approach is presented in Fig. 9.

The main idea in [63] is to introduce a new MAC layer for LoRa-based networks by giving the ability to schedule the transmissions such that the collisions are eliminated and the overhead induced by its headers is reduced. The solution proposed is called *FREE* (Fine-grained Scheduling for Reliable and Energy Efficient data collection). FREE considers EDs that do not have delay constraints and have the ability to store locally the sensor data in order to be transmitted whenever a gateway is within reach. This usually means that large amounts of data need to be transmitted in a short amount of time which leads to severe collisions taking place in an Aloha-like MAC layer. The increased number of collisions in a network implies a high-energy consumption and increased collection times. In the beginning, before synchronizing and having a schedule ready, the devices exchange information asynchronously in order to be able to synchronize their transmissions. This phase consists of two consecutive stages. In the first stage, the collection of joining requests from EDs is performed by the gateway, followed by the setting up of their transmission parameters (e.g., spreading factor, channel, transmission power). During the second stage, the calculation and the broadcast (using the highest spreading factor to reach all the devices) of the schedule for all spreading factors takes place. Thus, the nodes are configured and synchronized in an online fashion, as they contact the gateway to send their information. The scheduling algorithm in *FREE* runs centrally at the gateway based on information collected from the nodes: the size of the buffered data and the minimum possible spreading factor. In order for FREE to be able to create a transmission schedule, it structures time into frames, where each frame is divided into a number of uplink slots and one downlink slot at the end. There are six parallel frame structures, corresponding to LoRa's six spreading factors. The slot and the frame lengths are equal for the same spreading factor but they may not be equal for different spreading factors. The slot length and the number of uplink slots per frame depend on multiple factors (e.g., the packet length used, the number of devices per corresponding spreading factor, the guard time). The transmissions are scheduled in such a way that devices with the same spreading factor transmit sequentially and devices with different spreading factors transmit simultaneously. To construct the schedule, one of two contradicting scenarios should be decided. The first scenario is the minimization of the collection time and the second the minimization of the energy spent by the entire system. A simulation tool was created based on LoRaSim for evaluating the proposed solution. This tool considers a log-distance path loss model, a packet error model, the imperfect orthogonality of the spreading factors, the fading impact, the duty cycle limitation at both sides, bidirectional communication and the re-transmission strategy in case of confirmed uplink transmissions. Furthermore, it also considers an extended energy consumption profile. The results showed that joining and synchronizing with the network (i.e., the asynchronous phase) takes some time, which, however does not increase considerably as the number of devices increases. The collisions after that are almost zero, no packets are lost and the PDR is far superior compared to LoRaWAN rates. Even more, the energy consumption is lower, implying a significant improvement of the EDs' lifetime. The above results are similar for both confirmed and unconfirmed uplink transmissions.

Two algorithms, named Light and Global, are proposed in [123] for minimizing the total collection time of a number of known static EDs in a LoRa network while respecting

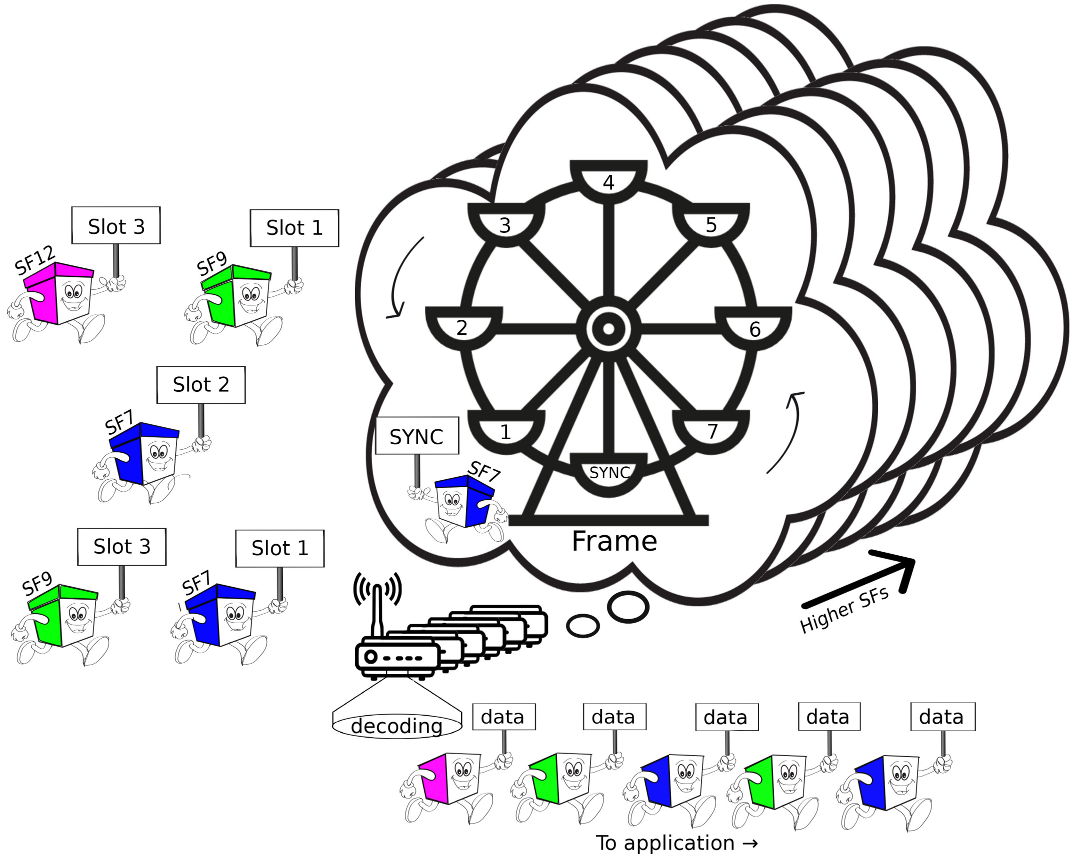

Fig. 9. A proposed collision-free time-slotted approach employing multiple parallel frames, one per SF [122].

the radio duty cycle restrictions. The role of the scheduling algorithms is to compute a frame period by finding the best allocation per node or per transmission so that the total data collection time is minimized. The algorithms schedule node transmissions in slots of different sizes depending on their SF. Transmissions with the same SF are scheduled in different slots to avoid collisions while those with different SF can occur in parallel. The above decisions came up as a problem to overcome in temporary gateway deployments, where a gateway is brought into the network at regular intervals to collect in bulk all the data gathered and saved by the nodes. Both algorithms propose a frame structure similar to *FREE* [63]. Moreover, both algorithms have as input the minimum SF for each node and the payload size per SF (Global also considers as input the ED's buffered data size). In the evaluation of the proposed solutions a specific deployment area is considered as well as a variable number of nodes that are randomly and uniformly scattered. In a scenario with a fixed data size in all EDs both solutions exhibit a reduced normalized (to PDR) data collection time and energy consumption as the number of nodes increases in comparison with LoRaWAN. In a scenario with variable data sizes in the EDs, Global performs better than Light due to its total transmission scheduling. However, because of the long schedule produced, Global is not scalable and Light seems to be the best option for large-size periodic applications, while Global's usage is limited to event-based applications where the time needed to send the schedule to the nodes can be covered by the reduced data collection time.

In [124], an autonomous way to create a time schedule is proposed for a synchronized LoRa network. This entails the decision of the frame length, the number of consisting slots and their assignment to EDs. How synchronization takes place is not examined. The main idea is to use the unique identifier of each device in an SF (DevEUI), along with the total number of devices in that SF in order to calculate the frame length and the assigned slot on each device. For this purpose, the gateway creates a set of N unique integers derived from the unique DevEUIs of each device, where N denotes the number of nodes in a specific SF. A slot number assignment takes place based on the result of the modulo operation between each unique integer and an integer K. K is the minimum integer divisor of the modulo operation that produces a unique result (slot number) for each device. K also represents the optimum number of slots that should exist in order for the network to be able to accommodate all the devices of the specific SF without collisions (and the way the slot assignment happens). Hence, and by having in mind the duty cycle restrictions, the frame length can be calculated. It is obvious, that in this way a large number of slots will remain unallocated, which is the weakness of this approach. The evaluation of this schedule-creation proposal took place in a simulation tool as well as experimentally. The results showed that the calculation of the minimum number of slots that a frame should contain increases rapidly as the number of devices increases, thus creating scalability problems. Nevertheless, as long as the number of nodes remains low the resulting PDR is near to 1.

In [122], a time-slotted approach (TS-LoRa) is proposed that addresses the inherent overhead of centralized scheduling methods in industrial environments. This work follows the remarks made in [125] that outlines the needed considerations that have to be dealt with in time slotted approaches in Industrial IoT. To deal with the schedule creation and dissemination, the joining phase of a node in a LoRaWAN network is exploited and, especially, the created DevAddr information which is returned to the node by the network server during this process. In TS-LoRa, the network keeps track of the joining nodes and reserves a slot number for each node - starting from slot 0 to slot S (i.e., the total number of slots that can be assigned to joining nodes). Having the respective slot number for each node during the joining of a node to a LoRa network, a process of calculating the appropriate DevAddr to be assigned takes place at the network server using the modulo operation of the hashed DevAddr to S. This process returns the desired slot number assigned in the previous step. This step is repeated a few times to discover the appropriate DevAddr that returns the specific slot number. When the appropriate DevAddr is found, it is returned to the node with the join-accept message from the LoRaWAN network server. Thus, each joined node can autonomously calculate its own transmitting slot in the created frames by executing a simple modulo calculation. The frame creation takes places per SF considering the number of joined devices (i.e., transmitting with the specific SF and BW) with the same known payload, the appropriately calculated guard times and the transmission duty cycle restriction imposed on the transmitting nodes. At the end of each frame, a Synchronisation/Acknowledgment (SACK) slot is added in order to synchronize the nodes. SACK also contains a group acknowledgment for the transmissions during this frame. Nodes of different SF are transmitting in different frames in the same channel frequency avoiding inter-SF interference by adjusting their transmit power appropriately [49], [63] or by using different channels. The experimental evaluation of TS-LoRa in a building environment with 25 transmitting SF7-9 nodes showed a PDR of over 0.99 and an overall low number of re-transmissions, while in the case of non-confirmed LoRaWAN PDR was not higher than 68%. In addition, using a power analyzer, a 50% more energy consumption per node is exhibited per frame at each node due to the receiving and processing of the SACK slot. However, if the two ACK downlink slots of LoRaWAN and the re-transmissions caused by the duty cycle shortage at the gateway are considered, TS-LoRa handles far more efficiently the available power at each node. Simulation results confirmed the above results showing the superiority of the proposed MAC over the confirmed LoRaWAN in terms of PDR and energy consumption.

C. Other Synchronised Solutions

In [126], a method to time schedule the LoRa nodes' transmissions is described. The basic idea is to schedule the transmissions of Class B nodes so as to improve the performance of the network in comparison with the Aloha-like network access. The idea in this work is to allocate same-SF transmissions in different channels and then schedule them during the same time-slotted period. Hence, the uplink transmissions in the same SF will have the same duration (same number of timeslots, assuming the same frame payload), and, given that some of them are assigned to the same timeslots (in different channels), a group acknowledgment in the same SF can be sent back (by the gateway) exactly after the end of the specific uplink transmission period. Thus, only a group acknowledgment signal is used for all the nodes. This signal is assigned in a specific time-slotted period and is used instead of sending individual ACKs to verify each node's transmission. Nodes in the same SF that are not assigned in a specific time-slotted period to transmit because there are not enough channels are assigned in the time-slots that follow. The same happens with nodes in different SFs. The performance evaluation results show that the proposed solution performs much better as the number of devices increases. The proposed 8-channel solution does not seem to be affected in terms of PDR as the network load increases. This is not the case with Aloha-based networks, which in the best-simulated scenario support only just above half of the transmitting nodes for a PDR of 90% than that of the proposed solution. The proposed solution starts declining only after there is no more time slots to be assigned in a timely fashion. However, a lower PDR than the Aloha-like networks is achieved in the case of two-channel and almost the same in the case of four-channel networks.

Rizzi *et al.* [127] examine the applicability of LoRa in Industrial IoT. The authors propose a slightly altered LoRaWAN MAC for IIoT applications which encompasses a time-slotted channel hopping strategy (TSCH). A network manager checks the network constantly and ensures contention-free network access by scheduling transmissions in time slots and deciding the SF and the channel frequency of each transmission that takes place during these time slots. The goal of this strategy is to maximize the transmission throughput and the reliability. It is shown experimentally that using different channels along with different SF assignments within a timeslot for concurrent transmissions improves PER. This is expected since the use of different channel frequencies essentially isolates the concurrent transmissions leading to essentially non-existing interference among them which is not the case with just using different SFs. Similar TSCH-based scheduling approaches are also employed in [128] and [129] to achieve multi-hop LoRa transmissions over the well-known RPL routing protocol and the 6TiSCH framework.

A lightweight algorithm to synchronize the LoRa nodes of an IoT network in an industrial environment is proposed in [130]. The proposal considers a network where the number of nodes is known and their identical transmission settings remain unchanged. It is also assumed, that the data rate of each node is the same and constant. Moreover, it is assumed that the data created by each event (i.e., sensor measurements) fit in one transmission packet. Thus, a specific synchronization period can be calculated to accommodate the required number

TABLE IX
SYNCHRONIZED & TIME-SLOTTED LORAWAN ALTERNATIVES

Approach	Medium access	Features & Advantages	Limitations & Drawbacks	LoRaWAN compatible?	Experimentally validated?
[118], [119]	S-Aloha	The nodes are responsible for synchronizing themselves based on the RW1 interval. A small exchange of information is required to achieve synchronization. Simplicity.	When nodes scarcely transmit to the gateway, some additional synchronization phases will be necessary to ensure nodes' clocks do not drift too much. Confidence intervals need to be adjusted according to the specific devices used and the transmission periodicity of data.	Yes, with some modifications	Yes
[117]	S-Aloha	Class-B beacons for synchronizing UL-DL transmissions and for defining slot transmissions times. The idea of skipping beacon sensing to improve energy efficiency.	The slot size is fixed and it is dependent on the longest ToA. The skipping of beacon sensing leads to considering longer slots due to desynchronization issues. Only SF7 has been used, Class-B-based synchronization.	Yes with some modifications	No
[120]	Scheduled	A space-efficient data structure, namely Bloom filters, to encode the time slot indexes, low number of collisions.	Single size slot based on the longest transmission ToA period among all SFs, false positives of the Bloom filters used for transmitting in time-slots.	Yes with some modifications	No
[121]	Scheduled	A two-step lightweight scheduling in which EDs are divided into groups where similar transmission powers are used to reduce the inter-SF capture effect.	The PER, throughput and fairness improvement of the proposal comes with the expense of more energy consumption, not collision-free, not compatible with LoRaWAN protocol.	No	No
[123]	Scheduled	Offline collision-free scheduling. Multiple SF schedule transmission is considered.	Designed for fast data collection so it increases energy consumption; unconfirmed transmissions only.	Yes with modifications	No
[63]	Scheduled	Collision-free data collection; energy-wise and data collection-wise versions; multiple SFs; confirmed and unconfirmed transmissions; grouped acknowledgments.	Very long registration time in the first phase of the process. Single gateway scenario is considered.	Yes with modifications.	No
[124]	Scheduled	Collision-free transmissions; autonomous DevEUI-based scheduling; zero changes on the server side.	Not scalable for networks over $\sim$200 nodes due to the high number of slots left unassigned.	Yes with a few modifications	Yes
[127]–[129]	Scheduled	Possibility of using TSCH over LoRa and multi-hop transmissions, Implementations on ContikiOS.	Fixed SF and time slot lengths; scheduling and routing imply high overhead.	No	Yes
[126]	Scheduled	Scheduling of same-SF confirmed uplink transmissions using class B EDs at concurrent time-slots on different channels followed by the respective group acknowledgements.	Not collision-free; how scheduling is communicated to the nodes is not described; Class-B-based synchronization.	Probably	No
[122]	Scheduled	Collision-free transmissions; multiple SF frames; variable slot size per frame; no scheduling is required; retransmissions; calibration takes place based on the perceived duration of the sync/ack slot; grouped acknowledgments; scalable.	Fixed data size; DLs are not encrypted; 2 or more gateways are required.	Yes with some modifications	Yes
[129]	Scheduled	Use of Contiki-oriented TSCH implementation for LoRa mesh topologies; multihop topologies.	Only one SF is considered; increased overhead; fixed data sizes	No	Yes

of nodes by taking into consideration their similar transmission settings and data requirements (i.e., specific BW, SF, CR and payload for all). The authors assume an optimal situation where the optimal LoRa configuration chosen is SF7, BW 500 kHz, and CR 4/5. The data generated by the sensors fit in a packet with a payload of 230B. This packet has a transmission time of about 90 ms and with the addition of a 4.5 ms guard time before and after each packet an ideal slot duration of almost 100 ms is formed. Considering the 1% duty cycle, the ideal number of nodes (slots) is 100 with a synchronization period of 10 seconds. This optimized scenario gives the maximum network throughput possible when applying the recommended solution. Synchronisation is handled by tracking the difference between the local and the gateway clocks.

D. Takeaways

As the Aloha-like way of accessing the medium is the main limiting factor regarding the performance of LoRaWAN networks, many efforts have been made towards alternative directions. Thus, to overcome MAC-related problems that rule LoRa networks several synchronized time-slotted works have been proposed (see Table IX). The number of collisions that seem to appear very easily is one of the identified issues. These collisions bring the network near to non-usability when the medium faces high network loads. The latter almost certainly has the side effect of increased energy consumption. The uncontrolled way of accessing the medium and of setting up of the transmission parameters also leads to transmission success unfairness among the EDs of a LoRa network. All these have the overall effect of limiting the QoS levels in LoRa cells.

Hence, time scheduling schemes have become a focal point of research in LoRa networks mainly for applications that require very high reliability for a given number of nodes.

Some of the proposed solutions employ overlay methods that use the underlining LoRaWAN functionalities realizing their functionality at a level near the application layer. Thus, an S-Aloha scheme is applied and tested achieving better performance than LoRaWAN [118], [119], [131]. S-Aloha schemes can be leveraged to mitigate the negative effect of massive collisions in Pure Aloha. Indeed, S-Aloha solutions seem to double the throughput according to the aforementioned reference studies. Similarly, the self-synchronization of the EDs and the efficient scheduling of the network servers are proposed in [120]. Better transmission reliability and network throughput than LoRaWAN are achieved. However, the synchronisation may lead to a higher energy consumption in low-utilized networks. In a series of more intrusive works, proposals for more efficient alternative MACs are presented. The use of multiple information carrying beacons that help schedule Pure-Aloha transmissions in channel groups of timeslots set up by the network server is proposed in [121]. Some other works have an on-the-field focus, defining schedules for known EDs that achieve small data collection times [122], [127], [130], [132]. In the more detailed research works besides synchronization and scheduling, also intra-LoRa interference, energy consumption, and collection-time factors [63], [120], [122], [123] are considered.

Many researchers choose collision-free (or almost collision-free) TDMA approaches to achieve better network performance in terms of collision ratio, reliability, throughput, and energy consumption. These approaches fit more in applications with a predicted limited capacity and, usually, with a low number of gateways. The practicality of the synchronized approaches mainly depends on three critical factors [133]: (a) how synchronization is achieved and how accurate it is, (b) how the schedule is disseminated, and (c) the communication overhead of the underlying protocol. The challenge in the first one is how to deal with the gradual desynchronization of EDs up until the next synchronization and do that as energy-efficiently as possible. In the literature, this is dealt by either the exchange of timestamped messages between the EDs and the gateway [63], [119], [120], [130] or by employing the Class B functionality in LoRaWAN [117], [126]. However, a weakness of the Class B mode of LoRaWAN is that it is not implemented in the majority of commercial devices making the practicality of these works questionable. Other works measure the time difference between a node's wake-up and the synchronization reception [122], [129]. Optimal re-synchronization periods are calculated by adding necessary guard intervals between successive slots. The time slot lengths are calculated per SF and usually equal the ToA of the maximum expected packet size plus the calculated guard intervals length. The challenge in the second factor is the transmission of the schedule over the low data-rate LoRa transceivers respecting, at the same time, the radio duty cycle rules. This issue is tackled by allowing the EDs to autonomously organize their transmissions [120], [122], [124]. EDs' reporting periods, duty cycle restrictions, number of serviced EDs, available channels, interference and desynchronization should be and are considered in most of the works. The frames are usually encompassing the same SF transmission slots that are concurrent with frames of different SFs. However, the latter is not always the case [126]. Finally, some of the works leverage the functionality of TSCH to achieve a high throughput in LoRa mesh topologies [127], [129]. However, these solutions suffer from increased overhead due to the signaling of the top-layers of TSCH (6TiSCH/RPL). An important factor that increases the overhead and energy consumption is the transmission of acknowledgments. The gateway may quickly run out of resources by transmitting acknowledgments one-by-one to all the EDs while the EDs may consider that as a transmission failure and re-transmit the packet in the next round. This is the reason why some approaches group the acknowledgments in a single downlink packet [63], [122].

Taking into account all the previous issues, only a few approaches seem to have a practical merit. In any case, synchronized LoRa approaches (collision-free or S-Aloha) suffer from increased energy consumption which, however, may have much a less negative impact than the re-transmissions that occur in a Pure Aloha LoRaWAN [122].

VIII. LoRa CAD-Based & CSMA Schemes

This section is dedicated to works aiming at alleviating packet collisions by performing Listen Before Transmit methods for accessing the common medium. Some of the works described assume a reliable carrier sensing mechanisms and some leverage the existence of the Channel Activity Detection (CAD) mechanism of the LoRa transceivers while studying and testing each proposed solution. CAD is part of the LoRa transceiver designed to detect preambles transmitted over the same channel and SF (see Fig. 10).

A. CAD-Based Schemes

Pham [134] examines the feasibility of using CAD as a means of sensing the existence of transmission activity on a LoRa channel. CAD is destined to detect only the preamble of the transmissions in a channel that uses a specific SF. It is shown experimentally that CAD does not only detect the preamble but the rest of the transmitted message as well. Hence, the author argues that CAD can also be used as a carrier sensing mechanism. However, incidents of no channel occupancy detection start to appear as the distance between the sensing node and the transmitting node gets larger. Thus, the total duration, where a number of consecutive CADs will appear so as to minimize the chance of not detecting a transmission was shown to be the near the maximum value *ToAmax* of a LoRa message (i.e., BW:125KHz, SF:12 PL:255B). Having all the above decided, the proposed CSMA method works as follows. When a node has data to transmit, it checks if the channel is free (i.e., starts consecutive CADs for a *ToAmax* period). If all CADs detect no transmission, a free channel is assumed and the node transmits. If even one CAD detects a transmission, the node defers its transmission for a *ToAmax* delay period. Then, after that delay period, the

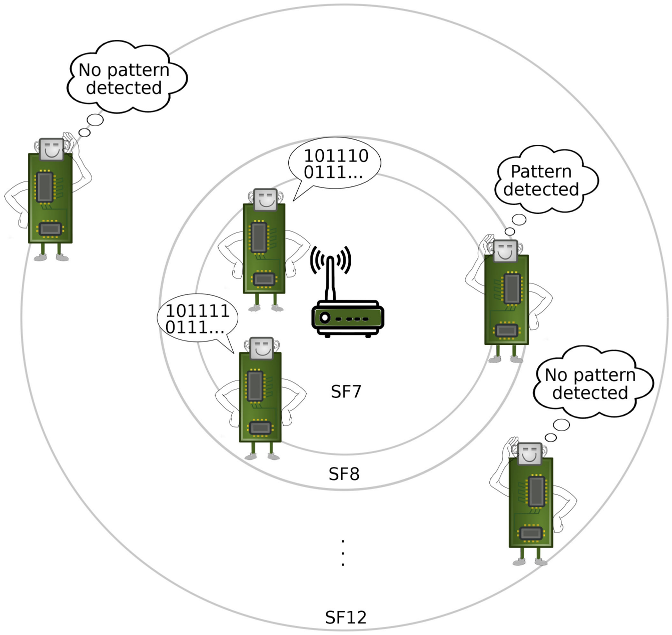

Fig. 10. Five EDs configured with three different SFs use CAD to detect transmissions on their corresponding SF. Two of the EDs (SF7 and SF8) are transmitting and the rest three are listening for activity on the channel. A single channel is assumed.

node checks if the channel is free as in the first step and the entire process is repeated. The process continues until a maximum number of successive unsuccessful efforts to transmit is reached. During the analysis of the above proposal's adaptation of the CSMA mechanism, it was proved to be a more energy efficient and a more feasible solution for LoRa networks than the classic CSMA (i.e., the one adapted from 802.11).

Bor *et al.* [78] tested CAD and the results showed that a transmission's preamble can be detected with a very high probability (97%) if the transmitter and the sensing receiver are set in the same SF/BW settings while the false positives are rare (0.092%). However, if the transmitter and the sensing receiver are set in different SF/BW settings but in close data rates then there is also a very high probability of wrongly detecting channel activity (false positives). These experimental results exhibit that the CAD functionality cannot be used reliably as a clear channel assessment mechanism.

O'Kennedy *et al.* [135] also explore the feasibility of using CAD as a reliable LoRa CSMA mechanism for an environmental monitoring application. As with other studies, the capability of CAD to detect both preambles and payloads is discovered. However, it is stressed that the detection of the payload may be unreliable. By proposing a carrier sensing similar to [134] but applied in conjunction with the RTS/CTS control frames of IEEE802.11, the authors conclude through a series of indoor and outdoor experiments that by taking 8 or more consecutive CAD measurements considerably improves the reliability of the system.

Ahsan *et al.* [136] propose improved mechanisms that leverage CAD for learning the channel occupancy status. Three CSMA mechanisms are described and compared to the solution of [134]. In their first approach (LoRa-BED), a node that wants to transmit senses the channel and if it finds it free it transmits after a random time selected from the range 0-*ToAmax* (where *ToAmax* is the specific node's assigned SF transmission time with the maximum payload). If the channel is occupied, the node tries to re-sense it after a certain delay. This delay decreases after each failed time to detect a free channel until a minimum is reached. In the second approach (LoRa-BEB), a node senses the channel and whenever it finds it free, it transmits. If not, it backs-off and re-senses it after an increasing (each time) time period. LoRa-BEH is a combination of the previous techniques. The simulations took place in MATLAB considering Class A devices with unconfirmed uplinks. Specific transmission settings were used in a single SF (SF11) with a varying payload and a total network load under 1%. The results showed better performance in all the cases compared to [134]. Specifically, improved channel utilization, PDR, and packet collision ratio are reported. The best results, the minimum energy usage and the smallest number of collisions, are exhibited by LoRa-BEB. However, as in [134], the radio duty cycle restriction is neglected.

Kouvelas *et al.* [137] propose an adaptive persistence p-CSMA approach as an alternative to the LoRaWAN MAC. They name their media accessing scheme persistent-Channel Activity Recognition Multiple Access (p-CARMA). In their proposal, they incorporate the use of the CAD mechanism acknowledging its weaknesses as a carrier sensing mechanism. They experiment on the CAD functionality underlining its probabilistic nature in successfully detecting a specific SF's packet transmission in a channel that is caused by its ability only to detect packet preambles and the non-negligible detection rate of possible ongoing transmissions that use other SFs (false positives). As with other studies, it was also found that the CAD preamble detection accuracy decreases as the distance increases, something that can be compensated with the usage of three consecutive CADs. The authors present a probabilistic back-off strategy to perform channel sensing using CAD. They also present a heuristic method which – among others – uses as input the feedback of the gateway regarding the successfully delivered packets and some information about the delay these packets were received with. Having this information as well as the actual transmitting times available, each node can adapt its transmission strategy accordingly. In NS3 the base code from [61] is used along with the authors' own module, that integrated the CAD's observed behavior during the experiments, for evaluating p-CARMA. p-CARMA exhibits a three up to twenty times higher PRR than LoRaWAN in a cell with thousands of devices. Also, it outperforms the fixed p-value CARMA by a factor of 5.25 when scaling up. In p-CARMA the adaptive way of modifying the persistence at each ED also exhibited lower energy consumption and higher channel utilization. Especially the p-CARMA with a buffer of 1 seems to outperform every compared MAC during the simulation measurements. P-CARMA can easily be utilized in existing LoRaWAN deployments with minor changes on the GWs and on the EDs.

A similar approach is taken in [138]. Firstly, the authors stress LoRa's capability to detect payloads using CAD. Based on this observation, that was made through a set of experiments, three CSMA approaches are proposed. In the first approach, called LMAC-1, a random back-off mechanism is executed once activity is detected on the channel. In the second approach (LMAC-2), the nodes are capable of switching channels and balancing the load among the list of available channels. In the last version (LMAC-3), the nodes listen to gateway beacons which contain information about the channel load. Having this information, the EDs can adapt their channel selection policy accordingly. The authors report high performance gains in terms of network reliability and energy consumption per delivered packet compared to Aloha. However, no comparison is made with existing CSMA approaches or using setups with a high number of nodes.

A CAD-based light-weight carrier sensing mechanism is proposed by Rochester *et al.* [139]. The authors present a theoretical packet collision model as well as an energy consumption model to demonstrate the benefits of using their approach. Even though they claim that their approach can work without back-off times they do not provide details on how this can be achieved. Simulation results show that – compared to the Aloha-based scheme – the same PDR can be achieved using more nodes in the network, an observation that has been made by other studies as well. Moreover, this PDR can be achieved by utilizing less energy per node than in Aloha.

B. Theoretical CSMA Schemes

The aim of [140] is to reach into a conclusion regarding the most appropriate media access control layer for accessing a LoRa network. A comparison among four MAC methods takes place by means of simulation (LoRaSim). These MAC methods are the Pure Aloha (Pure-Aloha – already used in LoRaWAN); the Delay Before Transmit (DBT) that proposes a systematic approach to delaying the transmission of data packets; the Random Frequency Hopping (RFH) where before transmitting each data packet a node randomly selects a transmit frequency from the list of available transmit frequencies; and, finally, yet more importantly, the Carrier Sense Multiple Access, in which a node selects a transmit frequency from the list of available transmit frequencies, and senses the channel for a specified duration of time. In CSMA, if there is no data activity on the channel, the data packet is transmitted. Otherwise, the node selects the subsequent transmit frequency, and repeats the sensing operation. If all frequencies are busy, the node backs-off for a random number of time slots. During simulation using LoRaSim, specific transmission settings, three transmit frequencies, and a specific payload are used. Periodic and event-based data-packet generation models are used [141]. Two metrics are examined in each MAC method. The Transmit to Target Ratio (TTR), which is the ratio of the total number of packets transmitted to achieve the target of a number (i.e., 1000 packets per node) of successfully received packets at the gateway; and the Network Total Energy Consumption (NTEC) that is equal to the total energy consumed by the transceiver for all the nodes in a network. The simulation results showed that Pure-Aloha is the least efficient and the least scalable MAC method whereas CSMA is the most efficient and most scalable one, as the increase of TTR and NTEC is relatively the smallest as the number of nodes increases.

The aim of To and Duda [142] is to evaluate the use of CSMA mechanisms in LoRa networks in terms of packet delivery rate, collision ratio, throughput, and energy consumption. To do so, an NS-3 module was created. An energy consumption model [143] as well as interference and possible capture effects were also taken into consideration in the simulation module. Two CSMA mechanisms were used during the evaluation. In the basic CSMA, when a device has a packet to send, it randomly selects a channel and checks the channel occupancy by another transmission. If the channel is free, the node transmits, if not, the device backs-off for a random number of seconds (i.e., chosen from the range 1 to $2n - 1$, for the *n*th transmission attempt, with 3 attempts in total) and then attempts to transmit again. In the other variant, CSMA-10, the node listens to the channel for a small time interval (10msec) before attempting a transmission. If the device detects a transmission during this interval, it backs off as in the basic CSMA. The comparison was among LoRaWAN's Aloha-like, CSMA and CSMA-10 media access methods. An increasing number of nodes (i.e., 1 to 10000) of class A devices with unconfirmed uplinks, randomly distributed around a gateway in an area of 10000m x 10000m size, was considered. A duty cycle of 1% was considered for the Aloha approach. The results showed that CSMA methods (CSMA-10 was the best performing) are performing better since they achieve better ratios in terms of PDR and of collision ratios as the number of LoRa nodes increases. In terms of energy consumption per node, the CSMA-based networks showed slightly greater values than the LoRaWAN network for numbers of nodes up to 5000. For numbers above 5000 the nodes in CSMA networks consume less energy than the ones in LoRaWAN networks due to the increased number of collisions in the latter. However, the authors do not justify the reason that the LoRaWAN nodes use more energy consumption as the number of nodes increases. Since no re-transmissions occur, the consumption should be constant. Nevertheless, the authors conclude that CSMA-based networks are scalable and efficient. Furthermore, the authors argue that since an LBT mechanism is employed, the duty cycle restrictions do not apply any more, implying a possibility of an even higher throughput.

In [144], the beneficial effects of CSMA, namely of p-CSMA, on LoRa networks are examined by simulation. A simulation module created in [61] was used as a basis and was extended to integrate the functionality of p-CSMA. A description of the new framework functionality is given and the application of the p-CSMA mechanism is explained. The p-CSMA mechanism employed works as follows. The node that has a packet to transmit senses the channel; if it finds it idle, it captures the channel and then it transmits. If it finds the channel occupied by another device in the vicinity, it backs off and continues sensing the channel. If the channel is sensed idle, the node retries to transmit with a certain persistence (i.e., probability). Collisions happen only when the transmissions of nodes outside the vicinity of a node that transmits occur in the same time period (hidden terminal). During the evaluation, given the improvement compared to LoRaWAN, only the performance of LoRa networks using the p-CSMA mechanism was examined in terms of PRR. The simulation results using different p values and two network scenarios (one with SF8 and one with SF8-10) showed that PRR increases as the persistence decreases and more SFs are used. However, as the network gets larger in terms of distances, PRR decreases.

C. Takeaways

Table X gives a synopsis of the works proposing CSMA solutions that can act as an alternative or as additions to the Aloha access. In order to achieve this, a reliable mechanism of assessing the channel occupancy is a prerequisite. Hence, several works choose and put into test the already existing CAD mechanism of the LoRa devices. CAD's out of the box functionality is to sense the channel and detect possible preamble transmissions so as to fully activate the LoRa ED's transceiver to receive the frame content that follows the preamble [145]. CAD compares a predefined known waveform pattern per SF to the acquired preamble waveform. If the two waveforms have a very high similarity, this means that the channel is occupied.

CAD-related research [78], [134], [135], [137] unveils some interesting features. First of all, the related studies converge to the fact that CAD cannot only detect a preamble but it can also detect payloads with a high probability. However, this method of detection returns a high number of false negatives [134]. To cope with that, a continuous repetition of the CAD process is proposed so as to have more chances to detect any likely ongoing transmissions [134], [137]. Whatever the case is, it seems that if a CSMA method is going to be adopted, it should happen in small area LoRa networks and with a great concern about the way that channel sensing takes place. Hence, in the relative research, the CAD mechanism is deemed as a reliable clear channel assessment mechanism for small distances and with carefully selected same SFs transmissions in the selected channel. Moreover, something that is not stated in most of the works is that CAD cannot be used to bypass the duty cycle restriction. This is because it cannot reliably detect payloads, it cannot reliably detect transmissions on different SFs, and it cannot detect transmissions from other radio technologies on the same frequency.

Nevertheless and on the basis of a(n) (ideal) reliable sensing mechanism – which however has not been invented yet – several studies have been published showing the superiority of adopting CSMA over the Pure-Aloha access of LoRaWAN in terms throughput, collision rate, scalability, reliability and energy consumption [140], [142]. Moreover, several studies have been made on various versions of CSMA, resulting always in favor of the less persisting CSMA versions [136], [144]. Also, in [137] an adaptive persistence value CSMA is presented, in which each ED initially considers only its conceived transmission context but as time progresses it also takes into account the GW's feedback, rendering this way each ED capable of adjusting its persistence value. However, it is questionable how and with what cost this feedback can be communicated to all the nodes in the network.

In conclusion, when CSMA is based on CAD, it seems to work and has a practical merit. Some researches prove that by conducting experiments which show the potential of CAD in detecting payloads and improving the PDR [134], [135], [137]. Moreover, an advantage of these solutions is that no extra hardware or changes in the LoRaWAN architecture are needed. However, it should be understood that the duty cycle rules still apply.

IX. Discussion & Open Research Areas

From the previous research presentation, five categories of capacity deciding factors stand out namely PHY Characteristics and Phenomena, Deployment Features and Hardware Selection, ED Transmission Settings and Features, LoRa MAC Protocols, Applications Requirements and Policies (Table XI). In this section, open research areas in each of these five categories are discussed after a careful consideration of the respective works.

A. PHY Characteristics & Phenomena

Several works have underlined the effect of several aspects of the physical level characteristics of LoRa signals on the performance. One very advantageous feature of the LoRa signals is that if they are of a different SF they can co-exist in the same channel. This characteristic increases throughput and capacity multiple times compared to Pure-Aloha networks [59], [61], [75], [79], [104]. This positive result is empowered from the fact that even in cases of concurrent same-SF signals, one signal can survive if it is stronger enough than the other(s) (i.e., capture effect) [78], [81]. However, as it is shown in many works SF-orthogonality is not perfect which means that even different-SF signals can possibly affect each other if their power difference is large enough [62], [65]–[67]. This leads to a non-negligible degradation of the performance in a LoRa cell if actions are not taken at least at theoretical level (considering SF power isolation thresholds) [49], [63], [98]. The latter is more obvious in non-saturated LoRa cells since in saturated ones co-SF interference is the leading cause [83], [84], [95]. Also, non-LoRa interference can possibly affect LoRa signals if the non-desired signals are strong enough [64], [65]. Nevertheless, even though these studies show that this is unusual to happen, it is of high importance to assess LoRa under interference by a multitude of parameters and other radio technologies that co-exist in the sub-GHz band.

All the above are interrelated with the transceiver chips used in the LoRa end devices and in the GWs and the exhibited sensitivity per SF/BW combination. Higher device sensitivity means a larger success possibility of a transmission, coverage, and possibly achievable capacity [100]. Furthermore, in cases of moving EDs the degradation of the transmission success probability due to the Doppler effect is apparent even for small speeds and should not be neglected in relevant applications [77].

TABLE X
CHANNEL SENSING LORAWAN ALTERNATIVES; CAD-BASED AND PURE CSMA PROPOSALS

Approach	Findings	CAD/CSMA proposals	Limitations & Drawbacks	LoRaWAN compatible?	Experimentally validated?
[134]	CAD can detect the payload apart from the preamble. False negatives appear as the distance increases.	A solution to improve CAD false negatives as the distance increases and a more energy-efficient back-off mechanism using CAD than IEEE802.11 CSMA.	Multiple CAD attempts are required per time which may make the device to wake-up multiple times or stay awake for long times and consume energy.	Probably yes, even though Pure LoRa was used.	Yes
[135]	CAD can sometimes reliably detect payloads; 8 or more consecutive CAD attempts may be required to reliably detect payloads.	A CAD-based CSMA approach using RTS/CTS commands of IEEE802.11 is proposed.	The energy consumption due to multiple CAD senses is not examined.	Yes	Yes
[78]	When the transmitter and the receiver use the same SF/BW combination the worst detection rate is 97%. CAD also detects signals in different SF/BW combinations, mostly for data rates that are adjacent to the current data rate.	-	Only one transmitter, one receiver, and one detector node were used.	Yes, even though the 125kHz BW was not tested	Yes
[136]	The exponential increase of the back-off time gives better results compared to the exponential decrease.	3 algorithms to compute the back-off time after a CAD sensing and a possible channel occupancy are proposed.	All nodes used the same settings, path-loss is ignored and the hidden terminal nodes are also ignored	Yes	No
[137]	The CAD preamble detection accuracy decreases as the distance increases, something which can be compensated with the usage of three consecutive CADs.	A probabilistic back-off strategy to perform channel sensing using CAD along with a gateway's feedback is presented.	The solution may be problematic in case of a saturated channel.	Modifications on both the nodes and the gateways sides are required.	Yes
[138]	The capability of CAD to detect payloads is demonstrated.	Three CAD - based approaches are proposed to avoid collisions with neighboring EDs by a) providing a random back-off strategy, b) balancing the number of transmissions per channel, and c) taking into account gateway-transmit beacons about the network load.	There is a 20-25% energy consumption increase due to multiple CAD readings.	Yes, the 3rd solution has to be implemented over LoRaWAN Class B.	Yes
[139]	More nodes can be utilized to achieve the same PDR as Aloha.	CAD-based mechanism without back-off times.	The approach is based on a very simplistic theoretical framework without considering, among others, inter-SF collisions and the capture effect.	Yes, even though modifications are needed on the node side.	Yes
[140]	CSMA seems to be a more energy-efficient and a more scalable solution compared to Pure Aloha, Delay Before Transmit, and Random Frequency Hopping.	-	An ideal CSMA scenario is examined. Currently there is no hardware available to implement such a solution.	Additional hardware/ software is required.	No
[142]	The superiority of ideal CSMA schemes with random and fixed back-off times over LoRaWAN is demonstrated.	An energy consumption model for NS-3 is proposed.	An ideal CSMA scenario is examined. Currently there is no hardware available to implement such a solution.	Additional hardware/ software is required.	No
[144]	No clear finding.	A CSMA back-off and a probabilistic retry scheme are proposed, NS-3 CSMA and battery modules were developed.	An ideal CSMA scenario is examined where the collisions occur only from "hidden terminal" nodes. Currently there is no hardware available to implement such a solution.	Additional hardware/ software is required.	No

All the above described characteristics are inherent ones in the LoRa physical layer and should be considered in LoRa-based deployments since they affect and define the performance baselines of these networks.

B. Deployment Features & Hardware Selection

As it is stressed in many papers, there are several deployment characteristics that have either a direct or an indirect impact on the achievable capacity or on the general

TABLE XI
FIVE CATEGORIES OF PERFORMANCE DETERMINANTS DERIVED FROM THE REVIEWED LORA AND LORAWAN LITERATURE AND OPEN RESEARCH AREAS

Section IV		Section VI	Sections V-A, VII, VIII	Sections III, V-B, V-C
PHY Characteristics & Phenomena	**Deployment features & hardware selection**	**ED Transmission Settings & Features**	**LoRa MAC Protocols**	**Application Requirements & Policies**
- sensitivity per SF/BW - Rx power isolation thresholds per SF - intra-SF interference - inter-SF interference - non-LoRa interference - capture effect - Doppler effect	Gateways: - population - 1- or 8-channel - half-duplex - elevation - position, indoor/outdoor - directional antennas - antenna gain Nodes: - density - antenna gain - position, indoor/outdoor - mobility	- SF selection - BW selection - CR selection - transmit power - ADR	- Aloha MAC - S-Aloha MAC - CAD-assisted MAC - CSMA - collision-free TDMA - Hybrid	Uplink traffic: - interval, pattern - payload size - # of channels - radio duty cycle - re-transmission policy Downlink traffic: - ratio of DL/UL traffic - radio duty cycle - # of receive windows - ACK policy
Open Research Areas				
- cross-technology interference	- multi-gateway network performance assessment - effect of half-duplexity on performance	- energy consumption with optimized settings - optimize settings over LoRaWAN specs - machine learning and AI on the edge	- assessment of synchronization cost - optimal number of CAD senses - low overhead mesh network solutions	- adaptive re-transmission policy - cope with high DL traffic - channel selection in RW2

performance of a LoRa network. The achievable capacity of a network is always accompanied by metrics that need to be optimized, such as PDR, PER or throughput [146]. Thus, improving such a metric affects almost certainly the achievable number of satisfied EDs.

The deployment position, the environment, and the device density are crucial factors affecting the achievable capacity. An ED's position heavily affects the propagation losses and the shadowing effects. Better deployment environments have the effect of being able to include more devices and to cover longer distances achieving finer and more efficient SF distributions that result in better throughput, PDR, and capacity [61], [70]. The device characteristics, such as the elevation of the gateways' and/or EDs's antennas [70] help mitigate various transmission area shortcomings. The gateways' and the EDs' antenna gains as well as the selected transmit power values are yielding similar results [72], [73]. From the gateway perspective, it is very important to select hardware that supports the simultaneous decoding of signals transmitted over 8 different channels and over all the available SFs per channel. Moreover, one should take into account that LoRa transceivers are half-duplex. In LoRaWAN, this is not an issue for the EDs but uplink transmissions cannot be received by the gateway when the latter switches to the downlink mode to send out acknowledgments. The effect of this issue has not yet been carefully examined in the literature and it is an interesting research topic to explore. Similarly, the number of deployed gateways has a critical impact on the performance of a LoRa network [59], [61], [88] because this is the only solution to achieve scalability in Aloha-based networks. Besides the extension of the range, an increase of the network reliability, throughput, fairness, and capacity can also be achieved by deploying multiple gateways. The use of multiple gateways means more possible receiving points of a node's transmission (i.e., gateway diversity) [72], more possible available gateway receive paths, and a greater possibility of an ACK to be returned [95]. All these lead to better chances of a gateway being able to receive a node's signal, of a signal surviving collisions and of an ED communicating more efficiently with the gateway (e.g., using smaller SFs). Hence, more gateways almost certainly means a larger achievable number of EDs addressing the set QoS metrics. Nevertheless, experimentation (including simulations) with multiple gateways has not attracted much attention in the literature. This is probably due to the high complexity of modeling such a system (in comparison with the single-gateway case) as well as due to the intensively high labor and computation (for simulations) cost.

The EDs' and the gateways' density distribution on the defined coverage areas has also an effect on the quality characteristics, such as on PDR, fairness, throughput, and conclusively on the achievable capacity [59], [75], [76], [88], [98], [104]. The latter happens due to more advantageous or not SF ratios that may occur during the process of assigning transmission settings to EDs, as it is stressed in the next subsection. For example, in cases of a large number of distant EDs, an extended usage of larger SFs is unavoidable jeopardizing severely the capacity of a single gateway LoRa cell (i.e., receive path unavailability due to usage from lengthy high SF transmissions and/or higher probability of collisions).

C. EDs Transmission Settings & Features

LoRa transmission settings greatly affect the network performance. Parameters such as the SF, the BW, and the CR have an effect on ToA and on the probability of collisions. Moreover, a larger ToA always means a larger energy consumption. A higher SF value corresponds to slower data rates and a larger ToA. A higher channel BW means higher data rates, smaller distances to the gateway, and a smaller ToA. The smaller the coding rate, the greater is the immunity of the transmitted signal to interference and noise errors but also the larger the ToA. Also, due to the latter, SF up-limits enlarge in terms of BER/SNR as the CR value increases, a fact that is used in efficient transmission setting schemes [107], [108].

The need of efficiently adjusting the EDs' transmission settings is exhibited in a large number of studies in the literature. LoRaWAN's answer to the need of dynamically adjusting the transmission settings is ADR (DR, transmit power, channel). Similarly, many studies aim to improve or replace ADR to improve capacity, fairness or network performance at the presence of mobility [97], [98], [105].

The means by which many researchers try to achieve their respective goals are by adjusting transmission settings such as the SF and the CR. As already mentioned, a work pattern is observed, which encompasses finding the optimal EDs' distribution ratios to SFs, that achieve a better PDR [101], a higher capacity given an average success probability [103], [105], and a higher packet success rate [107]. Similarly, several works focus on PDR fairness resulting, as in previous works, in optimally assigned SF ratios of EDs with an extra care of alleviating inter-SF interference by using transmit power adjustments [49], [98], [109]. Several researchers incorporated the heterogeneity of the events reported in a LoRa cell, in terms of traffic patterns as well as of events priority, in their models by employing machine learning approaches [111]–[113]. The goal here is to report as efficiently as possible events of different importance. The optimal transmission settings as well as an optimal reporting and/or updating policy are found. Machine learning is also employed in [102], [110] for calculating advantageous transmission settings allocations.

Despite the obvious benefits in terms of capacity, optimal or even sub-optimal SF assignments suffer from increased energy consumption. As shown in [103], optimally assigning SFs in a small cell to optimize the packet success probability for unconfirmed traffic, leads to a 30% higher capacity but the energy cost is almost 3 times higher compared to ADR (even worse if this comes with an increase of the CR as some studies suggest). This is because compared to ADR higher SFs are used on average, resulting in a longer ToA. If the extra energy cost can be covered by a reduced number of re-transmissions – in case of confirmed transmissions – is a different story which has very partially been covered in the literature. Moreover, this optimal performance corresponds to a specific snapshot of the system given certain node numbers, positions, and environmental conditions. In reality, as nodes join and leave the network, these conditions may change over time, leading to sub-optimal settings. As a consequence, the optimization algorithms need to be recomputed and the settings to be re-transmitted to the nodes, an action which may incur a tremendous communication overhead. Finally, many of the proposed methods require that the GW has to send out extra information about packet-related characteristics (e.g., RSSIs) or global network characteristics (e.g., number of nodes with the same SF). All these methods are not compatible (at least) with the current versions of LoRaWAN because more fields and commands need to be defined to encapsulate these pieces of information into the downlink packets. The authors believe that future studies should follow that direction. Moreover, with the advancement of computation and storage capabilities of the embedded computers, the EDs will be capable of running more complex machine learning and AI techniques to cope with interference and find optimal settings. Thus, the development of such techniques on the edge and the assessment of trade-offs between computation and energy cost will be one of the top research areas in LoRa networks. An open research area particularly for machine learning is how these approaches adapt in dynamic environments, what is their convergence time, and what is the practical computation and memory cost especially when applied on the edge.

D. LoRa MAC Protocols

The adopted media access control scheme seems to have the final saying regarding the achievable capacity of every case under study. The LoRaWAN specification employs a Pure-Aloha MAC, a not so favorable choice regarding the achievable capacity. The maximum of 18% channel capacity utilization of Pure-Aloha is not such an optimistic option to begin with. On one hand, the creators of LoRaWAN chose this medium access policy to support as many applications as possible, to minimize energy consumption, and to increase simplicity. As it was mentioned previously, they relied on the deployment of additional gateways to resolve scalability issues. However, even with the multiple channels availability, the multiple pseudo-orthogonal SF transmission capability and the favorable capture effect, LoRa networks seem to struggle when the number of transmissions increases.

Other works, seeing possible carrier sensing ability in the LoRa CAD mechanism, work on possible carrier sensing-based access methods. The determining factor in these works is the reliability of CAD as a clear channel assessment mechanism. The main issue with CAD is that it is made to detect preambles only. Even though some studies show that it can also detect payloads, this detection is not always reliable in cases of large cells and in cases of sensing cells where packet transmissions happen in neighboring data rates [134]. However, proposals on overcoming CAD shortcomings and relevant CSMA-based MACs are proposed [134], [137]. Another issue is the increased energy consumption because of the extra time needed to sense the medium. Some studies argue that this extra energy consumption can be covered by a reduced number of re-transmissions in the case of confirmed transmissions (compared to pure LoRaWAN). However, this is not experimentally validated and quantified with a high number of nodes and, thus it remains an open research area. Nevertheless, the advantage of CAD is that it can be used in LoRaWAN without considerable changes on the ED side.

Other works just assume a reliable CSMA mechanism [136], [142], [144]. Higher channel capacity utilization values can be achieved by adopting CSMA such as almost 50% for even higher network loads than Pure-Aloha [147]. Higher channel capacity utilization for higher load means higher achievable throughput for more occurring transmissions that also comes with less collisions. This also means a higher number of EDs reporting events as required. Even more, better values can be achieved for less persistent versions of CSMA as exhibited in [136], [144]. However, some of these solutions rely on an ideal CSMA mechanism which has not been invented yet and more likely will never be invented due to the presence of multiple SFs and the proprietary nature of many technologies that co-exist in the sub-GHz spectrum. Thus, the appearance of CSMA methods to allow duty-cycle-free transmissions is unlikely to happen.

Time division multiple access is the choice for applications that require a high network performance for a usually known number of EDs. The achievable throughput in these medium access mechanisms is almost proportional with the offered load. However, the necessary lengths of the extra guard intervals mean channel capacity losses. Moreover, the time-guard interval lengths are proportional to the defined re-synchronization periods. Thus, a balance between these two is usually one of the goals that should be reached in each case under study [130]. Similarly, the defined timeslot length, the timeslot assignments to EDs as well as the number of EDs, have a direct effect on the achievable throughput and on the delay in the service experienced by the EDs [133]. This is the reason that time-slotted synchronized mechanisms in LoRa cells are usually proposed in cases with a known number of EDs and known requirements in terms of data periodicity and packet size. Finally, due to synchronization, the time-slotted approach exhibits higher energy consumption compared to Aloha. Nonetheless, it has been shown that this extra cost can be covered by the reduced number (or the absence) of collisions [122] in networks with many nodes. However, it is unclear what is exactly the cost of synchronisation especially for nodes which transmit at sparse time intervals. Some concepts of synchronization proposed in the literature could be useful when designing multi-hop and mesh LoRa solutions [78], [126], [129], [148]–[150], where the overhead minimization and the energy conservation procedures are not trivial.

E. Application Requirements & Policies

Throughout the above discussion and the conclusions reached, there are still various application-specific requirements that need to be fulfilled. These relate to the size of the data that need to be transmitted, how often, and by how many EDs. The transmission rate can be periodic, exponentially distributed, event-based or even a combination of these methods. Several traffic patterns are used [61], [72], [75], [82], [88], [91], [93], [112], [140] for reporting events with packets of the same, different or varying size. Various concurrent traffic packets can also exist in a cell as examined in [85], [91]. In [111] various priority events are being dealt with and the network capability of reporting propagating events through spatially related EDs are examined in [93]. Several traffic generation models are employed in simulation environments [93], [140].

All these end up creating a number of packets that need to be timely transmitted, more abstractly known as network load, which shape the network traffic. More specifically, the payload has a direct impact on the ToA; a higher payload means a larger duration of the packet with a smaller packet overhead ratio, but with more chances of collisions. The latter is also the case when the transmission intervals get smaller and when ULs are confirmed with the presence or not of extra DL traffic. All of them lead to a smaller achievable capacity due to the increased demands of each ED. Thus, it seems that the network load is a determining factor of the achievable LoRa capacity, as it represents the application demands that need to be served efficiently.

Furthermore, the applications' requirements also dictate the EDs' selected way of reporting events with confirmed or unconfirmed ULs as well as the existence of DL traffic. The latter refers to data that need to be sent by the network/application to the EDs and seems to have no real impact in the performance of LoRa networks as long as it remains rare, which is usually the case. This is not true for the confirmed ULs that seem to affect the network performance negatively [70], [72], [75], [86]–[88]. The number of uplink and downlink channels plays an important role in the overall performance [75], [120]. Due to the nature of the LoRaWAN protocol and the radio duty cycle rules, a high congestion can occur at the gateway when these channels get saturated [45]. Re-transmissions that are performed because of non-acknowledged or because of collided packets substantially increase the traffic load. How to adapt re-transmissions according to the channel load is an open but also difficult to solve problem since the nodes do not have a global view of the network status. Furthermore, it should be noted that the current version of LoRaWAN does not give much room for improvement. For instance, it does not allow the network providers to add additional receive windows or change their order or add more channels in RW2.

X. CONCLUSION

In this paper, a study on the factors that affect the LoRa networks' capacity and performance was attempted. A literature study took place that included several works that outline the performance and the behavior of these networks along with attempts of improving and even substituting critical functionalities. A categorization of the literature was presented. Moreover, the complexity of the subject and the several factors that influence it was acknowledged. During this process, several characteristics stand out when the questions of performance and efficiency come up. Physical phenomena, transmission settings, deployment features, application requirements, and the selected MAC method seem to affect in one way or another the performance of these networks. As it is shown, these underlined characteristics of LoRa networks have a direct or an indirect impact on the number of sufficiently supported EDs. These characteristics coined as LoRa capacity shaping factors are analyzed and categorized.

Having gone through the research and having pointed out the most important capacity determinants in LoRa networks, several relative insights have been gained. Based on this fact, future possible open research areas have been outlined. Most of these areas require the employment of real world and large scale experiments to assess the behavior of the existing as well as of future LoRa solutions. Assessment of solutions with hundreds of gateways and thousands of nodes as well as the effect of the overhead of the solution at a large scale are some such examples. Moreover, there is a need for a better understanding of the interference levels between radio technologies co-existing in the sub-GHz bands and for an increasing interest of developing on the edge machine learning and AI solutions with the minimum possible human intervention. Finally, the potential of CAD-, CSMA-, and TDMA-based solutions has not fully been explored within or over the limits of LoRaWAN. As for the latter, many studies stress that the current version of LoRaWAN lacks of agility as regards with the downlink traffic. In the future, we expect to see solutions to improve the downlink throughput by better handling the downlink channels and the re-transmission policy.

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