Indonesian Journal of Electrical Engineering and Computer Science
Vol. 34, No. 2, May 2024, pp. 960~969
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v34.i2.pp960-969

Exploring open source and proprietary LoRa mesh technologies

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Article Info

Article history:

Received Jan 19, 2024
Revised Feb 2, 2024
Accepted Feb 14, 2024

Keywords:

Energy consumption
IoT
LoRa mesh
Open source
Routing algorithm

ABSTRACT

This paper explores low power wide area network (LPWAN) LoRa and its diverse variants, encompassing open-source and proprietary wireless mesh networks, operating over the physical LoRa or LoRaWAN layer. The primary challenge lies in defining an optimal LoRa mesh solution that balances cost-effectiveness, energy efficiency, low latency, long-range capability, and security. This study also comprehensively examines key LoRa mesh solutions from 2017 to 2024, as proposed by various authors. Furthermore, a detailed analysis is conducted to contrast open-source and commercial solutions, considering their applications, limitations, issues, characteristics, and pros and cons of mesh routing protocols. In the current landscape, the proliferation of open-source and proprietary LoRa mesh solutions has been instrumental in facilitating the connectivity of internet of things (IoT) devices. However, these solutions pose challenges related to energy consumption, latency, and suboptimal transmission throughput. These challenges are influenced by various LoRa characteristics such as spectrum factor, bandwidth, and transmission power, which directly impact the transmission range. Our research aims to perform a comparative analysis of existing LoRa mesh solutions by, systematically studying their advantages and disadvantages. This analysis offers valuable insights for making informed choices among these solutions in diverse domains for IoT applications.

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1. INTRODUCTION

Low power wide area networks (LPWANs) have profoundly reshaped the landscape of the internet of things (IoT), providing extensive connectivity to billions of devices [1]. LoRa networks have emerged as an essential pillar within this revolution, propelling various IoT applications [2]. While point-to-point and point-to-multipoint arrangements have long dominated the LoRa scene [3], the evolution toward LoRa mesh networks has opened up new perspectives. This evolution allows LoRa devices to transmit and receive data and act as relays, thereby creating extensive mesh networks suitable for transmission in environments with multiple obstacles, such as smart city networks and forested areas [4].

This study delves into this new frontier of LoRa mesh networks, exploring the various existing solutions that bring these infrastructures to life [5]. In addition, no study has comprehensively reviewed open-source and commercial solutions for LoRa mesh networks. We will examine the distinctive features of each approach, evaluate its performance, and discuss its potential applications in the vast domain of IoT [6]. By closely examining these LoRa mesh solutions, we aim to provide an in-depth understanding of the available choices, assisting decision-makers, engineers, and researchers in navigating this new era of LoRa connectivity. The article is organized as follows: in section 2, we introduce the LoRa physical technique. Moving on to section 3, we list the open-source solutions. In section 4, we provide an overview of the commercial solutions. Section 5 discusses the advantages and disadvantages of both LoRa mesh techniques. Finally, section 6 concludes the article.

2. OVERVIEW OF LORA

The LoRa technology originated from Cycleo, a French company. It was later acquired and patented by Semtech, which is currently marketing LoRa chips. The patent contains valuable insights into the physical layer, with a focus on the modulation scheme known as the chirp spread spectrum (CSS). Multiple spreading factors (SF) are outlined to regulate the bit rate [7], enhance the range [8], and reduce energy consumption.

LoRa operates within the industrial, scientific, and medical (ISM) frequencies [9], i.e. 433, 868, and 915 MHz. (see Table 1) To address interference concerns, regulatory authorities have defined a duty cycle ranging from 0.1% to 1%, depending on the specific subband used [10]. Unlike certain proprietary IoT technologies, LoRa’s network management is open, enabling individuals to deploy LoRa stations or networks and provide services. To do so, adherence to spectrum use regulations is essential. The upper layers of LoRa can be either proprietary or standardized, and the most widely embraced standard is LoRaWAN [11], implemented by the LoRa alliance [12].

Table 1. Main characteristics of LoRa

Parameters	LoRa
Frequency bands	868, 915, and 433 MHz
Bandwidth	125, 250, 500 kHz
Spreading factor	6 to 12
Maximum range	15 - 20 km
Data rates	0.25-50 kbit/s
Modulation	CSS
Payload	2 - 255 B
Transmitted power	10 - 18 dBm

2.1. Packet format of the LoRa physical layer

LoRa employs implicit and explicit packets for data transmission. Explicit mode in LoRa involves a packet with distinct components. These components collectively define the structure of the packet. Understanding both packet types is crucial for effective LoRa communication (see Figure 1):

- Preamble is used for synchronization.
- PHDR (physical header) is an optional field, that furnishes, data payload size and cyclic redundancy check (CRC).
- PHDR_CRC (header CRC) is an optional field that includes an error-detecting code designed to correct errors in the header.
- PHYPayload contains the entire frame produced by the MAC layer.
- CRC is an error-detecting code for rectifying errors in the payload of uplink messages.

The PHYPayload the user and CRC undergo encoding with one of the following coding rates (4/5, 4/6, 4/7, or 4/8). Mugerwa *et al.* [13], the frame is transmitted using one of the spreading factors (SF = 7 to 12). Figure 1-2 illustrates the physical layer structure [14], of both uplink and downlink packets using explicit mode. In implicit mode, the packet header is omitted, and the payload size, along with the coding rate, is either fixed or predetermined. Beacons use the implicit mode in LoRa radio packets to convey time-synchronizing messages from gateways to end devices. Figure 3 illustrates the structure of a LoRa packet employing the implicit mode.

Preamble	PHDR	PHDR_CRC	PHYPAYLOAD	CRC

Figure 1. Physical structure of the uplink packet [15]

Preamble	PHDR	PHDR_CRC	PHYPAYLOAD

Figure 2. Structural composition of a downlink packet [15]

PREAMBLE	BCNPAYLOAD

Figure 3. Physical structure of the beacon

3. OPEN-SOURCE LoRa MESH NETWORKING SOLUTION

The evolution of LoRa mesh networks has seen significant progress since the emergence of LoRa technology, which provides extensive connectivity while minimizing energy consumption [16]. The introduction of the LoRaWAN standard established open standards, promoting interoperability [17]. LoRa mesh networks subsequently emerged to extend the range by allowing nodes to relay data [18], enhancing coverage and resilience [19]. This evolution has been accompanied by optimizations in energy consumption [20], which are crucial for battery-powered IoT devices, and specific developments tailored to environments such as forested areas [21], smart cities [22], and industrial IoT. The overarching goal is to make LoRa mesh networks more efficient, robust, and suitable for various IoT applications [23].

3.1. MauMe LoRa mesh

The MauMe ("Message Me") protocol is a specialized communication protocol for single-channel LoRa radios, promoting collaboration among base nodes owned by different users. It prevents message overflow and broadcast storms by relying on users maintaining a continuous "home node" serving as a gateway. This strategic setup ensures a constant power supply for the home nodes, which act as repeaters for all messages. Additionally, users can enhance functionality by enabling Wi-Fi transmission in nodes, extending MauMe's range to include Wi-Fi devices, and simplifying connections for users between MauMe and LoRa nodes [24].

MauMe is a LoRa protocol for a messaging network, using affordable single-frequency radios. It operates without the need for an internet connection, allowing customization of LoRa networks. Unlike other methods, MauMe supports multi-hop transmission and doesn't require route request messages. While belonging to delay tolerant networks, it's less suitable for densely populated areas. Notably, MauMe relies on sink sector power, impacting energy consumption, and is a theoretical open-source study without proven low-power characteristics.

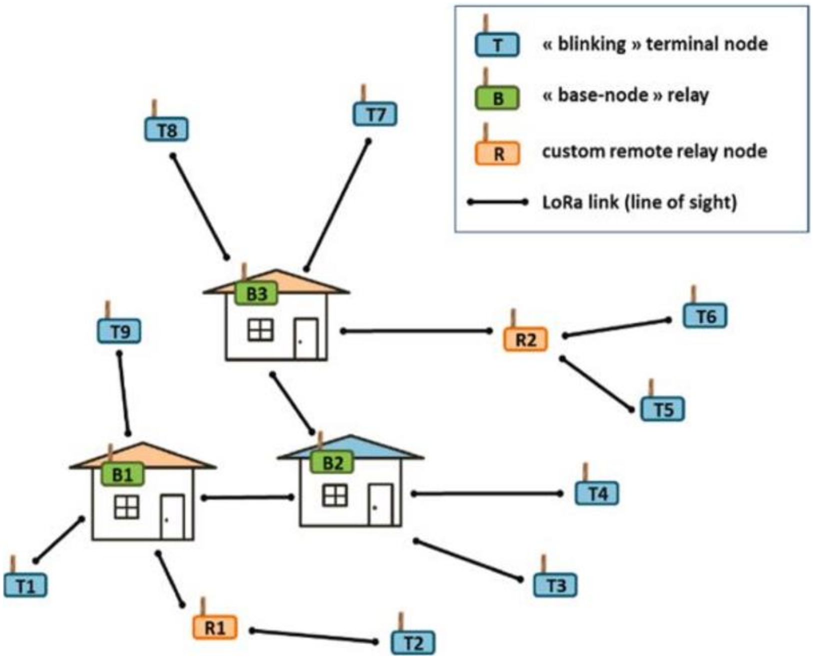

Figure 4. LoRa MauMe network concept

3.2. MRT-LoRa mesh

MRT-LoRa is a protocol designed to ensure minimal end-to-end delays in LoRa-based multi-hop networks. This protocol facilitates real-time communication over long distances while minimizing airtime at each hop, thereby reducing the impact on the duty cycle of individual nodes [25]. In MRT-LoRa, the network design process involves the offline organization of nodes, categorizing them into specific layers based on their hop distance from the sink, which is the central destination for all network messages. This hierarchical topology enables communication exclusively between adjacent layers (refer to Figure 5). The layer number increases with hop distance from the sink, with the sink itself designated as layer 0. Nodes positioned one hop away from the sink form layer 1, whereas those at the maximum hop distance constitute layer n. Each node with b in layer l_i has a defined route to reach the sink, represented as a list of i-1 nodes, each belonging to a distinct layer l_j, where $1 \leq j \leq i - 1$, MRT-LoRa accommodates various node types, see Table 2. Role of MRT-LoRa routing nodes. In an MRT-LoRa network, nodes have different energy consumption patterns ased on their roles and the power specifications of LoRa. The mains-powered sink primarily receives signals, whereas the energy usage of battery-powered nodes increases with the ascending network layer.

Table 2. Role of MRT-LoRa routing nodes

Type of node	Role
Sink	A device that can simultaneously listen to multiple channels and employ various spreading factors. The sink should be situated in the middle of the transmission zone.
End-node	A node generates messages and sends them to the sink. It supports two different categories of end nodes: stationary and mobile.
Relay-node	A node involved in routing receives messages from other nodes and forwards them to the sink.
Hybrid-node	A device that serves dual roles, operating as both an end node and a router node.

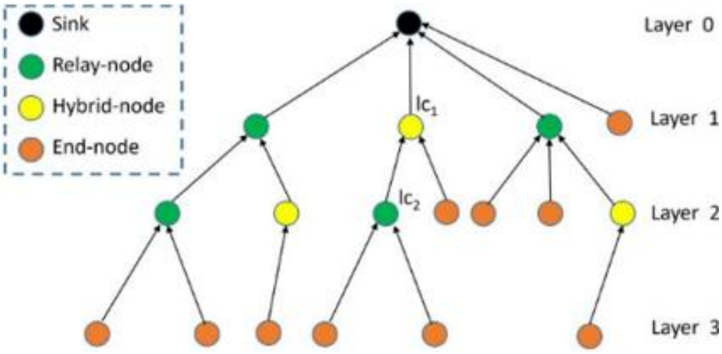

Figure 5. Topology of 3-layer MRT-LoRa network

3.3. Summarizing open-source LoRa mesh solutions

In this section, we will present a comparative analysis of various LoRa mesh solutions in a Table 3 outlining their functionality, application domains, advantages, and limitations. The goal is to compare them with commercial solutions to identify an optimal LoRa mesh solution regarding energy consumption, real-time capabilities, and low deployment cost [26], [27]-[35].

3.3.1. Advantages of the LoRa mesh

- Long range: LoRa mesh networks provide long-range communication, enabling connectivity over large distances, and making them suitable for applications such as smart cities and agriculture [36].
- Low power consumption: devices in LoRa mesh networks typically have low power requirements, extending the battery life of connected devices, which is crucial for remote and IoT applications [37].
- Scalability: LoRa mesh networks can scale efficiently, accommodating a growing number of devices while maintaining reliable communication. This scalability is beneficial for expanding IoT deployments [38].
- Cost-effective: implementing LoRa mesh using open-source solutions can be cost-effective because it allows users to customize and deploy solutions without the financial burden of proprietary licenses [39].
- Flexibility and Customization: Open-source LoRa mesh solutions offer flexibility and customization, allowing developers to tailor the network to specific application requirements, and fostering innovation [40].
- Community support: the open-source nature of LoRa mesh attracts a vibrant community of developers and users, providing ongoing support, bug fixes, and continuous improvement [41].

Table 3. Summarizing open source LoRa mesh solutions

Authors	Difficulties resolved	Use case	Methodology	Verification	Capability	Constraints
Dias and Grilo [27]	Extension of coverage without the addition of additional gateways	Areas of poor connectivity in urban installations	Router nodes employing destination sequence distance vector (DSDV)	Evaluation of a prototype involving four routing nodes.	Extension of the uplink of the LoRaWAN network	Absence of downlink transmissions
Sartori *et al.* [28]	Extensive coverage using a limited number of base stations.	IoT deployments that are either distributed or isolated	Enlarging routing protocol for low-power (RPL) through the incorporation of new objective functions and metrics on a large scale	Experimental setup within the dimensions of a building, with five nodes	IoT without traditional infrastructure, and relying on in-premises computing.	A network imbalance causes a bottleneck issue, particularly at the RPL root nodes.
Lundell *et al.* [29]	Broadening coverage without relying on an Internet backhaul.	Extensive sensor networks in rural areas and IoT deployments in urban environments.	Mesh gateways for seamless tunneling between nodes and servers.	Implementation of a proof-of-concept featuring four gateways on a campus scale.	Surveillance of expansive areas through a mesh network backbone facilitated by gateways.	Absence of downlink transmissions
Duong and Kim [30]	Networks covering vast distances in a linear topology.	Surveillance of linear utility installations.	Forward packets in a multi-hop manner from linear leaf nodes to a central sink.	Experimental setup on a campus scale involving five nodes.	Administration of infrastructure with a linear topology covering long distances.	Unidirectional transmission low PDR, and throughput
Abrardo and Pozzebon [31]	Underground networks are characterized by restricted coverage.	Surveillance of tunnels and underground utilities.	Multihop packet forwarding from a linear origin to a sink.	On-site measurements, experiments, and analytical analysis	Administration of infrastructure with a linear topology situated underground.	Unidirectional transmission and, node synchronization
Lee *et al.* [32]	Communication among indoor nodes in densely urban areas.	Monitoring environment on a campus scale.	Mesh system employing next-hop selection based on RSSI and hop count	An experimental testbed of campus-scale involving 19 nodes	LoRa mesh networks are designed for extensive coverage over large areas.	Lower node density compared with star topology.
Kim *et al.* [33]	Enhancing the data throughput for nodes operating on a single channel.	Networks with high traffic volume.	Adaptive spreading factor selection (ASFS)	An experimental testbed of campus-scale featuring 10 nodes.	Concurrently operating with multiple spreading factors in an overlaid configuration.	Optimal results necessitate the implementation of a sophisticated routing algorithm.
Nunez Ochoa *et al.* [20]	Optimizing energy consumption	End nodes with extremely limited energy resources.	Integration of star and mesh topologies.	Analytical calculations.	Prolonging the lifespan of battery-operated nodes.	Real-world network dynamics, lacking experimental verification.
Meshtastic [34]	Extensive-range data broadcasting.	Communication and location services for emergencies in outdoor and off-grid environments.	Smart data flooding for effective communication.	Readily accessible off-the-shelf devices.	Self-sustained communication for communities, independent of the grid	Scalability
Loratype [35]	The LoRa protocol offers noise-resistant communication, with a range of 1 km in cities and up to 7 km in clear line-of-sight areas.	No cost During disasters In a war zone or during mass protests When free messaging is essential	Meshtastic Research p2p LoRa	First factory-assembled Proto First 3D-printed enclosure	Free solution	The development of IoT applications is still limited

3.3.2. Disadvantages of the LoRa mesh

- Data rate limitations: LoRa networks have lower data rates than some other wireless technologies, which may limit their suitability for applications requiring high data throughput. We have different data rate values, which depend on the mesh technique used [36].
- Interference challenges: in crowded radio frequency environments, potential interference can affect the reliability of communication in LoRa mesh networks, especially in urban, and forest areas.
- Complex deployment: most open-source LoRa mesh solutions are primarily theoretical studies, with adaptations for specific applications [42]. The overall set comes with operational limitations and complexities.
- Limited real-time communication: LoRa networks are optimized for low-power, sporadic communication, making them less suitable for applications that require real-time, low-latency data transmission [43].
- Security considerations: all the studied LoRa mesh solutions address only the constraints of transmission performance, without explicitly addressing the security methods to be applied.
- Varied standards: LoRaWAN, a widely adopted standard, ensures interoperability; however, variations in implementation standards across different solutions may lead to compatibility challenges [44].

4. Commercial proprietary LoRa mesh solutions

Commercial LoRa mesh networks have applications in various industries, such as smart cities, industrial IoT, agriculture, and asset tracking [45]. The mesh topology allows for extended coverage [46], improved reliability, and the ability to adapt to changing network conditions. Commercial LoRa mesh networks are used to create efficient and cost-effective solutions for monitoring, control, and data collection in diverse environments. These networks are crucial in advancing IoT domains, offering connectivity for diverse devices across expansive areas see in Table 4 [26]. Furthermore, this multitude of industrial solutions, for the most part, is not compatible. Each equipment supplier provides various hardware, including routers, sensors, and gateways that are not interoperable with each other [47]. Consequently, each demonstrates distinct performance levels concerning energy consumption, range, throughput, and latency, which are influenced by different frequencies within the ISM band.

Table 4. A recap of the investigated multi-hop and proprietary LoRa mesh solutions

Authors	Difficulties resolved	Use case	Methodology	Verification	Capability	Constraints
Pymesh Pycom [48]	Adaptable network flexibility is achieved through decentralization.	Mesh networks that organize themselves with multiple gateways.	Routing protocol that supports multiple node roles	Commercially available development devices.	Integrating OEM components into standard products for enhanced functionality.	A proprietary, closed-source solution that may face compatibility challenges across diverse vendors.
NiceRF [49]	Transmission of encrypted serial data through a mesh network.	Functionality encompassing remote control, telemetry, and automation.	Involve multiple network roles via a routing protocol.	Commercially available development devices	Limitations linked to machine-to-machine (M2M) communications.	A proprietary, closed-source solution that may face compatibility challenges across diverse vendors.
Ebyt's LoRa mesh [47]	decentralized structure	The network enables unlimited routing depth in broadcast communication, forming a vast and interconnected mesh network.	The complete network consists of routing and sensor nodes.	Commercially available development devices	The theoretical networking capacity can accommodate up to 65,535 nodes.	A proprietary, closed-source solution that may face compatibility challenges across diverse vendors.
Neomesh LoRa [50]	decentralized structure	The network enables unlimited routing depth in broadcast communication, forming a vast and interconnected mesh network.	All nodes can be routers and sensors	Future product	The theoretical networking capacity can accommodate up to 65,535 nodes. Less power consumption	A proprietary, closed-source solution that may face compatibility challenges across diverse vendors.

5. DISCUSSION

Having analyzed various open-source and commercial solutions for mesh routing algorithms on the LoRa physical layer, the study focused on criteria such as low energy consumption, broad coverage, and low latency. Open-source solutions were primarily tailored for specific applications, including wildfire detection, agricultural field management, and smart cities [51]. In contrast, commercial solutions demonstrated versatility, being developed for deployment across diverse sectors such as agriculture, healthcare, industry, and natural disaster management [52]. A comprehensive overview of the advantages and disadvantages of both approaches is summarized in Table 5.

Lundell *et al.* [29] proposed a LoRa mesh solution over LoRaWan utilizing the hybrid wireless mesh protocol (HWMP) and ad-hoc on-demand distance vector routing (AODV). However, this solution, reliant on LoRaWAN characteristics, remains confined to theoretical studies and may not fully address practical considerations. Another noteworthy algorithm, MauMe, was introduced in reference [24], designed for small networks with a limited number of nodes, specifically focusing on transmitting emergency messages. Grounded in the epidemic delay tolerant network messaging protocol, MauMe provides a cost-effective method to extend the reach of individual LoRa networks.

Exploring routing protocols using CupCarbon software in [37], the authors favored the dynamic source routing (DSR) protocol due to its 11.32% reduction in energy consumption with the proposed adjustment algorithm. Although the AODV protocol demonstrated superior overall performance, it resulted in higher energy consumption, while the distance vector routing (DVR) protocol exhibited excellent latency but faced an increase in packet loss. Practically implementing these findings, the study suggests the use of the DSR routing algorithm over LoRa mesh protocols, highlighting its open-source nature and optimal energy consumption, particularly relevant in the context of smart cities.

Zhu *et al.* [46] introduced the tree-based spreading factor clustering algorithm (TSCA) to enhance the capacity of multi-hop LoRa networks. This algorithm distributes data traffic across multiple subnets, allowing concurrent packet transmission with varying spreading factors. TSCA is designed for static LoRa network topology, assuming consistent node positions and connectivity. However, it remains to be explored whether this open-source algorithm is suitable for static mesh networks.

Commercial LoRa mesh networks, such as NiceRF [53], NeoMesh over LoRa [54], and Pymesh Pycom [55], are tailored for industrial IoT applications. These solutions leverage the LoRa protocol for long-range communication and low energy consumption. NiceRF offers LoRa mesh modules for extended connectivity, while NeoMesh over LoRa stands out with robust and self-organizing communication. Pymesh Pycom focuses on flexibility with Python-programmable solutions. These technologies address specific needs in industrial IoT, smart cities, agriculture, and environmental monitoring, emphasizing customization, reliability, and energy efficiency.

Examining various research studies (Tables 3 and 4) on open-source LoRa mesh networks, a diverse array of routing algorithms was explored [56], encompassing mobile ad hoc routing, reactive, proactive, and hybrid approaches. Notable algorithms included DSR, AODV, DVR, LAR, OLSR, HWMP, and other open-source examples such as MauMe LoRa, MRT-LoRa, and TSCH-Over-LoRa [57]. The studies aimed to identify the optimal algorithm for data transmission in LoRa mesh networks, considering node density [58], transmission throughput, latency [59], packet loss rate, and energy consumption. However, some studies omitted discussions on optimal operating systems or the most energy-efficient hardware and secure algorithms. Proprietary solutions, including Pycom, and NiceRF have contributed secure routing algorithms and adaptable hardware for diverse IoT applications.

In summary, the study concluded that both open-source and commercial LoRa mesh solutions are inherently incompatible. This realization underscores the urgent need to establish a standardized LoRa mesh standard for wireless sensor networks (WSN), similar to the LoRaWAN standard in a star topology. Such standardization aims to facilitate seamless integration, whether for open-source or proprietary solutions.

Table 5. Comparison of advantages and disadvantages: open source vs. commercial LoRa mesh

Solutions	Advantages	Disadvantages
Open-source LoRa mesh	-Cost: typically, free or lower upfront costs. -Flexibility: customizable according to specific needs. -Community Support: Active communities provide support and updates.	-Not suitable for users without technical knowledge. -Development and troubleshooting can be time-consuming.
Commercial LoRa mesh	-Ready-to-use solutions with minimal setup. -Access to dedicated customer support. -Seamless integration with commercial services and platforms.	-Higher upfront costs and potential ongoing subscription fees. -Dependency on a specific vendor for updates and support. -May involve ongoing subscription or support fees.

6. CONCLUSION

This paper provides a concise overview of both open-source and proprietary LPWAN LoRa mesh networks based on LoRa technology. We conducted a detailed study of various LoRa physical configuration parameters, such as spreading factor, ISM frequencies, transmission power, and code rate, to design open-source and commercial routing algorithms. The goal of this study was to identify a LoRa mesh network that minimizes energy consumption and offers broad coverage, low latency, and enhanced security.

By exploring recent research developments in the specific field of LoRa mesh networks from 2017 to 2023 and examining patents from companies such as Pycom with Pymesh, NiceRF, and Neocortec with Neomesh over LoRa, we highlighted the limitations, challenges, features, advantages, and disadvantages of these solutions. We concluded that most open-source solutions were developed for specific applications, such as smart city management, wildfire detection, and other specialized uses. In contrast, commercial applications cover various IoT domains, including agriculture, Industry 4.0, and healthcare. Looking ahead, our research aims to develop a LoRa mesh standard for compatibility between open-source and commercial solutions, addressing WSN criteria such as low energy consumption, low latency, extended range, security, cost-effectiveness, and flexibility tailored to multiple IoT domains.

ACKNOWLEDGEMENTS

We express our gratitude to Mohammed First University for funding the research of the Applied Mathematical Laboratory in Computer Science and Signal Processing at the Higher School of Technology.

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