Telecommunication Systems
https://doi.org/10.1007/s11235-024-01192-9

REVIEW

LoRa interference issues and solution approaches in dense IoT networks: a review

B. Shilpa[1] · **Hari Prabhat Gupta**[2] · **Rajesh Kumar Jha**[3] · **Syed Shakeel Hashmi**[3]

Accepted: 21 June 2024
© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2024

Abstract

Low Power Wide Area Networks (LPWAN) are prominent option of wireless communication technology for dense Internet of Things (IoT) applications. With a growing population of resource-constrained IoT devices, meeting various communication requirements in dynamic and dense wireless networks has become a significant problem. Long Range (LoRa) was designed for LPWAN, which features long-distance communication, low-power consumption, and simultaneous transmission of multiple end devices. However, LoRa deployment in dense IoT networks facing several challenges like interference, scalability, security, and reliability. In recent times numerous techniques have been developed for interference mitigation. As these techniques used a range of methodologies to address the interference challenge, it is necessary to thoroughly analyze current solutions. This paper presents a comprehensive overview of the existing literature on interference issues and the solution approaches in LoRa. Initially, the challenges in dense IoT networks are discussed. We next present the fundamentals of LoRa and the classification of interference in the different categories. In each type of interference, the available methodologies are categorized based on their solution approaches. The analysis of different solution approaches is summarized by examining various issues of the LoRa network. Finally, the open issues and future directions related to the interference in the LoRa network are discussed.

Keywords Interference · Internet of things · LoRa · Low power wide area networks

1 Introduction

The Internet of Things (IoT) is a significant advancement that transforms the traditional Internet into a system of interconnected objects which collects data from the environment and integrates with the physical world [1]. The rapid growth of connected devices in IoT networks demanding scalable and energy-efficient wireless communication technologies. The upcoming technologies must be capable of providing concurrent services to a large number of devices in dense networks [2]. The available wireless communication technologies are grouped as short-range and long-range communication technologies.

Short-range technologies are used in critical IoT applications which require low latency and high availability, with battery life not being a major consideration [3]. Local area networks benefit from these technologies since they are simple to install, configure, and manage. Fast data rates, high availability, and occasional latency are the advantages of short-range technologies. Radio Frequency Identification, Near Field Communication, Bluetooth Low Energy, Wireless Highway Addressable Remote Transducer protocol, Zigbee, Zwave, IEEE 802.11ah, and Optical Wireless Communication are available short-range communication technologies [4]. In short-range technologies, Zigbee and Bluetooth were most considered to develop IoT applications. These standards feature low power consumption, which is a crucial requirement of IoT devices. The restricted range of these

---

✉ B. Shilpa
shilpa181188@gmail.com

Hari Prabhat Gupta
hariprabhat.cse@iitbhu.ac.in

Rajesh Kumar Jha
rajeshjha@ifheindia.org

Syed Shakeel Hashmi
hashmi@ifheindia.org

[1] Department of Computer Science and Engineering, AVN Institute of Engineering and Technology, Hyderabad, India

[2] Department of Computer Science and Engineering, Indian Institute of Technology (IIT BHU), Varanasi, India

[3] Department of Electronics and Communication, IcfaiTech (Faculty of Science and Technology), IFHE University, Hyderabad, India

Published online: 03 July 2024

communication technologies is a major obstacle, especially in applications that need to serve across city-wide. On the other hand, a wireless cellular network features longer communication range. But a large number of IoT devices seeking connection via a single base station will generate additional signalling and control traffic difficulties. As a result, Low Power Wide Area Networks (LPWANs) has emerged as an ultimate option, working in both the licensed and unlicensed spectrum and picking up the slack. The LPWAN is a modern wireless communication technology with features like low-power consumption and a longer communication range. These features enable LPWAN as vital part of the wide range of IoT applications. Though Sigfox [5] and LoRa [6] were among the first LPWAN technologies, there are a plethora of options now like Wi-SUN [7], Narrow Band-IoT (NB-IoT) [8], etc.

NB-IoT uses a licensed band and is a strong competitor for unlicensed LPWAN technologies [9]. All essential communication components of IoT networks, such as minimal complexity, low energy consumption, and broad range are included in the NB-IoT. The standard includes a 180 kilohertz bandwidth and transmission rates of 250 kilo bytes per second with a half-duplex service, among other characteristics [8]. NB-IoT devices will have shorter battery life, high cost, high latency, and do not support handover. Because of these limitations, NB-IoT is not a viable option for mobile IoT applications.

Apart from cellular IoT technologies, other LPWAN technologies use unlicensed parts of the Industrial, Scientific, and Medical (ISM) radio band to carry communications. LoRa, Sigfox, Weightless, Ingenu, and DASH7 are examples of unlicensed LPWAN technologies [10]. Sigfox was the first low-power wide-area network technology to be offered in the IoT market, and it was developed in 2009. The Sigfox network's physical layer employs ultra narrow band (UNB) technology combined with differential binary phase shift keying (DBPSK) and gaussian frequency-shift keying (GFSK) modulation, which was selected as the primary communication protocol due to its extensive range and low power requirements [11]. The constraint of Sigfox is the limited number of uplink messages, i.e., 140 per day and restricted payload to 12 bytes for each uplink message [12]. In addition to this constraint, its unopened network model not allowing the rapid development as competitors. LoRa is most favored LPWAN technology which allows for low-cost autonomous network setup. LoRa's openness makes it an ideal option for a wide range of IoT deployments [13].

1.1 Challenges in dense IoT networks

The enormous growth in mobile traffic from the past couple of years is mostly because of the easy availability of battery-powered, small, and low-cost IoT devices. Due to this exponential growth in mobile traffic, the wireless network sector creates and collects an unprecedented amount of data [14]. As per the International Data Corporation, there would be around 42 billion devices linked to the Internet by 2025, and 80 zettabytes of data will be generated [15]. Current wireless technologies need to overcome numerous challenges [16] to provide seamless services to IoT devices in dense networks. Some of the challenges are listed below:

- Scalability: Scalability is one of the major challenges in IoT networks because of the high number of devices that require simultaneous connectivity. The scaling problem is multifaceted [17], including the communication network's cost, complexity, and bandwidth efficiency. Future wireless technologies serving dense IoT applications must have efficient bandwidth and high capacity to handle millions of successful transmissions and an increased number of new devices joining the network every day [18].
- Privacy and security: Privacy and security are ongoing concerns for IoT applications due to the lack of standards in conventional deployments. Even though newly developing technologies [19, 20] are trying to overcome the security issues with updated standards, the inter-dependency of security, trust, and privacy for IoT networks is becoming a major challenge [21].
- Inconsistent network: Unlike consumer applications, most industrial deployments occur in remote areas with asymmetric terrain, structurally dense surroundings. The accessibility of wireless technologies in these environments is very low. In such scenarios, instead of conventional cellular technologies, it is advised to use LPWAN, which operates in the Sub-GHz frequency bands. The LPWAN technologies provide a broad range and great penetration capabilities for secure data connections throughout tall buildings and structurally dense, geographically scattered industry parks [10].
- Interference: The license-free ISM band of frequencies has become a popular alternative for many wireless radio technologies due to its free availability. Intra-network and Inter-network interference are becoming more of a problem as many connected devices use the same license-free radio range [13].

1.2 Need for survey

As IoT deployments continue to grow exponentially, the demand for efficient and reliable communication in dense IoT networks becomes crucial. However, the proliferation of IoT devices in close proximity can lead to interference issues, degrading the performance and reliability of LoRa networks. This interference can arise from factors such as co-channel interference, adjacent channel interference, and external interference sources. To ensure the optimal operation of LoRa networks in dense IoT environments, it is essential to address these interference issues effectively.

LoRaWAN is an essential technology for connecting low-power devices, hence there are a number of specialized surveys covering a range of topics. In Table 1, we outline the several extant LoRaWAN survey papers and provide brief descriptions of each. We believe that there is a need for a particular survey for interference in LoRaWAN after looking at other LoRaWAN review papers. Hence, this article presents a comprehensive survey on LoRa interference issues and solution approaches in IoT networks. It explores the challenges faced by LoRa networks in the presence of interference and discusses various techniques and strategies proposed by researchers and industry practitioners to mitigate interference and improve network performance. Additionally, this survey delves into the open issues and future directions related to interference in LoRa networks. While significant progress has been made in understanding and mitigating interference challenges, there are still areas that require further investigation and improvement. By highlighting the open issues, such as the impact of mobility on interference, the scalability of interference mitigation techniques, importance of SF allocation, and the coexistence of LoRa with emerging technologies, this survey aims to shed light on the research gaps that need to be addressed. The rest of the paper is organized as follows. The fundamentals of LoRa are presented in Sect. 2. LoRa interference is discussed in Sect. 3. Sect. 4 discusses about the solution approaches to mitigate the interference in LoRa. Finally, the open issues and direction of research are given in Sect. 5.

Table 1 Summary of review articles related to LoRaWAN

References	Year	Description of survey
[22]	2017	This article discusses the framework and protocol of LoRaWAN. Research possibilities and outstanding difficulties related to LoRaWAN applications have been discussed
[23]	2017	This study analyzes the LoRaWAN literature and compares the developed testbeds to determine the network's strengths and weaknesses. Additionally details LoRaWAN's limitations
[24]	2017	This research assesses LoRa modulation in light of the need for IoT devices
[25]	2018	This study surveys the literature on the topics of security, physical layer, and MAC layer published in the IEEE explore database between 2015 and 2018
[26]	2018	This paper presents a summary of the literature on LoRa networking specifically
[13]	2019	This paper provides a brief overview of contemporary LoRa-related challenges, including energy consumption, communication range, error correction, and multiple access
[27]	2019	This paper introduces readers to LoRaWAN technology by addressing architectural and MAC protocol concerns and offering exploratory research possibilities
[18]	2020	The most up-to-date findings on Adaptive Data Rate algorithms for LoRaWAN Technology are reviewed in this article
[28]	2020	The challenges that LoRaWAN faces in an extremely dense network are reviewed in this study
[29]	2020	This article analyzes and reviews the security and privacy concerns with LoRaWAN
[30]	2020	This article provides a review and classification of LoRaWAN mesh networks with focus on multi-hop communication in LoRaWAN mesh networks
[31]	2021	This article provides an overview of simulation tools for LoRaWAN in ns-3
[32]	2021	The review aims to enhance understanding of the key elements influencing the performance of LoRa technology
[33]	2022	This study provides an in-depth overview of LoRa networking techniques and focuses on their applicability and effectiveness in large-scale and long-term IoT deployments

2 Fundamentals of *LoRa* technology

LoRa is a popular LPWAN that is intended to enable wireless communication to embedded devices with good endurance over very long distances. It allows functionality that is comparable to that of cellular data service, but it is tailored specifically for applications that are centered on the IoT. When it comes to embedded functions, LoRa shines because of its ability to trade off data speeds for very long ranges and great durability. The LoRa technology comprises two main layers: the physical layer and the Medium Access Control (MAC) layer. These layers work together to provide efficient and robust communication for LoRaWAN-based IoT networks.

2.1 LoRa

LoRa is a physical layer acquired and developed by Semtech corporation that possesses higher-level properties for implementing LPWANs. LoRa's patented spread spectrum

Table 1 (continued)

References	Year	Description of survey
[34]	2022	Review of different approaches for SF allocation in LoRaWAN to provide insights into the effectiveness and performance of SF allocation schemes
[35]	2022	This article provides an overview of the latest advancements in LoRa technology
[36]	2022	This study provides a broad overview of the energy efficiency of LoRaWAN networks and suggests some future research possibilities
[37]	2023	Explores the requirements and deployment scenarios of LoRa technology and discusses the challenges associated with LoRa technology implementation and operation
[38]	2023	Highlights the potentials and challenges associated with implementing LoRaWAN for massive IoT deployments

modulation method, based on Chirp Spread Spectrum (CSS), incorporates Forward Error Correction (FEC) [39] to provide significant processing advantages for link budget improvements and resilience to multipath and interference. The LoRa technology operates within the unlicensed sub-GHz ISM radio band, with specific frequency ranges depending on the region of deployment as 433–868 MHz (EU), 865–867 MHz (IN), 915MHz (AUS and US), and 923 (ASIA). However, it also adheres to the duty cycle regulations. The duty cycle refers to the proportion of time a device is actively transmitting within a given period. These regulations are essential in unlicensed frequency bands to prevent any single device from monopolizing the channel, ensuring fair access and reducing interference. LoRa technology adheres to strict duty cycle regulations, especially in unlicensed ISM bands. For example, in Europe, devices in the 868 MHz band are typically limited to transmitting for 1% or 0.1% of each hour, depending on the sub-band. When compared to cellular and other short-range wireless protocols, LoRa technology excels in terms of transmission range and power usage. It has a range of up to 15 km in rural regions and up to 5 km in urban areas, a device battery life of up to 10 years, and a data rate of between 0.3 and 37. kilobits per second [40].

In LoRa modulation [41], the signal is distributed throughout the spectrum by creating a chirp signal, which is characterized by a linear increase from f to f_{max} (up-chirp) or fall f_{max} to f (down-chirp) in frequency with time. The chirp-based modulation method used by LoRa allows for symbols to be derived by taking into account various circular shifts of the fundamental upchirp signal. For each symbol, the time-varying characteristics are divided into chips of time $T_{chip} = 1/BW$, where $BW = f_{max} - f$ is the signal's bandwidth. The resulting expression for the modulating signal of the n^{th} generic LoRa symbol is

$$S(t) = \left\{ \begin{array}{ll} f\_max + k(t - n.T\_chip) & for\ 0 \leq t \leq n.T\_chip \\ f + k(t - n.T\_chip) & for\ n.T\_chip < t \leq T) \end{array} \right\} \quad (1)$$

where $k = (f_{max} - f)/T$ is the slope of the frequency variations.

The receiver performs a "de-chirp" operation during demodulation by multiplying each received symbol with a down-chirp, which is the conjugate of an up-chirp. A single frequency tone is produced as a result of this multiplication. The output is then subjected to a Fast Fourier Transform (FFT) by the receiver. The peak in the spectrum that the FFT generates corresponds to the original frequency. The modulation and demodulation process are structured as shown in Fig. 1 and the LoRa chirp signals are visualized in Fig. 2.

LoRa device transmission settings allow for customized connection performance and power consumption. The key parameters involved in configuring a LoRa transmission are:

Transmission Power (TP): The range of a LoRa radio is dependent on its transmission power, which may be adjusted from − 4 dBm to + 20 dBm, but is otherwise fixed between − 2 dBm and + 20 dBm owing to hardware implementation constraints. In addition, technical limitations restrict the utilisation of power levels beyond 17 dBm to a 1% duty cycle [43].

Carrier frequency (CF): The carrier frequency is the primary frequency used for data transmission and can be fine-tuned in 61 Hz steps within the range of 137–1020 MHz. However, for LoRa chips, the available frequencies are generally between 860 and 1020 MHz.

Bandwidth (BW): Bandwidth indicates the width of the transmission band. Increasing the BW results in a faster data rate and less time on-air, but decreases sensitivity due to additional noise. Conversely, a smaller BW improves sensitivity but lowers the data rate. For instance, a 125 kHz bandwidth corresponds to a chip rate of 125 kbps. While the available bandwidth ranges from 7.8 to 500 kHz, typical LoRa networks operate at bandwidths of 500 kHz, 250 kHz, or 125 kHz.

Coding rate (CR): The LoRa device coding rate may be set to one of four values (4/5, 4/6, 4/7, or 4/8) to optimize its FEC for use against bursts of interference. The trade-off for increased safety from a higher CR is more time on air.

Spreading factor (SF): Spreading factor is a parameter in LoRa modulation that determines the spreading of data symbols over time and frequency. It specifies the degree of spreading or expansion applied to the transmitted signal, impacting the data rate, range, and sensitivity of LoRa communication. The ratio of symbols per second to chips per

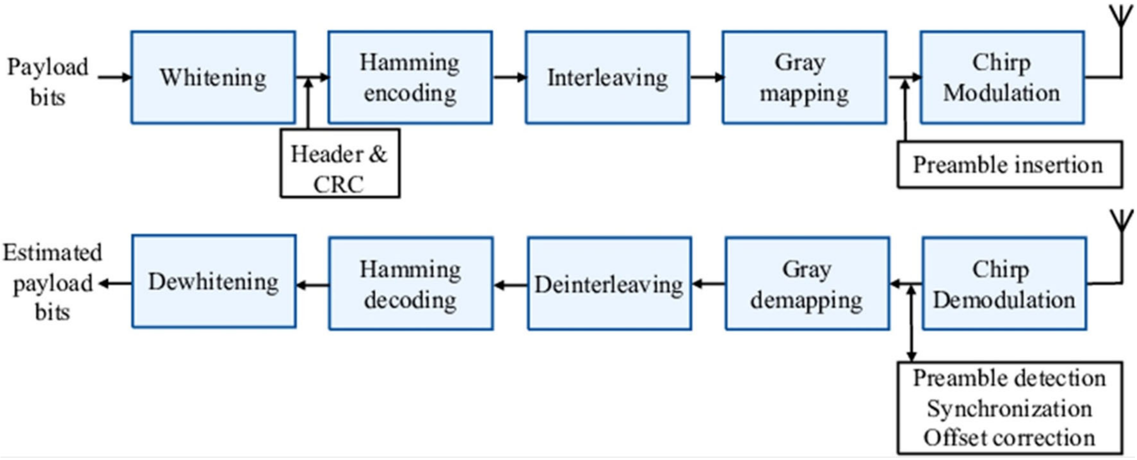

Fig. 1 Process flow diagram of LoRa modulation and demodulation [42]

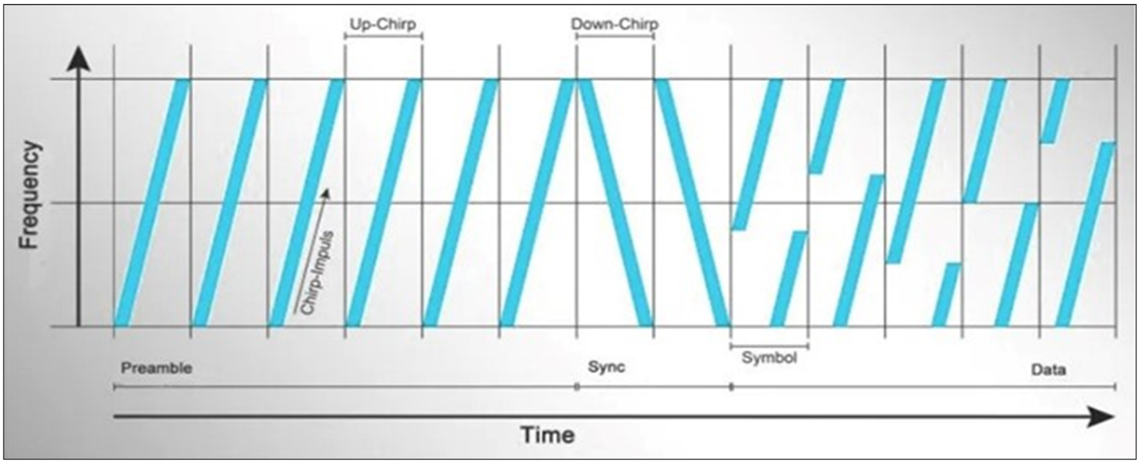

Fig. 2 An illustration of LoRa chirp symbol [19]

second is known as the spreading factor. Mathematically SF can be defined as $SF = \log_2 R_c/R_s$, where R_c and R_s are chip rate and symbol rate, respectively.

2.2 LoRaWan

LoRaWAN is an open-access MAC layer protocol standardized by LoRa Alliance. The LoRaWAN MAC layer dictates the network topology, which in this case is a star of the star [44]. The LoRaWAN network architecture is comprised of three distinct functional units known as LoRa Nodes (LNs), LoRa Gateways (LGs), and Network Servers (NS), as depicted in Fig. 3. LNs are categorized into three types: class A, class B, and class C. LNs operating in class A and B modes are often battery-powered, but LNs that work in class C mode are typically mains-powered. Class A devices have the lowest energy use, followed by classes B and C. LNs of class A wait for an acknowledgement from the network server inside one of two receive windows. By sending out beacon packets, gateways can create more receive windows in class B mode. Class C mode can receive downlink messages at any time (except while transmitting) and is not limited in this regard. The timing diagram of different device classes is shown in Fig. 4. LGs serve as transparent bridges between LNs and NS. Connections between LGs and NS are often made through a non-LoRa network. Since LGs do not enforce higher-level protocols, application data is encrypted before being sent to the LNs. NS is the environment in which the application's actual purpose is carried out. Before arriving at the application server, packets from gateways are analyzed and possible duplicates are rejected by NS.

LoRaWAN provides services including medium access, adaptive data Rate (ADR), and security. LoRaWAN MAC layer employs the primitive ALOHA MAC protocol [45] by default, allowing LNs to begin transmitting without the need for channel discovery and time synchronization immediately after wakeup. ADR plays a crucial role in LoRaWAN as it allows LNs to dynamically configure different data

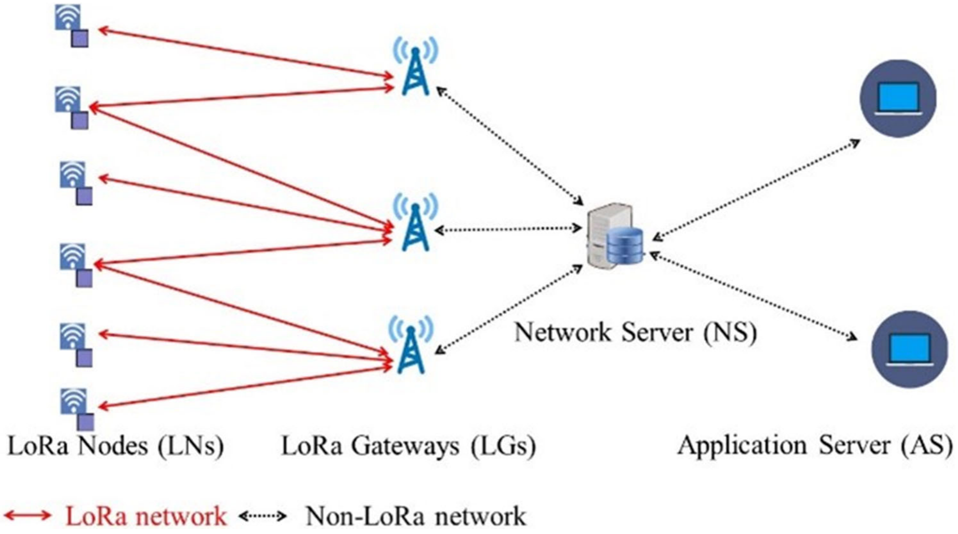

Fig. 3 An illustration of the LoRaWAN network architecture

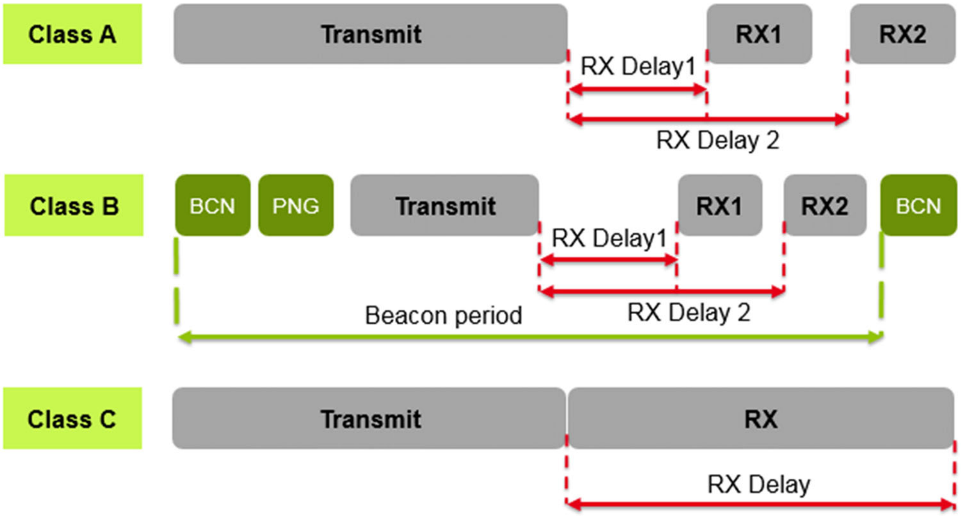

Fig. 4 Timing diagram of different LoRaWAN device classes

rates based on network conditions. LoRaWAN uses two 128-bit, unique session keys called NwkSKey and AppSKey in addition to advanced encryption standard (AES) methods to offer security. These keys are used for data encryption, message integrity verification, and node authentication. Two activation processes are available for obtaining session keys: activation by personalization (ABP) and over-the-air activation (OTAA).

3 Interference in loRa

Wireless communication systems are inherently prone to interference due to the high probability of simultaneous transmissions over the same communication medium. The operation of an IoT system in unlicensed ISM bands has both benefits and drawbacks. On the positive side, there are no license fees involved. However, the shared utilization of the spectrum results in a gradual escalation of background noise due to the continuous addition of new radiating devices. ETSI TR 102 691 [46] has raised awareness regarding a potential concern related to electromagnetic interference affecting IoT networks. This interference is particularly noticeable in the network link that connects the sensors and gateways. The document serves as an introduction to the subject, covering such ground as the possible targets and implications of electromagnetic interference on Machine-to-Machine (M2M) networks, which are essential parts of the IoT. The document identifies two main sources of interference: intentional and unintentional. Intentional sources are typically associated with attempts to gain unauthorized access to telemetric data during transmission or manipulate it. On the other hand, unintentional sources result from unintended electromagnetic interactions that can disrupt the connectivity between IoT end-devices and their corresponding gateways. Similarly, In the case of LoRa, there are two distinct sources that

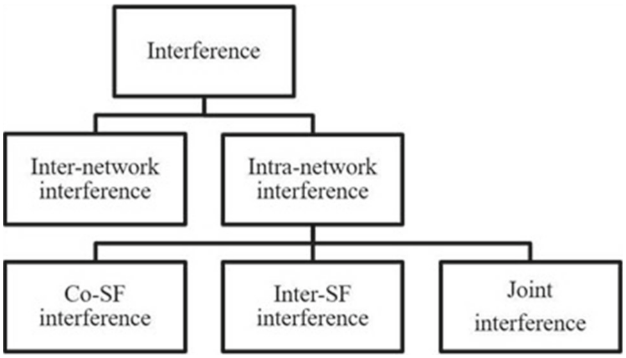

Fig. 5 Classification of interference in LoRa network

can be identified: LoRa signals themselves and signals from other sources. Interference occurs when two or more LoRa-enabled devices are sending and receiving data at the same time using the same set of transmission parameters (f_c, BW, SF). Use of the unlicensed ISM band and an exponential rise in the number of devices are further contributing factors to LoRa interference. Interference in LoRa networks is broadly categorized into two types: inter-network interference and intra-network interference, as illustrated in Fig. 5.

Inter-network interference Unlicensed spectrum is appealing because it allows network operators and individual consumers to install wireless equipment without having to deal with complicated and expensive regulatory overhead. This adaptability has facilitated the creation of numerous applications in IoT. As a result, a rising number of individual networks are competing for transmission time in the unlicensed spectrum. These networks are extremely diverse in features like radio frequencies, data rates, range, power consumption, and reliability. As LoRa operates in the Sub-GHz band, it may experience interference from the other communication technologies in the Sub-GHz band.

Intra-network interference The success of LoRa among all LPWAN technologies is due to a diverse collection of parameters. LoRa is capable of satisfying long-range transmissions with low-power consumption by actively tuning the network parameters. When the number of nodes per gateway grows, so does the number of concurrent LoRa transmissions, increasing the likelihood of collisions. Despite the smart resource allocation, the end nodes still experience interference based on the SF used. Interference could occur between devices that have the same SF or between devices that have different SF. Figure 6 shows these types of interferences.

Co-SF interference The interference which occurs when two or more LoRa nodes employ the same SF to transmit data to a certain LoRa gateway at the same time is known as Co-SF interference. If the desired transmission's Signal-to-Interference Ratio (SIR) falls below a specific level, this might limit the scalability in practical high-density installations.

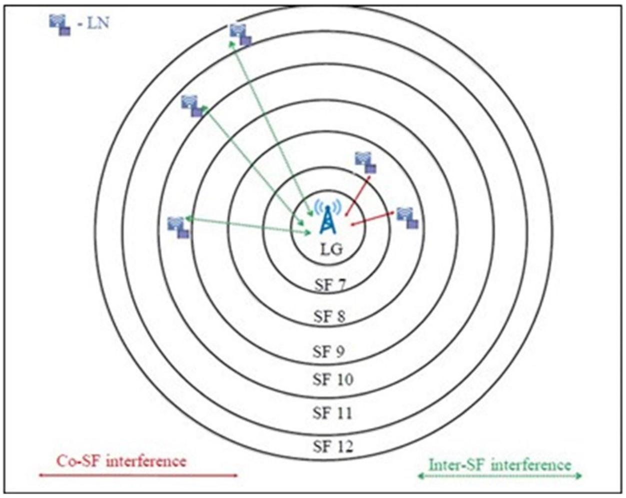

Fig. 6 Illustration of Co-SF and Inter-SF interference in LoRa

Inter-SF interference: The imperfect orthogonality of several SFs leads to Inter-SF interference. The transmissions from distinct SFs are not completely resistant to transmissions from adjacent SFs, necessitating some degree of SIR defense.

3.1 Impact of interference on *LoRa* networks

Interference significantly affects the performance and reliability of LoRa networks. It degrades signal quality, leading to increased bit error rates and packet loss, limiting the range and coverage of the network [32]. Interference also reduces data throughput, increases energy consumption, and causes network congestion and collisions. This results in unreliable communication, impacting critical applications and consuming more power. To better grasp and measure this impact, this section highlights key performance degradation metrics, specifically focusing on packet success rate (PSR), bit error rate (BER), and signal-to-interference-plus-noise ratio (SINR).

3.1.1 Packet success rate

PSR is a vital metric representing the percentage of successfully received packets out of the total transmitted packets. Both Co-SF and Inter-SF interference can significantly reduce PSR. When multiple nodes use the same spreading factor and transmit simultaneously (Co-SF interference), the likelihood of packet collisions increases, resulting in lower PSR. Research has shown that in high-density networks, PSR can experience a substantial decline due to Co-SF interference [47]. Additionally, imperfect orthogonality among different spreading factors (Inter-SF interference) can cause interference, particularly when the signal strengths of the interfering signals are comparable. This can also lead to a reduction in PSR even in moderate network densities [48].

3.1.2 Bit error rate

BER measures the number of bit errors divided by the total number of transmitted bits. BER is a direct indicator of the quality of the communication link and is adversely affected by interference. Increased Co-SF interference results in higher BER due to the overlapping of signals. Experimental results have demonstrated that BER can increase by an order of magnitude under heavy Co-SF interference conditions [49]. Moreover, due to imperfect orthogonality, signals from different spreading factors can interfere with each other (Inter-SF interference), causing an increase in BER. This is particularly problematic in environments with high signal density.

3.1.3 Signal-to-interference-plus-noise ratio

SINR is a measure of signal quality relative to the level of interference and background noise. Higher SINR values indicate better signal quality and improved network performance. Interference negatively impacts SINR in several ways. When multiple nodes transmit using the same spreading factor (Co-SF interference), the cumulative interference reduces SINR, leading to poorer signal quality. Field tests have demonstrated that in environments with significant Co-SF interference, SINR can decrease markedly [50]. Additionally, imperfect orthogonality among different spreading factors results in cross-interference, further reducing SINR. This reduction varies based on network configuration and signal strengths, but it can be significant.

The impact of interference on LoRa networks emphasizes the need for surveys and research on LoRa interference issues and approaches. Understanding the sources, characteristics, and effects of interference is crucial for developing effective mitigation strategies.

4 Solution approaches for interference in LoRa

With the increasing proliferation of IoT devices operating in the ISM band, LoRa communication systems face significant challenges due to high levels of interference. This interference poses a major obstacle to the efficient deployment of IoT applications, particularly in environments where interference levels are high. On the other hand, controlled spectrum environments, where a single operator manages Quality of Service (QoS), experience less interference. Therefore, future LoRa-based IoT networks need to take into account the effect of various types of interference and the features of the propagation environment. To address this, researchers have developed frameworks [51] that estimate network coverage using empirical interference data, providing insights into the spectro-temporal behavior of shared band traffic and enabling more reliable network planning. In dense environments, where numerous sources interfere with the transmitted signal, causing noise and performance degradation. Studies have evaluated the performance of LoRa systems under different types of interference scenarios. The study of these evaluations help identifies interference mitigation techniques and optimize system performance in challenging environments. The existing approaches to mitigate the interference are summarized in Table 2. To analyze the existing methods to overcome the interference challenge, in this study two main approaches are employed: interference avoidance and interference mitigation.

Interference avoidance focuses on preventing or minimizing interference before it occurs. It involves strategies and techniques that aim to optimize network parameters, select suitable frequency channels, and employ intelligent scheduling algorithms. By carefully managing the network resources and avoiding congested or noisy frequency bands, interference can be minimized, leading to improved network performance and reliability. Enhancing SF assignment schemes is one of the initial solutions proposed to address LoRa co-technology interference caused by high connectivity demands. The capability of networks using the default LoRa ADR capabilities to handle data rate via fine-tuning LoRa physical settings is applicable in limited applications. As a result, alternatives have been offered to the distance-based strategy [93] that gives the SF to LNs in proportion to their physical distance from the LG.

Interference mitigation aims to address interference that has already occurred or is unavoidable. It involves techniques that enhance the robustness of the LoRaWAN system against interference. These techniques may include advanced modulation schemes, error correction coding, adaptive power control, and interference cancellation algorithms. Interference mitigation techniques help mitigate the impact of interference, reduce packet loss, and maintain reliable communication even in the presence of challenging interference conditions. To address the non-orthogonality of SFs and reduce co/inter SF interference, interference cancellation has been shown to be effective [94], however it does necessitate dynamic signal processing approaches [95].

4.1 Solutions of Co-SF interference

In a dense IoT environment, a LoRa network is made up of a high number of LNs. Co-SF interference arises when multiple LNs use the same SF to transmit data to the LG at the same time.

Table 2 Summary of LoRa interference solution approaches

Reference	Year	Type of interference	Methodology	Evaluation metrics	
				Throughput	Others
Afisiadis et al. [52]	2021	Co-SF	Mathematical model for coherent LoRa receiver	0.7 × non coherent receiver	
Kumari et al. [53, 54]	2020	Co-SF	SF allocation and scheduling using game theory		Network and device utility have been enhanced
EF-LoRa [55]	2020	Co-SF	Resource allocation using optimization		Improved the energy fairness by 177.8%
M-ASFA [56]	2020	Co-SF	Mobility-aware SF assignment scheme		Packet success rate: 0.3xADR
FlipLoRa [57]	2020	Co-SF	Encoding with interleaved quasi-orthogonal up-down chirp	3.84 × conventional LoRa	
Nscale [58]	2020	Co-SF	Non-stationary amplitude scaling down-chirp	3.3 × conventional LoRa at SNR loss < 1.7 dB	
SCLoRa [59]	2020	Co-SF	Multi-dimensional cumulative spectral coefficient	3 × conventional LoRa	
Temim et al. [60]	2020	Co-SF	Successive interference cancellation		Decreases the number of retransmitted packets
Afisiadis et al. [50]	2020	Co-SF	Low-complexity formulas for symbol and frame error rates		–
E-ADR [61]	2019	Co-SF	Mode of configuration based on the estimated location of a device calculated using historical locations and the trilateration technique		3xADR reduction in energy consumption
Laporte-Fauret et al. [62]	2019	Co-SF	Signal time shift estimation and interference signal attenuation		Improved spectrum efficiency
Elshabrawy et al. [49]	2018	Co-SF	Numerical approximation of BER as a function of SNR and SIR		0.2xcoverage
Rachkidy et al. [63]	2018	Co-SF	Frequency comparison and timing information	2.5 × conventional LoRa	
Noreen et al. [64]	2018	Co-SF	Serial interference cancellation	2 × ALOHA	
Georgiou et al. [65]	2017	Co-SF	Stochastic geometry		–

Table 2 (continued)

Reference	Year	Type of interference	Methodology	Evaluation metrics	
				Throughput	Others
AlignTrack [66]	2023	Inter-SF	Aligning windows and splitting packets based on peak height	5.5 × conventional LoRa	
Fawaz et al. [67]	2021	Inter-SF	Iterative gradient ascent, Game theory, learning-based approaches for SF allocation	2 × conventional LoRa	
Pyramid [68]	2021	Inter-SF	Monitor peak height variation with a sliding demodulation window	2.11 × conventional LoRa	
Shahid et al. [69]	2021	Inter-SF	Concurrent Interference cancellation	4 × conventional LoRa	
FREE [70]	2020	Inter-SF	Scheduling approach to synchronize transmissions		100% data delivery and > 10 years battery lifetime
CoLoRa [71]	2020	Inter-SF	Considered spectral peak ratio as feature to separate collided packets	14 × conventional LoRa	
mLoRa [72]	2019	Inter-SF	Iterative successive interference cancellation	3 × conventional LoRa	
Korbi et al. [73]	2018	Inter-SF	An analytical model of a single cell LoRaWAN under unsaturated traffic, duty cycle and multi-channel deployment conditions		Imperfect spreading factors' orthogonality in LoRaWAN slows down the network performance
Staniec et al. [47]	2018	Inter-SF	Experimental evaluation		–
EXPLoRa [74]	2017	Inter-SF	"Ordered water filling" approach for SF allocation	3 × ADR	
Benkhelifa et al. [75]	2021	Joint SF	Unfair/Fair SF allocation algorithms, max–min throughput optimization		Interference is the main limitation to throughput performance
Garlisi et al. [76]	2021	Joint SF	LoRa receiver design with successive interference cancellation and time synchronization		50% improvement in performance

Table 2 (continued)

Reference	Year	Type of interference	Methodology	Evaluation metrics	
				Throughput	Others
Tapparel et al. [77]	2021	Joint SF	Successive interference cancellation, bit-interleaved coded modulation		4.7 × capacity
Guo et al. [78]	2021	Joint SF	Experimental evaluation		50% reduction in transmission time
Ftrack [79]	2020	Joint SF	Time-domain misaligned edges and signal frequency continuity	3 × conventional LoRa	
Croce et al. [80]	2020	Joint SF	Analytical framework to model the performance of LoRa cells	2.5 × conventional LoRa	
Amichi et al. [81]	2019	Joint SF	SF allocation algorithm based on matching theory	0.2 × conventional LoRa	
Beltramelli et al. [82]	2018	Joint SF	Stochastic geometry and geometric probability		Intercell interference reduces system performance in dense multi-cell LoRa networks
Reynders et al. [83]	2017	Joint SF	Optimizing the power and spreading factor for each node by allocating distant users to different channels		Improvement of 50% in packet error rate
Van den Abeele et al. [84]	2017	Joint SF	Scalability study of LoRaWAN in NS3 by considering an error model	4.5 × conventional LoRa	
Bankov et al. [85]	2017	Joint SF	Mathematical model with capture effect		–
ICSLoRa [86]	2021	Inter-NW	An analytical model using parallel logical network		Capacity gain of 42%
Marquez et al. [87]	2020	Inter-NW	Experimental evaluation of external interference		14-dBm external interference creates total packet losses
OCT [88]	2020	Inter-NW	Preamble detection, SFD detection, and		
packet decoding with time and power offsets	3 × conventional LoRa				

Table 2 (continued)

Reference	Year	Type of interference	Methodology	Evaluation metrics	
				Throughput	Others
Andri et al. [89]	2018	Inter-NW	Experimental evaluation, frame structure analysis		–
RS-LoRa [90]	2018	Inter-NW	Two-step lightweight scheduling at gateway and nodes	0.5 × LoRa	
Orfanidis et al. [91]	2017	Inter-NW	Experimental evaluation to investigate interference interactions between LoRa and IEEE 802.15.4 g networks		LoRa is much more tolerant than IEEE 802.15.4 g under interference
Thiemo et al. [92]	2017	Inter-NW	Simulation evaluation using directional antenna		Deploying multiple base stations outperform the use of directional antennae

4.1.1 Interference avoidance

Kumari et al. [53] found a different approach to allocate the SF based on the needs of the node rather than the fixed time. This methodology helps to overcome the interference by estimating the time period of usage of specific SF per node. Popular optimization techniques like Nash equilibrium and Stackleberg game concepts are used for interactions among LoRa devices and gateways. Optimal time duration is founded for the nodes to use specific SF which helps to reduce the interference. After finding the time duration they have also proposed a scheduling algorithm [54] to allocate the SFs for a particular time duration. This methodology reduces the waiting time in the network and increases the revenue, and performance of the network. Gao et al. [55] proposed a resource allocation algorithm for achieving fair energy consumption at LoRa devices. The resource allocation problem is modeled as a max–min optimization process, with the goal of increasing the worst-case energy efficiency of LNs. When solving the max–min optimization problem, both energy consumption and transmission efficiency are taken into account. The system model is designed for multiple gateways and also considered the impact of SFs, channels, and transmission power.

In [56], the authors proposed a method to dynamically assign the SF to each stationary and mobile LoRa user. By rescheduling SFs for mobile nodes according to the received signal strength from the destination LG, the ToA is decreased, and packet loss and retransmission are minimized, resulting in a higher packet success ratio. The enhanced-ADR [61] provides a dynamic allocation to minimize packet loss and transmission time for each LoRa transmitter, but it only takes into account mobile nodes that follow a certain pattern.

4.1.2 Interference mitigation

As there is a lack of synchronization between LoRa gateway and LoRa devices, Temim et al. [60] come up with a new design for a receiver. The proposed receiver is capable of synchronizing and decoding simultaneous non-orthogonal LoRa signals. This design is considered for uplink communication and implemented by the use of successive interference cancellation (SIC) algorithm. The synchronization process consists of iterative calculations of fast fourier transform (FFT) of de-chirped samples which increases the complexity. This methodology is only suitable for Higher SFs and not effective for lower SFs. The SF is one of the transmission parameters of LoRa. The authors in [52] designed a coherent receiver model by considering the same SF interference. They derived expressions for symbol error rate and frame error rate. The complexity of expressions is reduced by the usage of bounds and approximations. With the use of simulation, compared the performance of the coherent receiver with the non-coherent receiver and proved the improvement in performance by 0.7dB. The authors in [50] proposed an interference model by considering the interference which is not in alignment in phase or chip with the signal of interest. Laporte-Fauret et al. [62] designed a receiver to decode two simultaneous LoRa signals with the same SF. This model is designed by considering the particular structure of the received signal, in which the time shift between two signals is calculated. The results of the model are supported by simulation and also with the experimental setup.

The use of a constant SIR threshold of 6dB to declare coverage can significantly underestimate the coverage likelihood of LoRa signals under the same SF interference. This is analyzed by the authors in [49]. The authors derived a numerical approximation for BER under the same SF interference by considering the impacts of both Signal-to-Noise Ratio (SNR) and SIR on the coverage probability. The scalability of LoRa is limited by many factors, one such factor is identified in paper [65]. The effect of Co-SF interference is investigated by the use of a stochastic geometry model. It is been analyzed that despite various interference protective measures available to LoRa, efficiency decays exponentially with the number of LNs, limiting its scalability. Rachkidy et al. [63] proposed two algorithms for decoding synchronized and slightly desynchronized LoRa signals. These algorithms are implemented by using the timing information of the signals.

In [64], the researchers explore the capture effect and SIC as key techniques to establish a robust LoRa-based system, effectively mitigating collisions and supporting channel sensing in scenarios where the LG's wide coverage area poses challenges. The SIC approach involves combining received signals to recognize concurrent transmissions successfully. On the other hand, the capture effect enables successful demodulation of a minimum of one signal in the presence of several colliding signals. By implementing these techniques, the throughput of LoRa network is significantly enhanced. However, it's important to note that best outcomes were observed when difference in power between the received signals was above a particular threshold.

4.2 Solutions of inter-SF interference

In the early phases of research on LoRa, numerous studies have been conducted to explore resource optimization methods aimed at enhancing the efficiency of the LoRa system by mitigating the interference. However, it is important to note that the earlier literature assumes perfect SF orthogonality, which, unfortunately, does not accurately reflect real-world scenarios. Recognizing the limitations of the idealized SF orthogonality assumption, researchers have begun to delve into exploring techniques that account for the effects of imperfect SF orthogonality.

4.2.1 Interference avoidance

Fawaz et al. [67] utilized various optimization algorithms to fairly allocate SFs in a multi-operator LoRa network to maximize the throughput. The authors also used RNN for predicting the success rate of the SF so that each network will assign SFs with minimum cooperation with other networks. Abdelfadeel et al. [70] proposed a fine-grained scheduling algorithm called FREE to support bulk data transmissions. This algorithm allocates SFs to achieve concurrent transmissions without collisions. The synchronization and allocation of SF add overhead to the algorithm and also increases energy consumption. This work is carried out by considering only the applications which do not have hard delay requirements so it may not be applicable to other types of applications. The formulation of the packet success probability was determined for co-SF interference scenarios with respect to SNR values using stochastic geometry, which was then used to construct a heuristic SF allocation algorithm.

A more intelligent SF selection technique, called EXPLoRA-SF is presented by Cuomo et al. [74] to reduce interference among groups of devices with different SFs and to boost overall network performance. This technique aims to demonstrate that by allocating larger-than-needed SFs, network capacity can be improved. This follows a simple heuristic approach for allocating SF's. The advanced version EXPLoRA-AT [96] uses 'ordered water filling' strategy to allocate SF's which achieves the same time on air for each group of interferers. These algorithms are developed by considering the single gateway scenario so the extension for multiple gateways is in scope. Many of the earlier research works on LoRa considered that the network of multiple gateways can be analyzed as a simple superposition of independent sub-networks. But collisions can hinder the proper reception of simultaneous transmissions employing different SFs in near-far conditions. The impact of imperfect orthogonality of SFs is experimentally proved by Croce et al. in [48]. In this work, LoRa modulation is mathematically analyzed and simulation findings are tested by real-time experiments. The authors in [73] presented a model which analyzes the LoRaWAN performance under both perfect and imperfect SF orthogonality by considering the duty cycle, unsaturated traffic, and multi-channel deployment conditions.

The authors of [97] discuss the necessity of a high SF for robust LoRa communication over a channel with high time-variability. In particular, they make use of the exponential relationship between Rayleigh fading and the frame error rate of a LoRa receiver using CSS modulation. They found that as the payload size increased, the reliability of LN deployed with high SF and transmitting over quickly shifting channels degraded. The experiment reported in [98] used a public LoRaWAN network with many LGs to collect data from a variety of LNs spread over a medium-sized city. The objective was to determine the multipath fading, loss burstiness, frame length, and FEC needed for reliable LoRa communication. By modifying the SF and the number of frame repetitions, this technique was used to improve the target LoRaWAN network's reliability and time-on-air performance. In order to measure the LoRa communication system's immunity to interference and multipath fading concerns, three distinct sensitivity areas were designed in [47]. The primary characteristics of LoRa SF, BW, CR were used to create these groups.

4.2.2 Interference mitigation

The authors in paper [72] developed a protocol called mLoRa to decode the multiple collided packets from different LoRa devices. In this protocol, the special features of LoRa like CSS, M-FSK modulation and demodulation are utilized. The decoding process is split into two categories like chirp level and sample level to make implementation easier. The authors also worked on the enhancement of the protocol to reduce the impact of noise and frequency offset. Experimental results showed that this protocol has achieved 3 times of conventional LoRa throughput. Without utilizing power offset, mLoRa will be invalid for tiny time offsets. In the same line, Tong et al. [71] developed CoLoRa to enable the multi-packet reception in LoRa. In this protocol, the packet time offset is used to decode the multiple collided packets from one collision. The time offset is converted into frequency features to make it easy for the calculation of symbols. A method to extract precise peak ratios by canceling the inter-packet interference is presented. The effect of redundant packet reception at multiple gateways on data reliability is investigated by Minming et al. in [99]. The probability of a successful reception without re-transmission is measured by Average Successful Transmission Probability (ASTP). This is a function of the LNs density, gateway density, and traffic intensity.

In [100], the capacity of the legacy LoRa network was boosted to accommodate more LNs. This enhancement was achieved by developing a comprehensive receiver with an interference cancellation scheme, channel estimation, and packet detection models. However, the implementation of these improvements posed significant challenges. An alternative uplink scheme was introduced in [101], utilizing SIC and exploiting the unique characteristics of received superposed LoRa-like signals. To preserve the limited energy resources of LNs, the proposed schemes were implemented in LGs, resulting in reduced energy consumption for LNs and improved spectral efficiency through fewer re-transmitted packets. Conversely, [102] focused on enhancing the downlink in LoRa-like networks by designing a novel multiuser detector. The objective was to effectively limit the number of acknowledgments sent after successful packet reception, which directly impacted the overall reliability of the LoRa-based network.

4.3 Solutions of joint interference

The solutions for reducing the interference in LoRa network by considering both Co-SF and Inter-SF interferences are discussed here.

4.3.1 Interference avoidance

The authors in [81] proposed SF allocation algorithm by considering the joint interference. For optimization of SF allocation, they approached max–min optimization and proposed an algorithm based on matching theory. In [103], the joint SF and power allocation problem has been solved. Assigning SFs with a fixed amount of power and allocating resources with a limited number of SFs are two separate parts of the problem. For optimal SF allocation proposed an algorithm based on matching theory and for optimal power allocation used linear and quadratic approximation functions. The joint optimal SF and Power allocation is also analyzed by Benkhelifa et al. [75]. In this work, it is introduced to use the energy harvesting time to maximize the minimum time-averaged data rate. For SF allocation, proposed fair and unfair algorithms which allocate the same and different SF's to LoRa devices. In order to optimize the packet error rate in a LoRaWAN cell, the power and SF of each node need to be optimized. Therefore, Reynders et al. [83] proposed a scheme for the optimal distribution of SF by considering the perfect power control.

4.3.2 Interference mitigation

In order to simulate interference, Van den Abeele et al. [84] developed an NS3 model. This research presents a novel technique by first creating a LoRa error model utilizing thorough and complicated baseband bit error rate simulations and then employing the model in an interference analysis. The effectiveness of the LoRa receiver was measured while it was subjected to both Co-SF and Inter-SF interference by Zhu et al. [104]. Concurrent transmissions of LoRa with identical and different SFs are simulated. With results, it is shown that higher SFs are more immune to interference. SF pipeline scheduling is introduced to improve the performance of concurrent transmissions in LoRa. The authors in [105] developed a simulator for LoRaWAN and conducted simulations under three different conditions to evaluate the impact of collisions. Collision models accounting inter-SF interference, co-SF interference, and capture effect were found to be able to obtain higher throughput than the baseline model. This means that any collision results in the loss of all colliding packets. Xia et al. [79] presented a model called Ftrack, which uses a time domain and frequency domain features of a signal to decode the collided transmissions. To remove interference, signal frequency continuity is detected and then time-domain information from symbol edges is used to recover symbols from all collided frames. By considering joint interference, LoRa link level performance is analyzed in [80] by Daniele et al. In this study, the effect of high capture probability and imperfect orthogonality of SF on the capacity of LoRa cell is analyzed. Capture effects and inter-SF collisions have a significant impact on LoRa link-level efficiency, which can result in a loss if the interference power is high enough. Beltramelli et al. [82] designed a model for evaluating the uplink performance of LoRa in a multicell system. In this work, joint interference is considered and intra-cell and intercell interference is also considered to calculate the success probability under different distributions of the gateway. It is been observed that inter-cell interference causes a negative impact on the network performance which can be reduced by allocating proper SF by considering not only interference within the cell but also need to consider the interference in neighboring cells.

Another analytical model is given in the paper [106] considered joint interference and calculated the single gateway LoRaWAN throughput under the necessary conditions for successful transmission. It is been noticed that imperfect orthogonality of SF and allocation strategies will have a non-negligible impact on the throughput of the network. Scalability of multiannuli single-cell LoRa Network under joint interference is analyzed by Mahmood et al. in [107]. The interference field is represented as a Poisson-Point-Process using Stochastic Geometry. Using three distinct allocation strategies, the authors investigated how SF allocation affects network performance. A similar approach was employed in [108], which evaluated success and coverage probability while lowering the computational complexity required to acquire these probabilities for all interference types.

In [85], a mathematical model was introduced as an extension of [109], which incorporates the capture effect in the LoRaWAN channel access process. By precisely specifying the data transmission process, suggested model increases the network's capability and guarantees consistent LoRa-based transmission, particularly with regard to the power difference of signals received concurrently from numerous LoRa transmitters. In [76], a LoRa receiver called LoRaSyNc was designed to push the limits of LoRa network capacity further. This receiver goes beyond standard demodulation methods by bringing a clock tracking mechanism into the frame reception process and synchronizing the superimposed signals. These enhancements contribute to enhancing the network's performance. The authors of [77] developed a SIC LoRa receiver to address the instability of LoRaWAN networks. To find and eliminate the strongest interfering signal, the two-user detector employs bit interleaved coded modulation. It considers a soft-demodulator and soft-decoder to achieve reasonable error rates, particularly in the challenging low SNR zone of LoRa communication.

The performance study of the LoRa receiver discussed the benefits of multi-hop LoRa networks over single-hop LoRa networks for assuring broad network coverage and improving indoor penetration in [110]. Additionally, the SIR required to permit the orthogonality of SFs was examined and it was determined that when numerous LNs used the same SF to transmit time-synchronized packets, the LoRa network was immune to interference. The reception performance of LoRa packets was tested experimentally in [78]. It was discovered that there is a compromise between the physical parameter and packet reception performance when the SNR is negative. LoRa performance was found to be significantly impacted by packet length. This realization led to the creation of a transmission method that manages three critical factors: delay, power consumption, and reliability.

4.4 Solutions of inter-network interference

LoRa is mainly used for applications that need to cover a large area. Long-distance LoRa communications are susceptible to interference from a variety of sources, which can increase background noise and decrease system performance. The literature presented in earlier sections have looked at the efficiency and scalability of LoRa communication by considering the interactions between and within LoRa networks. However, research into the coexistence of LoRa and other wireless communication technologies has seen less exposure. online concurrent transmission (OCT) at LoRa gateway is a revolutionary approach presented by Wang et al. [88] that recovers collision packets at the gateway and, in turn, increases LoRaWAN throughput. OCT allows a LoRa gateway to concurrently accept several collided packets from separate LoRa ends. Edward et. al in [111] and [86] introduced interleaved chirp spreading (ICS) LoRa to increase the capacity of LoRa by adding one additional bit per symbol in each transmission. Later they deployed ICS LoRa as a parallel logical network to traditional LoRa and studied the inter-network interference and also developed a model to find the BER of LoRa under the interference of ICS LoRa. Reynders et al. [90] used a scheduling approach to overcome the collisions. The capture effect can be mitigated by using a two-stage lightweight scheduling approach that groups nodes with similar transmission strengths. In order to avoid packet collisions, the gateway's coarse-grained scheduling instructed the nodes to use multiple SFs for concurrent broadcasts.

Marquez et al. [87] developed a model to determine the immunity region for the uplink LoRa system with LOS conditions. Experimentally determined the amount of electromagnetic interference needed for blocking a channel in LoRa. Cross-technology interference between LoRa and IEEE 802.15.4g was experimentally evaluated by the authors of [91]. LoRa is typically more resistant to interference than

IEEE 802.15.4g, with the radio settings (SF and BW) being critical to the level of tolerance. Lauridsen et al. [112] performed a measurement study for finding the signal activity in ISM band 868 MHz. The measurements showed the degradation of the SIR which may block access to the target channel and will impact the coverage and capability of LPWANs.

Sun et al. [113] introduced the PSR scheme to address the challenge of cross technology interference (CTI) in LPWANs, particularly focusing on LoRa technology. Their method identifies and uses uncorrupted LoRa chips for reliable packet recovery, significantly improving packet reception from 45.2 to 82.2% in real-world testbeds. The authors demonstrate the effectiveness of PSR under various interference scenarios, highlighting its robustness against Wi-Fi, ZigBee, and Bluetooth interference. Xu et al. [114] designed SLoRa, a systematic framework to enhance interference resilience in LPWANs by integrating symbol recovery and soft decoding. SLoRa employs a two-stage analysis to accurately recover corrupted symbols and estimates the confidence of these symbols to improve error correction. The framework is evaluated using real-world testbeds, demonstrating a 1.4 × improvement in CTI protection with minimal computational overhead. This comprehensive approach provides a significant advancement in mitigating cross-technology interference in LPWANs, ensuring reliable performance in diverse interference scenarios.

4.5 Intentional interference in LoRa

Intentional interference, commonly referred to as jamming, poses a significant threat to the reliability and security of LoRa networks. Unlike unintentional interference, which occurs due to electromagnetic interactions, intentional interference is a deliberate attempt to disrupt communication by overpowering the signal with noise or other signals. Given the widespread use of the unlicensed ISM bands for LoRa, the risk of jamming is an important consideration.

Jamming attacks in LoRa networks pose a substantial threat to network performance and reliability. These attacks involve malicious transmitters emitting radio frequency signals to disrupt communication between LoRa end nodes and gateways. Research indicates that while the LoRa physical layer is robust, it remains vulnerable to high-power, synchronized jamming chirps, which can prevent gateways from receiving data from nodes across the network. An empirical study [115] demonstrates that although LoRa PHY is designed to be resilient, synchronized jamming chirps can still effectively disrupt communication, rendering traditional protection solutions like collision recovery and parallel decoding ineffective. To counter this, a new method has been proposed that separates LoRa chirps from jamming chirps by leveraging their differences in received signal strength within the power domain, showing promising results in experimental setups using commercial off-the-shelf (COTS) LoRa nodes and software-defined radios. Selective jamming, which targets specific channels or transmission windows, exacerbates the problem. Utilizing commodity hardware, attackers can execute practical jamming attacks that exploit the slow modulation type used in LoRa protocols. This type of attack can selectively disrupt certain communications without affecting others, making it particularly insidious. The vulnerabilities of LoRa and LoRaWAN protocols to such selective jamming attacks have been highlighted, with suggestions for a range of countermeasures to mitigate these threats in [116].

Experimental studies further reveal the extent of the impact that jamming can have on network performance. When attackers emit RF interference signals simultaneously with LoRa end nodes, it results in packet collisions and transmission failures, significantly degrading network performance. These studies [117] involve implementing a LoRa jammer on commercial devices and adjusting jammer settings to evaluate the impact of transmission configurations on jamming effectiveness. The findings emphasize that non-orthogonality in LoRa transmission can influence the effectiveness of jamming attacks, pointing to the need for countermeasures to alleviate such threats. Moreover, performance evaluations under various jamming scenarios indicate that LoRaWAN networks are particularly vulnerable to jamming attacks. Simulations show that network throughput can decrease by approximately 56% when multiple jammers continuously send unauthenticated packets within the network [118]. The performance of gateways is also dramatically affected, as resources required to process packets from jammers can be up to 100 times higher than that for regular end-devices. The impact of jammers is highly correlated with their classification, with channel-oblivious jammers affecting the network performance broadly, while channel-aware jammers have more localized effects [119]. These insights underscore the need for robust jamming mitigation strategies tailored to different jamming types.

5 Discussion and future directions

Existing research has highlighted that the connectivity requirements of massive IoT surpass the capabilities of LoRaWAN due to its limited features such as SFs ranging from 7 to 12, available BWs of 125 kHz, 250 kHz, and 500 kHz, and CR of 4/5, 4/6, 4/7, and 4/8. Managing the massive connectivity demands and minimizing the impact of interference in ultra-dense deployments using LoRaWAN's standard ADR and CSS modulation is a challenging task. This leads to issues such as interference and collisions between concurrent transmissions, resulting in significant network performance degradation, making the traditional version of LoRaWAN unsuitable for such scenarios. In response to these issues, researchers have proposed a number of changes to the LoRaWAN protocol to make the LoRa network more robust and scalable. However, there are still several open research challenges that need further investigation, including efficient management of massive connectivity demands, interference mitigation and collision avoidance, network scalability, energy efficiency, and security and privacy concerns. Additionally, methodologies for detecting interference and standard parameter allocation to improve network performance are areas that require further exploration. Open problems in the interference of LoRa networks, which have not been fully considered in existing solutions, also need to be addressed.

5.1 Mobility

The mobility of nodes will have a substantial influence on network interference. The mobility of nodes introduces additional challenges in managing interference and optimizing resource allocation. When nodes move, their positions relative to other nodes and gateways change, resulting in varying signal strengths and interference patterns. This dynamic nature of node mobility can impact the overall network performance and necessitates the development of appropriate solutions.

Almost all research works presume LoRa nodes to be stationary and formulate solutions based on such assumption. However, in practice, LoRa nodes do not need to be fixed and may move because no particular handover mechanism is required. As a result, resource allocation methods, scheduling algorithms, and any other strategies used to reduce interference must take this parameter into account and develop solutions appropriately.

Furthermore, the impact of node mobility on interference needs to be thoroughly understood and characterized. Research efforts should focus on analyzing the effects of node movement on signal propagation, interference patterns, and collision probabilities. This analysis can provide insights into designing efficient interference mitigation techniques and optimizing network performance in the presence of mobile nodes. Considering node mobility in LoRa networks opens up new avenues for research and development. It enables the design of adaptive and robust solutions that can handle the challenges associated with dynamic node positions and varying interference conditions.

5.2 SF allocation and scheduling

One of the first proposed remedies to interference brought on by rising connectivity needs in LoRa networks is to improve SF assignment mechanisms. Adjusting LoRa physical parameters with the standard LoRa ADR feature is now at its limit. LNs can adjust their signal strength and range according to the amount of bandwidth and frequency being used via SF allocation. SFs may be allocated at random, in accordance with the distance between the LN and the LG, or in accordance with the data requirements and communication link quality. Efficient and reliable data transfer over a fair LoRaWAN has been investigated, although this is not guaranteed due to the fact that fairness considerations generally ignore time-variable event occurrence rates, data arrival rates, and LN mobility. While the previously mentioned SF assignment techniques have shown promise in lowering interference and increasing network scalability, the restricted number of SF variants still prevents the seamless connecting of a large number of LNs in large-scale IoT deployments. SF assignment could be implemented into a cross-layer protocol that bridges the gap between LoRa's physical layer qualities and LoRaWAN's MAC layer capabilities, with the added bonus of transmission scheduling, to alleviate this limitation. With this strategy, LoRaWAN capacity would be increased and problems brought on by large-scale IoT deployments would be resolved.

5.3 Gateway densification

One suggested approach for improving network performance is the deployment of multiple gateways in a network. However, as the number of gateways increases, the risk of collisions also rises, posing a challenge. Researchers can draw inspiration from cellular networks to devise innovative densification strategies for LoRa networks while considering inherent constraints like duty cycle restrictions and low throughput. Most existing research focuses on interference reduction strategies for single-gateway networks, making them inadequate for multiple-gateway scenarios. It becomes essential to enhance these methodologies to address the unique requirements and challenges presented by networks with multiple gateways. However, architectural adjustments may be required to adapt the existing LoRaWAN to these improvements. Densification strategies should be carefully crafted to allow for coordinated action within and across cells without increasing the likelihood of collisions between simultaneous LG transmissions.

To address the challenges associated with increased collisions in multi-gateway scenarios, innovative interference mitigation techniques and efficient scheduling methods are required. One approach could involve implementing centralized or distributed coordination mechanisms that allow gateways to share information and schedule transmissions in a way that minimizes overlap and interference. Machine learning algorithms could also be employed to predict and dynamically adjust to changing network conditions, optimizing the use of available spectrum and reducing collision rates. Additionally, developing protocols that enable gateways to sense their environment and make real-time decisions based on interference levels could enhance the overall performance and reliability of the network.

5.4 Efficiency in interference mitigation

In managing LoRa networks, it is crucial to effectively handle power resources due to the low-power nature of the technology. While LoRa transmissions are generally low-power, addressing collisions and interference challenges requires complex computations. Therefore, any solution approach must carefully consider the low-power characteristic and design strategies accordingly to ensure efficient power management.

Interference cancellation techniques are implemented either on LNs or LGs to decode several overlapping LoRa signals delivered using distinct SFs. Fast Fourier transform and discrete Fourier transform are two signal processing techniques that can separate overlapping signals. The capture effect, in which only the signal with the greatest strength is deciphered, is another possibility that might be looked into. Effective decoding involves identifying frame preambles from the received signal. However, these methods can be time-consuming and require additional energy consumption, particularly when exchanging information about the SF and CR used for transmission. These factors make these approaches unsuitable for time-sensitive data and drive up the cost of receivers, neither of which is acceptable in LPWANs. There must be a compromise between network performance and cost when adopting interference mitigation solutions for LoRa signals, especially in regard to the received packet rate.

When devising interference mitigation approaches for LoRa networks, energy efficiency becomes a crucial consideration. Balancing the reduction of interference while maintaining low power consumption is essential. Solutions should strive to optimize energy usage while effectively managing interference, ensuring a reliable and efficient network. This involves exploring techniques that minimize energy-intensive computations, prioritize time-sensitive information, and find the right balance between cost and performance. By focusing on energy efficiency in interference mitigation strategies, LoRa networks can achieve both effective interference management and optimized power resource utilization.

5.5 Scalability of mitigation techniques

The scalability of interference mitigation techniques is critical for ensuring that LoRa networks can support a growing number of devices without significant performance degradation. Current techniques often struggle with the increasing density of LoRa nodes, leading to higher rates of collisions and interference. Future research should focus on developing scalable solutions that can dynamically adapt to varying network conditions. This includes exploring advanced algorithms for adaptive data rate management, dynamic SF allocation, and more sophisticated scheduling mechanisms. Additionally, leveraging machine learning techniques to predict network congestion and adjust parameters proactively could provide significant improvements in scalability.

5.6 Energy efficiency

Energy efficiency remains a paramount concern for LoRa networks, particularly because many IoT devices are battery-powered and expected to operate for extended periods without maintenance. Effective interference mitigation should not come at the cost of increased energy consumption. Future research should explore low-power algorithms and protocols that can effectively manage interference while preserving energy resources. Techniques such as energy-efficient MAC protocols, duty cycling strategies, and energy-aware routing can help in maintaining a balance between performance and energy consumption. Additionally, energy harvesting and management techniques could be integrated to prolong the operational life of IoT devices.

5.7 Adding intelligence

As LoRa networks continue to expand and face challenges related to interference, machine learning and deep learning techniques emerge as promising solutions for effective interference mitigation. By leveraging the capabilities of these advanced computational approaches, LoRa networks can enhance their interference detection, prediction, and management capabilities, leading to improved network performance and reliability.

The characteristics of LoRa demodulation are utilized in numerous research works to decode received information in the presence of interference. Even though numerous optimal approaches have been proposed, decoding each sample is an iterative and complex process. Upgrading the traditional modulation-demodulation process with the current machine-learning techniques is one of the most essential study efforts in this sector. Adding intelligence to the process may lessen the complexity.

By implementing autonomous resource allocation, LNs have the capability to independently determine their transmission parameters, such as SF and CR, based on their own communication needs. This allows for a more efficient utilization of the available network resources and reduces the likelihood of interference. Moreover, distributed scheduling schemes enable LNs to coordinate their transmissions in a distributed manner, ensuring that concurrent transmissions do not result in collisions. Through collaborative self-organization, LNs can exchange information about their transmission schedules, network conditions, and interference patterns. This collaborative approach empowers the LNs to make informed decisions regarding their transmissions, enabling them to dynamically adjust their transmission parameters to avoid interference with neighboring nodes.

These autonomous and distributed resource allocation and scheduling schemes promote efficient use of network resources while minimizing interference and collisions in LoRa networks.

6 Conclusion

LoRa technology holds great promise for providing reliable long-range communication in massive IoT networks. However, the scalability of the system is hindered by difficulties such as signal interference and collisions during concurrent transmissions. This survey looks at state-of-the-art technologies for interference reduction and intends to analyze the scalability problems associated with installing LoRaWAN in ultra-dense IoT networks. This work stands out by offering a comprehensive review of LoRaWAN interference issues and solutions that goes beyond previous surveys on the topic. It provides a broad overview of interference in LoRaWAN and categorizes the different types of interference, while also discussing the existing solutions available in the literature for each category. Many of the existing solutions leverage the unique features of LoRa to increase network capacity, while others propose new protocols or receiver designs and employ signal processing techniques to mitigate interference. Despite the progress made, there is still a need for additional efforts to create reliable and scalable LoRa-based massive IoT systems. As a result, the survey highlights several promising research directions that can provide valuable guidance to researchers aiming to design efficient and scalable LoRaWAN systems.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by B Shilpa, Hari Prabhat Gupta, Rajesh Kumar Jha and Shakeel Hashmi S. The first draft of the manuscript was written by B Shilpa and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

References

1. Al-Fuqaha, A., Guizani, M., Mohammadi, M., Aledhari, M., & Ayyash, M. (2015). Internet of Things: A survey on enabling technologies, protocols, and applications. *IEEE Communications Surveys Tutorials, 17*(4), 2347–2376.
2. Vashi, S., Ram, J., Modi, J., Verma, S., & Prakash, C. (2017). Internet of Things (IoT): A vision, architectural elements, and security issues, In 2017 *Proceedings of I-SMAC* (pp. 492–496).
3. Bembe, M., Abu-Mahfouz, A., Masonta, M., & Ngqondi, T. (2019). A survey on low-power wide area networks for IoT applications. *Telecommunication Systems Modelling Analysis Design and Management, 71*(2), 249–274.
4. Wang, H., & Fapojuwo, A. O. (2017). A survey of enabling technologies of low power and long-range machine-to-Machine communications. *IEEE Communications Surveys Tutorials, 19*(4), 2621–2639.
5. Sigfox, https://www.sigfox.com/ Accessed on [March 18, 2022].
6. Semtech, https://www.semtech.com/lora Accessed on [Feb 8, 2022].
7. Wi-SUN alliance, https://wi-sun.org/, Accessed on [July 18, 2022].
8. Hoglund, A., Lin, X., Liberg, O., Behravan, A., Yavuz, E. A., Van Der Zee, M., Sui, Y., Tirronen, T., Ratilainen, A., & Eriksson, D. (2017). Overview of 3GPP release 14 enhanced NB-IoT. *IEEE Network, 31*(6), 16–22.
9. Dawy, Z., Saad, W., Ghosh, A., Andrews, J. G., & Yaacoub, E. (2017). Toward massive machine type cellular communications. *IEEE Wireless Communications, 24*(1), 120–128.
10. Centenaro, M., Vangelista, L., Zanella, A., & Zorzi, M. (2016). Long-range communications in unlicensed bands: The rising stars in the IoT and smart city scenarios. *IEEE Wireless Communications, 23*(5), 60–67.
11. Ikpehai, A., Adebisi, B., Rabie, K. M., Anoh, K., Ande, R. E., Hammoudeh, M., & Mbanaso, U. M. (2018). Low-power wide area network technologies for Internet-of-Things: A comparative review. *IEEE Internet of Things Journal, 6*(2), 2225–2240.
12. Gomez, C., Veras, J. C., Vidal, R., Casals, L., & Paradells, J. (2019). A Sigfox energy consumption model. *Sensors, 19*(3), 681.
13. Sundaram, J. P. S., Du, W., & Zhao, Z. (2020). A Survey on LoRa Networking: Research Problems, Current Solutions, and Open Issues. *IEEE Communications Surveys & Tutorials, 22*(1), 371–388.
14. Bi, S., Zhang, R., Ding, Z., & Cui, S. (2015). Wireless communications in the era of big data. *IEEE Communications Magazine, 53*(10), 190–199.
15. IDC, https://www.idc.com/ Accessed on [Nov 18, 2022].
16. Chen, S., Xu, H., Liu, D., Hu, B., & Wang, H. (2014). A vision of IoT: Applications, challenges, and opportunities with China perspective. *IEEE Internet of Things Journal, 1*(4), 349–359.
17. Saluja, D., Singh, R., Baghel, L. K., & Kumar, S. (2021). Scalability analysis of LoRa network for SNR-based SF allocation scheme. *IEEE Transactions on Industrial Informatics, 17*, 6709–6719.
18. Kufakunesu, R., Hancke, G. P., & Abu-Mahfouz, A. M. (2020). A survey on adaptive data rate optimization in LoRaWAN: Recent solutions and major challenges. *Sensors, 20*(18), 5044.
19. H. Yang et al., (2023).ChirpKey: A Chirp-level Information-based Key Generation Scheme for LoRa Networks via Perturbed Compressed Sensing. In proceedings of *IEEE INFOCOM 2023–IEEE Conference on Computer Communications*, New York City, (pp. 1–10).
20. H. Yang et al., (2022).Vehicle-Key: A Secret Key Establishment Scheme for LoRa-enabled IoV Communications. In *proceedings*

of IEEE 42nd International Conference on Distributed Computing Systems (ICDCS), Bologna (pp. 787–797).

21. Gao, J., Xu, W., Kanhere, S., Jha, S., Kim, J. Y., Huang, W., & Hu, W. (2021). A novel model-based security scheme for LoRa key generation. In *proceedings of the 20th International Conference on Information Processing in Sensor Networks (IPSN '21), Association for Computing Machinery*, NY (pp. 47–61).
22. de Carvalho Silva, J., Rodrigues, J. J., Alberti, A. M., Solic, P., & Aquino, A. L. (2017, July). LoRaWAN—A low power WAN protocol for Internet of Things: A review and opportunities. In *2017 2nd International multidisciplinary conference on computer and energy science (SpliTech)* (pp. 1-6). IEEE.
23. Marais, J. M., Malekian, R., & Abu-Mahfouz, A. M. (2017). LoRa and LoRaWAN testbeds: A review. *IEEE Africon, 2017*, 1496–1501.
24. Lavric, A., & Popa, V. (2017). Internet of things and LoRa™ low-power wide-area networks: a survey. In *2017 International Symposium on Signals, Circuits and Systems (ISSCS)* (pp. 1-5). IEEE.
25. Haxhibeqiri, J., De Poorter, E., Moerman, I., & Hoebeke, J. (2018). A survey of LoRaWAN for IoT: From technology to application. *Sensors, 18*(11), 3995.
26. Saari, M., bin Baharudin, A. M., Sillberg, P., Hyrynsalmi, S., & Yan, W. (2018, May). LoRa—A survey of recent research trends. In *2018 41st international convention on information and communication technology, electronics and microelectronics (MIPRO)* (pp. 0872-0877). IEEE.
27. Ertürk, M. A., Aydın, M. A., Büyükakkaşlar, M. T., & Evirgen, H. (2019). A survey on LoRaWAN architecture, protocol and technologies. *Future Internet, 11*(10), 216.
28. Alenezi, M., Chai, K. K., Chen, Y., & Jimaa, S. (2020). Ultra-dense LoRaWAN: Reviews and challenges. *IET Communications, 14*(9), 1361–1371.
29. Noura, H., Hatoum, T., Salman, O., Yaacoub, J. P., & Chehab, A. (2020). LoRaWAN security survey: Issues, threats and possible mitigation techniques. *Internet of Things, 12*, 100303.
30. Cotrim, J. R., & Kleinschmidt, J. H. (2020). LoRaWAN mesh networks: A review and classification of multihop communication. *Sensors, 20*(15), 4273.
31. Silva, J., Flor, D., de Junior, V. A., Bezerra, N., & Medeiros, A. (2021). A survey of LoRaWAN simulation tools in ns-3. *Journal of Communication and Information Systems, 36*(1), 17–30.
32. Gkotsiopoulos, P., Zorbas, D., & Douligeris, C. (2021). Performance determinants in LoRa networks: A literature review. *IEEE Communications Surveys & Tutorials, 23*(3), 1721–1758.
33. Li, C., & Cao, Z. (2023). LoRa networking techniques for large-scale and long-term IoT: A down-to-top survey. *ACM Computing Surveys, 55*(3), 1–36.
34. Maurya, P., Singh, A., & Kherani, A. A. (2022). A review: Spreading factor allocation schemes for LoRaWAN. *Telecommunication Systems, 80*, 449–468.
35. Sun, Z., Yang, H., Liu, K., Yin, Z., Li, Z., & Xu, W. (2022). Recent advances in LoRa: A comprehensive survey. *ACM Transactions on Sensor Networks, 18*(4), 1–44.
36. Cheikh, I., Aouami, R., Sabir, E., Sadik, M., & Roy, S. (2022). Multi-layered energy efficiency in LoRa-WAN networks: A tutorial. *IEEE Access, 10*, 9198–9231.
37. Ayoub Kamal, M., Alam, M. M., Sajak, A. A. B., & Mohd Su'ud, M. (2023). Requirements, deployments, and challenges of LoRa technology: A survey. *Computational Intelligence and Neuroscience, 2023*(1), 1–5.
38. Jouhari, Mohammed et al. (2022). A Survey on scalable LoRaWAN for massive IoT: Recent advances, potentials, and challenges. ArXiv abs/2202.11082
39. Reynders, B., & Pollin, S. (2016). Chirp spread spectrum as a modulation technique for long-range communication. In *Symposium on Communications and Vehicular Technologies (SCVT)*, (pp. 1–5).
40. Shilpa, B., Radha, R., & Movva, P. (2022). Comparative analysis of wireless communication technologies for iot applications. In *Artificial Intelligence and Technologies*, 806.
41. Semtech Corporation, LoRa Modulation Basics," AN1200.22, 2015.
42. Tapparel, Joachim et al. (2020). An open-source LoRa physical layer prototype on GNU radio. In 2020 *IEEE 21st International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)* (pp1–5). IEEE.
43. Semtech, N. S., Semtech, M. L., IBM, T. E., IBM, T. K., & Actility, O. (2016). LoRaWAN specification. LoRa Alliance.
44. LoRa Alliance. (2021). LoRaWAN for developers. [Online]. Available: https://loraalliance.org/lorawan-for-developers
45. Gamage, A., Liando, J. C., Gu, C., Tan, R., & Li, M. (2020). LMAC: Efficient carrier-sense multiple access for LoRa. In *26th Annual International Conference on Mobile Computing and Networking*, (pp. 1–13).
46. ETSI (2010). Machine-to-machine communications (m2m): Smart metering use cases. ETSI TR TR 102 691, 1.1.1, (2010–05).
47. Staniec, K., & Kowal, M. (2018). LoRa performance under variable interference and heavy-multipath conditions. *Wireless Communications and Mobile Computing, 2018*(1), 6931083.
48. Croce, D., Gucciardo, M., Mangione, S., Santaromita, G., & Tinnirello, I. (2018). Impact of LoRa imperfect orthogonality: Analysis of link-level performance. *IEEE Communications Letters, 22*(4), 796–799.
49. Elshabrawy, T., & Robert, J. (2018). Analysis of BER and coverage performance of LoRa modulation under same spreading factor interference. In *Proceedings of PIMRC* (pp. 1–6). IEEE.
50. Afisiadis, O., Cotting, M., Burg, A., & Balatsoukas-Stimming, A. (2020). On the error rate of the LoRa modulation with interference. *IEEE Transactions on Wireless Communications, 19*(2), 1292–1304.
51. Al Homssi, B., Dakic, K., Maselli, S., Wolf, H., Kandeepan, S., & AlHourani, A. (2021). IoT network design using open-source LoRa coverage emulator. *IEEE Access, 9*, 53636–53646.
52. Afisiadis, O., Li, S., Tapparel, J., Burg, A., & Balatsoukas-Stimming, A. (2021). On the advantage of coherent LoRa detection in the presence of interference. *IEEE Internet of Things Journal, 8*(14), 11581–11593.
53. Kumari, P., Gupta, H. P., & Dutta, T. (2020). Estimation of time duration for using the allocated LoRa spreading factor: A game-theory approach. *IEEE Transactions on Vehicular Technology, 69*(10), 11090–11098.
54. Kumari, P., Gupta, H. P., & Dutta, T. (2020). An incentive mechanism-based stackelberg game for scheduling of LoRa spreading factors. *IEEE Transactions on Network and Service Management, 17*(4), 2598–2609.
55. Gao, W., Du, W., Zhao, Z., Min, G., & Singhal, M. (2019). Towards energy fairness in LoRa networks, In *Proceedings of IEEE ICDCS* (pp. 788–798). IEEE.
56. Farhad, A., Kim, D. H., Kim, B. H., Mohammed, A. F. Y., & Pyun, J. Y. (2020). Mobility-aware resource assignment to IoT applications in long-range wide area networks. *IEEE Access, 8*, 186111–186124.
57. Xu, Z., Tong, S., Xie, P., & Wang, J. (2020). FlipLoRa: Resolving collisions with up-down quasi-orthogonality. In *2020 17th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON)* (pp. 1-9). IEEE.
58. Tong, S., Wang, J., & Liu, Y. (2022). Combating packet collisions using non-stationary signal scaling in LPWANs. *IEEE/ACM Transactions on Networking, 30*(3), 1104–1117.

59. Hu, B., Yin, Z., Wang, S., Xu, Z., & He, T. (2020). SCLoRa: Leveraging multi-dimensionality in decoding collided LoRa transmissions. In *2020 IEEE 28th International Conference on Network Protocols (ICNP)* (pp. 1-11). IEEE.
60. Temim, M. A. B., Ferré, G., Laporte-Fauret, B., Dallet, D., Minger, B., & Fuché, L. (2020). An enhanced receiver to decode superposed LoRa-like signals. *In IEEE Internet of Things Journal, 7*(8), 7419–7431.
61. Benkahla, N., Tounsi, H., Ye-Qiong, S., & Frikha, M. (2019). Enhanced ADR for LoRaWAN networks with mobility. In 2019 *15th International Wireless Communications Mobile Computing Conference (IWCMC)* (pp. 1–6). IEEE.
62. Laporte-Fauret, B., Temim, M. A. B., Ferre, G., Dallet, D., Minger, B., & Fuch´e, L. (2019). An enhanced LoRa-like receiver for the simultaneous reception of two interfering signals. In *Proceedings of PIMRC* (pp.1–6). IEEE.
63. Rachkidy, N. E., Guitton, A., & Kaneko, M. (2018). Decoding superposed LoRa signals. In *Proceedings of LCN* (pp. 184–190). IEEE.
64. Noreen, U., Clavier, L., & Bounceur, A. (2018). LoRa-like CSS-based PHY layer, Capture Effect and Serial Interference Cancellation. In *European Wireless 2018; 24th European Wireless Conference* (pp. 1–6).
65. Georgiou, O., & Raza, U. (2017). Low power wide area network analysis: Can LoRa scale? *IEEE Wireless Communications Letters, 6*(2), 162–165.
66. Chen, Q., & Wang, J. (2021). AlignTrack: Push the limit of LoRa collision decoding. In *2021 IEEE 29th International Conference on Network Protocols (ICNP)* (pp. 1-11). IEEE.
67. Fawaz, H., Khawam, K., Lahoud, S., Martin, S., & Helou, M. E. (2021). Cooperation for spreading factor assignment in a multioperator LoRaWAN deployment. *In IEEE Internet of Things Journal, 8*(7), 5544–5557.
68. Xu, Z., Xie, P., & Wang, J. (2021). Pyramid: Real-time lora collision decoding with peak tracking. In *IEEE INFOCOM 2021-IEEE Conference on Computer Communications* (pp. 1-9). IEEE.
69. Shahid, M. O., Philipose, M., Chintalapudi, K., Banerjee, S., & Krishnaswamy, B. (2021). Concurrent interference cancellation: Decoding multi-packet collisions in LoRa. In *Proceedings of the 2021 ACM SIGCOMM 2021 Conference* (pp. 503-515).
70. Abdelfadeel, K. Q., Zorbas, D., Cionca, V., & Pesch, D. (2020). FREE—Fine-grained scheduling for reliable and energy-efficient data collection in LoRaWAN. *IEEE Internet of Things Journal, 7*(1), 669–683.
71. Tong, S., Xu, Z., & Wang, J. (2020). CoLoRa: Enabling multi-packet reception in LoRa. In *Proceedings of IEEE INFOCOM* (pp. 2303–2311). IEEE.
72. Wang, X., Kong, L., He, L. & Chen, G. (2019). mLoRa: A multi-packet reception protocol in LoRa networks. In *2019 IEEE 27th International Conference on Network Protocols (ICNP)*, Chicago, (pp. 1–11).
73. Korbi, I. E., Ghamri-Doudane, Y., & Saidane, L. A. (2018) LoRaWAN analysis under unsaturated traffic, orthogonal and non-orthogonal spreading factor conditions. *In Proceedings of NCA*, 2018, (pp. 1–9). IEEE.
74. Cuomo, F., Campo, M., Caponi, A., Bianchi, G., Rossini, G. & Pisani, P. (2017). EXPLoRa: Extending the performance of LoRa by suitable spreadinfactor allocations. *In Proceedings of WiMob* (pp. 1–8). IEEE.
75. Benkhelifa, F., Qin, Z., & McCann, J. A. (2021). User fairness in energy harvesting-based LoRa networks with imperfect SF orthogonality. *IEEE Transactions on Communications, 69*(7), 4319–4334.
76. Garlisi, D., Mangione, S., Giuliano, F., Croce, D., Garbo, G., & Tinnirello, I. (2021). Interference cancellation for LoRa gateways and impact on network capacity. *IEEE Access, 9*, 128133–128146.
77. Tapparel, J., Xhonneux, M., Bol, D., Louveaux, J., & Burg, A. (2021). Enhancing the reliability of dense LoRaWAN networks with multi-user receivers. *IEEE Open Journal of the Communications Society, 2*, 2725–2738.
78. Guo, Q., Yang, F., & Wei, J. (2021). Experimental evaluation of the packet reception performance of LoRa. *Sensors (Switzerland), 21*, 1–23.
79. Xia, X., Zheng, Y., & Gu, T. (2020). FTrack: Parallel decoding for LoRa transmissions. *IEEE/ACM Transactions on Networking, 28*(6), 2573–2586.
80. Croce, D., Gucciardo, M., Mangione, S., Santaromita, G., & Tinnirello, I. (2020). LoRa technology demystified: From link behavior to cell-level performance. *IEEE Transactions on Wireless Communications, 19*(2), 822–834.
81. Amichi, L., Kaneko, M., Rachkidy, N. E., & Guitton, A. (2019). Spreading factor allocation strategy for LoRa networks under imperfect orthogonality. In *2019 Proceedings of ICC* (pp. 1–7). IEEE.
82. Beltramelli, L., Mahmood, A., Gidlund, M., Österberg, P., & Jennehag, U. (2018, October). Interference modelling in a multi-cell LoRa system. In *2018 14th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)* (pp. 1-8). IEEE.
83. Reynders, B., Meert, W., & Pollin, S. (2017). Power and spreading factor control in low power wide area networks. In *2017 IEEE International Conference on Communications (ICC)* (pp. 1-6). IEEE.
84. Van den Abeele, F., Haxhibeqiri, J., Moerman, I., & Hoebeke, J. (2017). Scalability analysis of large-scale LoRaWAN networks in ns-3. *IEEE Internet of Things Journal, 4*(6), 2186–2198.
85. Bankov, D., Khorov, E., & Lyakhov, A. (2017). Mathematical model of LoRaWAN channel access with capture effect. In *2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio communications (PIMRC)* (pp. 1-5). IEEE.
86. Edward, P., El-Aasser, M., Ashour, M., & Elshabrawy, T. (2021). Interleaved chirp spreading LoRa as a parallel network to enhance LoRa capacity. *IEEE Internet of Things Journal, 8*(5), 3864–3874.
87. Marquez, L. E., Osorio, A., Calle, M., Velez, J. C., Serrano, A., & Candelo-Becerra, J. E. (2020). On the use of LoRaWAN in smart cities: A study with blocking interference. *IEEE Internet of Things Journal, 7*(4), 2806–2815.
88. Wang, Z., Kong, L., Xu, K., He, L., Wu, K., & Chen, G. (2020, July). Online concurrent transmissions at LoRa gateway. In *IEEE INFOCOM 2020-IEEE Conference on Computer Communications* (pp. 2331-2340). IEEE.
89. Rahmadhani, A., & Kuipers, F. (2018). When loRaWAN frames collide. In *Proceedings of the 12th International Workshop on Wireless Network Testbeds, Experimental Evaluation & Characterization* (pp. 89-97).
90. Reynders, B., Wang, Q., Tuset-Peiro, P., Vilajosana, X., & Pollin, S. (2018). Improving reliability and scalability of LoRaWANs through lightweight scheduling. *IEEE Internet of Things Journal, 5*(3), 1830–1842.
91. Orfanidis, C., Feeney, L. M., Jacobsson, M., & Gunningberg, P. (2017, October). Investigating interference between LoRa and IEEE 802.15. 4g networks. In *2017 IEEE 13th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)* (pp. 1-8). IEEE.
92. Voigt, T., Bor, M., Roedig, U., & Alonso, J. (2017). Mitigating inter-network interference in LoRa Networks. In *proceedings of International Conference on Embedded Wireless Systems and Networks (EWSN '17)* (pp. 323–328).
93. Lim, J. T., & Han, Y. (2018). Spreading factor allocation for massive connectivity in LoRa systems. *IEEE Communications Letters, 22*, 800–803.

94. Shilpa, B., Kumar, P. R., Jha, R. K. (2023) Spreading factor optimization for interference mitigation in dense indoor LoRa networks. *IEEE IAS Global Conference on Emerging Technologies (GlobConET)* (pp. 1–5).
95. Shilpa, B., Kumar, P. R., & Jha, R. K. (2023). LoRa DL: A deep learning model for enhancing the data transmission over LoRa using autoencoder. *The Journal of Supercomputing, 79*, 17079–17097.
96. Garlisi, D., Tinnirello, I., Bianchi, G., & Cuomo, F. (2021). Capture aware sequential waterfilling for LoRaWAN adaptive data rate. *IEEE Transactions on Wireless Communications, 20*, 2019–2033.
97. Bapathu, H. R., & Borkotoky, S. S. (2021). The LoRa modulation over rapidly-varying channels: Are the higher spreading factors necessarily more robust?. In *2021 IEEE 18th Annual Consumer Communications and Networking Conference, CCNC, Institute of Electrical and Electronics Engineers Inc.* (pp. 1–4). IEEE.
98. Coutaud, U., Heusse, M., & Tourancheau, B. (2021). LoRa channel characterization for flexible and high reliability adaptive data rate in multiple gateways networks. *Computers, 10*(4), 44.
99. Ni, M., Jafarizadeh, M., & Zheng, R. (2019). On the effect of multi-packet reception on redundant gateways in LoRAWANs. In *Proceedings of ICC* (pp. 1–6). IEEE.
100. Tesfay, A. A., SIMON, E. P., Ferre, G., & Clavier, L. (2020). Serial interference cancellation for improving uplink in LoRa-like networks. In *2020 IEEE 31st Annual International Symposium on Personal, Indoor and Mobile Radio Communications* (pp. 1–6, 2020). IEEE.
101. Tesfay, A. A., Simon, E. P., Nevat, I., & Clavier, L. (2020). Multiuser detection for downlink communication in lora-like networks. *IEEE Access, 8*, 199001–199015.
102. Temim, M. A. B., Ferre, G., Tajan, R. & Laporte-Fauret, B. (2020). A novel approach to process the multiple reception of non-orthogonal LoRaLike signals. In *ICC 2020-2020 IEEE International Conference on Communications (ICC)* (pp. 1–6). IEEE.
103. Amichi, L., Kaneko, M., Fukuda, E. H., El Rachkidy, N., & Guitton, A. (2020). Joint allocation strategies of power and spreading factors with imperfect orthogonality in LoRa networks. *IEEE Transactions on Communications, 68*(6), 3750–3765.
104. Zhu, G., Liao, C. H., Suzuki, M., Narusue, Y., & Morikawa, H. (2018). Evaluation of LoRa receiver performance under co-technology interference. In *2018 15th IEEE Annual Consumer Communications & Networking Conference (CCNC)* (pp. 1-7). IEEE.
105. Markkula, J., Mikhaylov, K., & Haapola, J. (2019). Simulating LoRaWAN: On importance of inter spreading factor interference and collision effect. In *ICC 2019-2019 IEEE International Conference on Communications (ICC)* (pp. 1-7). IEEE.
106. Waret, A., Kaneko, M., Guitton, A., & El Rachkidy, N. (2019). LoRa throughput analysis with imperfect spreading factor orthogonality. *IEEE Wireless Communications Letters, 8*(2), 408–411.
107. Mahmood, A., Sisinni, E., Guntupalli, L., Rondón, R., Hassan, S. A., & Gidlund, M. (2019). scalability analysis of a LoRa network under imperfect orthogonality. *IEEE Transactions on Industrial Informatics, 15*(3), 1425–1436.
108. Qadir, Q. M. (2021). Analysis of the reliability of LoRa. *IEEE Communications Letters, 25*(3), 1037–1040.
109. Bankov, D., Khorov, E., & Lyakhov, A. (2017). Mathematical model of LoRaWAN channel access. In *2017 IEEE 18th International symposium on A World of Wireless, Mobile and Multimedia Networks (WoWMoM)* (pp. 1-5). IEEE.
110. Lumet, E., Le Floch, A., Kacimi, R., Lihoreau, M., & Beylot, A. L. (2021). LoRaWAN relaying: Push the cell boundaries. In *Proceedings of the 24th International ACM Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems* MSWiM (pp. 217-220).
111. Edward, P., Elzeiny, S., Ashour, M., & Elshabrawy, T. (2019, October). On the coexistence of LoRa-and interleaved chirp spreading LoRa-based modulations. In *2019 International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)* (pp. 1-6). IEEE.
112. Lauridsen, M., Vejlgaard, B., Kovacs, I. Z., Nguyen, H., & Mogensen, P. (2017, March). Interference measurements in the European 868 MHz ISM band with focus on LoRa and SigFox. In *2017 IEEE Wireless Communications and Networking Conference (WCNC)* (pp. 1-6). IEEE.
113. Sun, K., Yin, Z., Chen, W., Wang, S., Zhang, Z., & He, T. (2021, November). Partial symbol recovery for interference resilience in low-power wide area networks. In *2021 IEEE 29th International Conference on Network Protocols (ICNP)* (pp. 1-11). IEEE.
114. Xu, Q., Sun, K., Wang, S., Chen, P., & Yin, Z. (2023, October). SLoRa: A Systematic framework for synergic interference resilience in LPWAN. In *2023 IEEE 31st International Conference on Network Protocols (ICNP)* (pp. 1-11). IEEE.
115. Hou, N., Xia, X., & Zheng, Y. (2021). Jamming of LoRa PHY and countermeasure. *IEEE INFOCOM 2021-IEEE Conference on Computer Communications* (pp. 1–10).
116. Aras, E., Small, N., Ramachandran, G. S., Delbruel, S., Joosen, W., & Hughes, D. (2017). Selective jamming of LoRaWAN using commodity hardware. In *Proceedings of the 14th EAI International Conference on Mobile and Ubiquitous Systems: Computing, Networking and Services* (pp. 363-372).
117. Huang, C. Y., Lin, C. W., Cheng, R. G., Yang, S. J., & Sheu, S. T. (2019, April). Experimental evaluation of jamming threat in LoRaWAN. In *2019 IEEE 89th Vehicular Technology Conference (VTC2019-Spring)* (pp. 1-6). IEEE.
118. Martinez, I., Tanguy, P., & Nouvel, F. (2019, September). On the performance evaluation of LoRaWAN under Jamming. In *2019 12th IFIP Wireless and Mobile Networking Conference (WMNC)* (pp. 141-145). IEEE.
119. Martinez, I., Nouvel, F., Lahoud, S., Tanguy, P., & El Helou, M. (2020, July). On the performance evaluation of LoRaWAN with re-transmissions under jamming. In *2020 IEEE Symposium on Computers and Communications (ISCC)* (pp. 1-7). IEEE.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

B. Shilpa is an assistant professor in the Department of Computer Science and Engineering, AVN Institute of Engineering & Technology, Hyderabad, India. She received her PhD degree in wireless communication from Faculty of Science and Technology, IFHE University in 2024. Her areas of interest are wireless communication, wireless sensor networks, IoT and deep learning.

Hari Prabhat Gupta is an assistant professor in the Department of Computer Science and Engineering, Indian Institute of Technology (BHU), Varanasi, India. He received his Ph.D. degree in computer science and engineering from IIT Guwahati in 2014. His research interests include wireless sensor networks, distributed algorithms, and the Internet of Things.

Rajesh Kumar Jha is an assistant professor in the Department of Electronics and Communication Engineering, Faculty of Science and Technology, IFHE, Hyderabad, India. He received his Ph.D. degree in electronics and communication engineering from IIIT Allahabad in 2020. His research interests include very largescale integration and the Internet of Things.

Syed Shakeel Hashmi is an assistant professor in the Department of Electronics and Communication Engineering, Faculty of Science and Technology, IFHE, Hyderabad, India. He received his PhD from JNTUA, Anantapur in 2021. His areas of interest are Wireless Communication, Heterogeneous wireless networks and signal Processing.