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A Systematic Review of Real-Time Deployments of UAV-Based LoRa Communication Network

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ABSTRACT The term Internet of Things (IoT) has emerged in recent decades because this network revolutionizes almost every aspect of our daily life, including products such as smartphones and intelligent vehicles, and crucial tasks such as precision agriculture and environmental monitoring. Myriads of communication technologies have been developed to fulfill the two main features of the IoT: long-range transmissions and low power consumption. Long-range (LoRa) has become one of the vital parts of IoT communication. In this study, the real-time deployments of an unmanned aerial vehicle (UAV)-based LoRa communication network are systematically reviewed, with a focus on the communication setup and its reported performance. Importantly, the UAV-based LoRa communication network has a low bit rate connectivity to ensure the high reliability of connections, especially in applications that require long transmission ranges. This study provides recommendations for researchers on what research perspectives need to be explored when implementing UAVs for IoT-based LoRa communication. This study also describes publication trends related to UAV-based LoRa communication networks. A supplementary Excel file that contains the reported publications on UAV-based LoRa communication networks is included to show this publication trend.

INDEX TERMS UAV, LoRa, real-time, IoT, wireless communication.

I. INTRODUCTION

The world has entered a new phase of embedded systems and internet-based technology known as the Internet of Things (IoT). The IoT can be defined as an information network that can connect various kinds of sensors and control equipment via the internet, with intelligent communication between connected equipment [1]–[3]. It allows the remote control of objects through an access network and provides direct integration of various physical objects into a computer system. The high-level architecture of the IoT system is shown in Fig. 1. It consists of device, network, and application domains. The device domain includes sensors and actuators to sense and collect relevant data regarding specific IoT applications. Communication technologies such as Bluetooth, Wi-Fi, ZigBee, and LoRa belong to the network domain and enable communication between IoT devices in the device domain and the application domain [4]. Finally, the application domain serves as an interface that delivers application-specific services to the user, enabling the status monitoring of the IoT systems [5]. Different IoT system architectures have been proposed by different researchers over the years, and these architectures were further studied in [5]–[8]. Focusing on the communication technologies used in the IoT field, ultranarrowband networks such as Sigfox and Weightless-N [9] and spread-spectrum communication such as LoRa make communication across up to a few kilometers possible, creating low-power wide-area networks (LPWANs) that can work without the development of complex multihop topologies [10], [11]. LPWANs are constructed to permit low-power wide-area connectivity at a low bit rate [10], as per the IoT requirements. Popular LPWAN communications include LoRa/LoRaWAN, Sigfox, NB-IoT, and Ingenu. A comparison between them is provided in Table 1 [12]–[17].

UAVs are flying vehicles that can operate without onboard pilots. Initially, their applications were exclusively

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TABLE 1. Comparison between different LPWAN technologies.

	LoRa	Sigfox	NB-IoT	Ingenu
Modulation	Chirp spread spectrum (CSS)	D-BPSK (UL), GFSK (DL)	RPMA-DSSS (UL), CDMA (DL)	QPSK, 16QAM, 64QAM
Data rate	0.3 kbps to 50 kbps	100 bps (UL), 600 bps (DL)	78 kbps (UL), 19 kbps (DL)	20 kbps (UL), 200 kbps (DL)
Coverage	Up to 5 km (urban) and 15 km (rural)	Up to 10 km (urban) and 50 km (rural)	Up to 15 km (urban)	Up to 35 km
First released	2015	2009	2016	2010

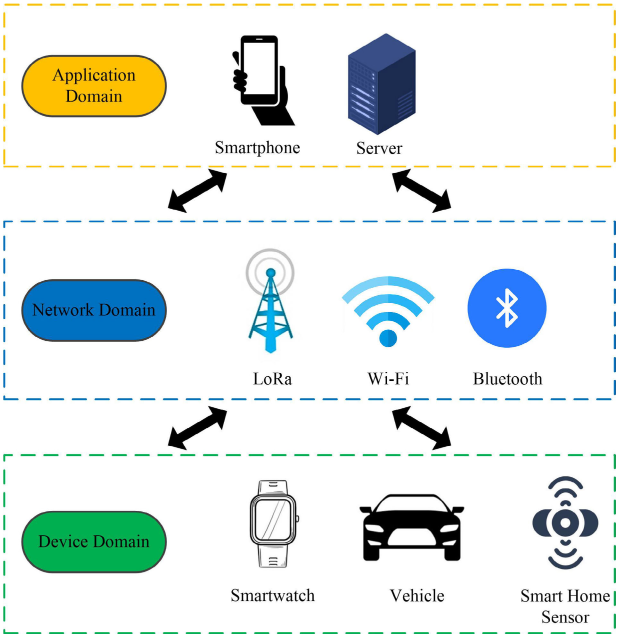

FIGURE 1. The high-level architecture of IoT system.

for military purposes, but UAVs are now commercially available for public users, and their affordable cost makes them appealing for many applications in a wide range of scenarios [18]–[21]. A UAV is typically equipped with a global positioning system (GPS), propellers, brushless motors, a flight controller, and an electronic speed controller (ESC), and it is controlled by a radio channel transmitter and receiver. What makes UAVs interesting is that they can be modified according to individual needs by installing some hardware and applying some algorithms. In the consumer market, UAVs are mainly utilized for capturing aerial pictures and videos, whereas their commercial applications are more widespread, including parcel delivery, mapping of geographical areas, crop monitoring, data collection, and surveillance [22]–[24]. UAVs are also being applied in tasks such as crime prevention, weather and meteorology, search and rescue operations, border and maritime patrol, and forest fire monitoring.

Studies on the role of UAVs in LoRa communication networks have attracted considerable attention from the research community. Solutions that are based on this paradigm promise long transmission ranges (more than 15 km) while preserving the end device battery. Both factors are valued for real-time deployment of IoT networks in remote locations or with difficult access. In addition, due to their high robustness, LoRa communication networks provide a promising solution to the industrial IoT [25], [26]. However, LoRa communication networks have a lower data throughput than Wi-Fi or Global System for Mobile Communications (GSM) networks [27]. Compared to ground-based LoRa communication systems, UAV-based LoRa networks have the advantage of a direct line-of-sight between UAVs, flying at an altitude of tens of meters. This ensures direct visibility among themselves and even with some ground base LoRa stations, allowing the users to exchange data across longer ranges than are possible with ground communication [28]. Real-time UAV-based LoRa communication network can be classified by two different roles (UAV as a LoRa node or LoRa gateway) and objectives (communication or localization). As a LoRa node, the UAV carries a LoRa module and sensors to perform measurements and collect data. Then, it communicates with the nearest LoRa gateway, where protocol conversion is performed from LoRa to message queuing telemetry transport (MQTT) or other formats, so the payload can be read by a web server. A UAV-based LoRa gateway can replace a compromised fixed LoRa gateway or be delivered to a specific remote location to increase the network coverage of specific IoT devices. One of the main advantages of using UAVs as LoRa gateways is that they can be deployed on demand, and increasing their number can increase the efficiency of the system [29].

Several review papers describing LoRa have been published over the years. Saari *et al.* [27] discussed the most recent trends in research and practical applications of LoRa based on a review of more than 50 related articles. They concluded that the recent research trends regarding LoRa are the technical evaluation of LoRa's performance and real-time deployments of LoRa based on the developed prototypes. Marais *et al.* [30] focused on previous LoRa communication studies conducted by other researchers and determined the limitations and strengths by comparing their created testbeds. Murdyantoro *et al.* [16] reviewed the LoRa communication network but focused only on its deployment for rural area development in Indonesia. Similar work has been done by

TABLE 2. The research questions to be answered in this study.

Research Question (RQ)	Motivation
(RQ 1) What is the latest publication trend in terms of year, types of UAV applied, country, and application?	The answer to this question helps identify the origin and focus of research studies.
(RQ 2) How are UAV-based LoRa communication networks set up, including the hardware used?	The answer to this question allows identification of the hardware required to set up a UAV-based LoRa communication network.
(RQ 3) What ranges of LoRa communication have been achieved when deployed on a UAV in a real environment?	Answering this question helps readers know the expected range of LoRa network when deployed with a UAV in a real environment.
(RQ 4) How is the UAV-based LoRa communication performance measured?	The answer to this question allows identification of performance indicators for UAV-based LoRa networks.
(RQ 5) What are the research scopes or perspectives that can be explored in relation to UAV-based LoRa communication networks?	Answering this question can help identify the research gaps in this field.

Kolobe *et al.* [31] but with a focus on Botswana and South Africa. After studying 21 relevant research articles from 2010 to 2019, it can be concluded that more work is needed in terms of field testing, as no articles could be found on the real-time deployment of LoRa or its performance in South Africa or Botswana despite the presence of LoRa networks in both countries. LoRa technology and its applications in traffic monitoring, agriculture, and localization were discussed in detail by Haxhibeqiri *et al.* [32]. However, this survey was three years ago, and myriads of new LoRa applications are currently available that were not reported in their work, especially those involving UAVs. Thus, motivated by [27], we focused on real-time deployments of LoRa communication, as it was considered a hot research topic related to LoRa. However, we narrowed the scope to UAV-based real-time LoRa deployments because both LoRa and UAV are very important in emerging IoT applications. In addition, a review of the role of UAVs in LoRa applications has not yet been done, which is the novelty of this article. The real-time UAV-based LoRa application means that the vital systems of the proposed technology can be remotely monitored by the user. In this study, we reported practical applications that deploy a self-developed or commercial UAV and LoRa in a real-world environment that is fast enough to transmit relevant data such as real-time telemetry for monitoring purposes. We also aim to answer the research questions listed in Table 2.

This article is organized as follows. In the next section, we explain our research approach for this manuscript. Then, we introduce the theoretical framework of LoRa in Section 3. Section 4 highlights the LoRa communication system set up for UAVs, which is further divided into UAV-based LoRa nodes, UAV-based LoRa gateways, and LoRa network servers. In Section 5, we describe the UAV-based LoRa communication performance in terms of the communication range between LoRa modules, packet loss rate, received signal strength indicator (RSSI), and signal-to-noise ratio (SNR). The discussions and findings of our review are presented in Section 6, and we conclude our study in Section 7.

II. RESEARCH APPROACH

A comprehensive literature review was conducted to answer the three research questions. We employed the systematic literature review (SLR) approach [33] to collect the relevant primary studies regarding the real-time deployment of LoRa in UAVs. First, we classified the articles and the selected papers were then analyzed and differentiated through the content analysis method. The results can be classified into five main categories:

1) Survey, where review articles published by other researchers on LoRa communication are discussed.
2) Technical evaluation, where the LoRa performance is tested, especially its communication range, specifically when using UAVs. Simulation works on UAV-based LoRa communication also fall into this category.
3) Real-time applications. This category includes the real-time deployment of a UAV-based LoRa network for specific applications such as environmental monitoring and agriculture.
4) Performance comparison, where the performance of UAV-based LoRa communication is compared with that of fixed LoRa or other LPWAN technologies.
5) Prototype development, which explains the hardware involved in UAV-based LoRa communication.

The databases used for the electronic search were Multidisciplinary Digital Publishing Institute (MDPI), Institute of Electrical and Electronics Engineers (IEEE) Xplore, Association for Computing Machinery Digital library (ACM), ScienceDirect, Web of Science, Wiley, ResearchGate, Springer, Scopus, and Google Scholar. To refine the search results, a set of inclusion and exclusion criteria were used to identify relevant articles, as listed in Table 3. The article searching process started by selecting the main search term: "LoRa". The second search term was "UAV". Thus, the search sentence was ("LoRa" AND "UAV"). These simple keywords were chosen to obtain good coverage of potential studies. Fifty related studies were targeted to provide enough information for categorization and research trends. Next, we classified all the selected articles into the aforementioned categories. The total number of suitable articles collected was 40, and some of the articles could be classified into more than one category. The classification is shown in Fig. 2.

TABLE 3. The inclusion and exclusion criteria used for article searching in this study.

Inclusion Criteria	Exclusion Criteria
Articles within one of the five categories mentioned in this study	Articles that are not written in English
Articles that meet both the search terms	Articles that are not related to the UAV-based LoRa communication network
Articles published or accepted during the period between 2001 and 2021 (20 years)	Duplicated articles
Articles listed in at least one of the research databases	
Articles published in or accepted at a conference, journal, magazines, or thesis	

III. THEORETICAL FRAMEWORK OF LoRa

LPWANs overcome the limitations of short-range wireless technologies such as Bluetooth and Wi-Fi, and have become a good choice for communication networks in urban-scale IoT applications. This is because they can supply long-range communication to various devices at low cost and with minimal energy expenditure. LoRa is one of the LPWAN technologies from Semtech that currently attracts considerable attention because it can efficiently trade communication ranges with big data rates, thus allowing IoT applications at an urban scale. Compared to Sigfox and NB-IoT, LoRa is more resilient to interference and jamming [34]. Based on Fig. 3, a typical LoRa communication network consists of the following components:

1) Sensor nodes. This is where relevant measurements are performed using sensors, and they are usually located in remote areas.
2) LoRa gateway. This component receives communications from the sensor nodes and aggregates the data onto a backhaul connection, which can be Ethernet, 4G/Long-Term Evolution (LTE), or Wi-Fi.
3) Network server. This component serves as a network manager by managing security, removing duplicate packets, and adapting data rates.
4) Application server. This is where further analysis of the collected sensor data is performed.

The core of LoRa technology is its chirp spread spectrum (CSS) modulation. This technology also transmits in the sub 1 GHz ISM bands, and by using the long range wide area networks (LoRaWAN) protocol, it contains a message payload of up to 243 bytes [35], [36]. The terms LoRaWAN and LoRa are often misinterpreted and interchangeable. LoRaWAN is the standard protocol for wide area network (WAN) communications, and LoRa is used as a WAN technology. The carrier signal of LoRa is composed of chirps, which are signals that have a fluctuating frequency over time. LoRa's chirps permit the signal to move over long distances and to be demodulated even at a power up to 20 dB lower than the noise level [37]. However, LoRa's drawback is that the signals transmitted by different LoRa networks, which operate at different configurations, could cause false detections due to interference [38].

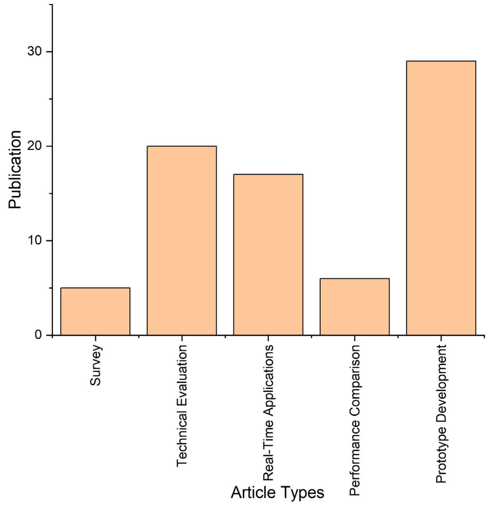

FIGURE 2. Classification of selected research articles.

TABLE 4. Summary of LoRa's configurable settings and their impact on communication performance.

Settings	Values	Effects
BM	125 to 500 kHz	The higher the BM is, the higher the data rates for transmitting packets. However, the communication range and receiver sensitivity are reduced.
SF	2^6 to $2^{12}\ \frac{\text{chips}}{\text{symbol}}$	The higher the SF is, the higher the SNR and radio sensitivity
Coding rate	4/5 to 4/8	The larger the coding rates are, the greater the resilience to the interference bursts
Transmission power	-4 to 20 dBm	The higher the transmission power is, the lower the SNR. However, the energy consumption of the transmitter will be larger

LoRa's communication performance depends on adjusting several PHY settings, which include the bandwidth (BM), coding rate (CR), spreading factor (SF), carrier frequency, and transmission power, as summarized in Table 4 [37]. The influence of each PHY parameter on the transmission range, data rate, receiver sensitivity, and energy efficiency is discussed in later subsections of this manuscript.

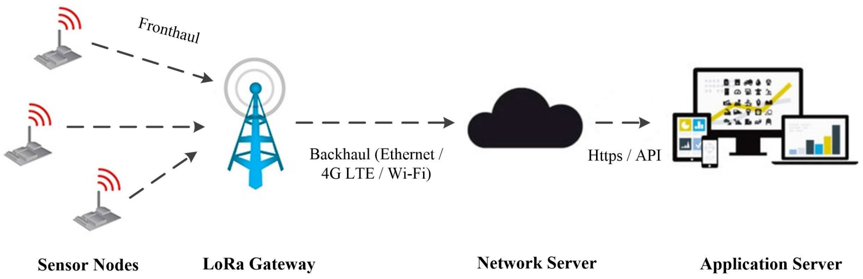

FIGURE 3. **LoRa communication network, which is made up of sensor nodes, gateway, network, and application server.**

A. BANDWIDTH

BM is the range of frequencies over which the LoRa chirp spreads. BM is inversely proportional to the air time and radiosensitivity [39]. A lower BM also needs a more precise crystal to reduce the problems related to clock drift. LoRaWAN only uses three BM ranges: 125 kHz, 250 kHz, and 500 kHz. LoRa's chip-rate, R_C is represented as follows:

$$R_C = \text{BM} \tag{1}$$

where R_C has a unit of chips/s.

B. SPREADING FACTOR

LoRa ''spreads'' each symbol over several chips to improve the receiver's sensitivity in a data transfer process. The higher the SF is, the better the SNR and the longer the transmission times [39]. The SF of LoRa varies from 6 to 12, which results in a spreading rate ranging from 26 to 212 chips/symbol [40]. The symbol-rate, R_S can be defined as follows:

$$R_S = \frac{R_C}{2^{\text{SF}}} = \frac{\text{BM}}{2^{\text{SF}}} \tag{2}$$

where R_S is measured in symbols/s. The modulation bit-rate, R_M can be computed as:

$$R_M = \text{SF} \times R_S = \text{SF}\frac{\text{BM}}{2^{\text{SF}}} \tag{3}$$

where R_M has a unit of bits/s. The packets transmitted with different SFs in the LoRa communication network are orthogonal to each other, and a collision will not occur if the packets are transmitted concurrently.

C. CODING RATE

CR is the proportion of transmitted bits that actually carry information [41]. To increase the resilience to corrupted bits, LoRa implements forward error correction (FEC) in every data transmission. This is done by encoding 4-bit data with redundancies into 5-, 6-, 7-, or 8-bit data. The resulting bit-rate, *BR* of LoRa is expressed as follows:

$$\text{BR} = R_M \times \frac{4}{4+\text{CR}} = \text{SF} \times \frac{\text{BM}}{2^{\text{SF}}} \times \frac{4}{4+\text{CR}} \tag{4}$$

where BR is measured in bits/s. A higher CR is necessary to increase the probability of successful packet reception when more interference bursts are expected. Although more protection can be offered, a higher CR will prolong the time on-air.

D. TRANSMISSION POWER

LoRa's transmission power is the energy required to transmit the LoRa message. It is adjustable, thus changing the energy required to transmit the message. The LoRa transmission power is directly proportional to the power consumption. Most LoRa radio support transmission power from −4 dBm to 20 dBm. However, for transmission powers greater than 17 dBm, the radio duty cycle is limited to a maximum of 1% by legal regulations and hardware limitations [37].

E. CARRIER FREQUENCY

LoRa transceivers use sub-GHz frequencies for their communication. These frequencies can be 433 MHz and 868 MHz for European countries, 915 MHz for the USA and Australia, 865 MHz to 867 MHz for India, and 920 MHz to 928 MHz for other Asian countries [42]. LoRa devices such as the Semtech SX1272 and HopeRF RFM95 support communication in the frequency range of 860 MHz to 1020 MHz.

IV. LoRa COMMUNICATION SYSTEM SETUP FOR UAV

It is critical for a UAV-based LoRa communication network to have a low bit rate connectivity to withstand the low bit rate pressure of LoRa technology while ensuring high reliability in connections. Decreasing the SF of LoRa can increase the bit rate; however, the transmission range will be reduced [43], [44]. Since a UAV is restricted by flight time, it is paramount to determine the priority between transmission range and bit rate in a specific LoRa application. The time duration for the transmission of sensor data can also be increased to achieve a low bit rate and stable connectivity [45]. However, it should be fast enough for the user to react accordingly, especially in monitoring applications. Several bit rates applied by the UAV-based LoRa network reported in this manuscript are listed in Table 5.

A LoRa communication system typically consists of LoRa nodes and a LoRa gateway, which are vital components for its interaction with the environment and transferring the data to the LoRa network server for analysis [46]. LoRa nodes

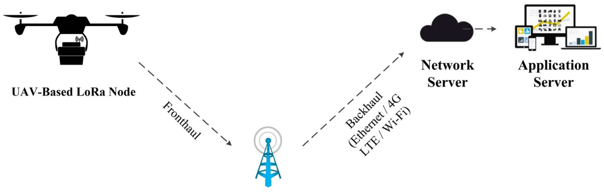

FIGURE 4. The UAV-based LoRa node communication network.

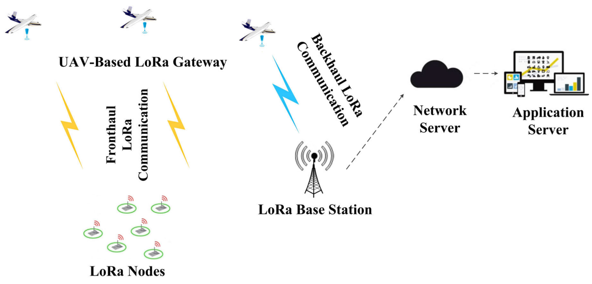

FIGURE 5. The UAV-based LoRa gateway communication network.

TABLE 5. Bit rates applied by the UAV-based LoRa communication network reported in this study.

References	LoRa Device	Bit Rate
[28]	TTGO T-Beam LoRa	5.5 kbps
[29]	iC880A-SPI-LoRaWAN concentrator	250 bps and 5 kbps
[47]	LoRa ES920LR	293 bps
[48]	LoRa SX1278	3.1 kbps
[49]	LoRa SX1276	5.4 kbps

consists of a battery, LoRa module, sensors, etc., and perform one or more tasks per application requirements. A LoRa gateway acts as a relay by forwarding all uplink radio packets to the LoRa network server. Focusing on the UAV, some authors used the UAV as the LoRa gateway, and some employed it as a LoRa node. In either case, for the real-time deployment of LoRa in a UAV, several devices are required for the LoRa node, LoRa gateway, and network server, with the consideration of the overall mass that would be added to the UAV system. The roles of UAVs in LoRa communication are illustrated in Figs. 4 and 5. In Fig. 4, the UAV acts as a LoRa node and is equipped with relevant sensors to measure and collect data in the air, before sending the data to the fixed LoRa gateway in the ground. Fig. 5 shows the role of the UAV as a LoRa gateway, where it will fly over the fixed LoRa nodes on the ground to collect and transmit data to the LoRa base station or directly to the network server. In other words, the role of the UAV can be seen in the device domain and network domain in Figs. 4 and 5, respectively. The data obtained will then be uploaded into the LoRa network.

A. UAV-BASED LoRa NODE

As a LoRa node, UAVs have to be equipped with hardware that can aggregate data coming from various sensors, such as temperature, humidity, accelerometer, magnetometer, and gas sensor data [50]–[52]. Then, the sensor data are transmitted using a LoRa module implementing the LoRaWAN protocol. This hardware is typically composed of a LoRa module, a LoRa compatible board, a battery, and related sensors. To employ UAVs as LoRa nodes, this hardware must be lightweight enough that it remains within the limits of the theoretical maximum take-off weight (MTOW). Several devices have been employed by researchers on UAVs to act as LoRa nodes. Angrisani *et al.* [53] used the Nucleo STM32L073RZ microcontroller for LoRa implementation on UAVs to monitor the air quality in dangerous areas. This controller is equipped with an ARM M0 + processor, which was developed for low-power applications. DJI F550, a hexacopter-type UAV, was used to take measurements before sending the data to the central station for processing. A LoRa node that comprises an SX1276 LoRa module and an Arduino UNO was used by Rahmadhani *et al.* [54] on a UAV to transmit UAV telemetry data such as altitude, latitude, longitude, and horizontal speed in UAV delivery applications. The data will be transmitted from the UAV hovering approximately 55 m above ground level to the ground station, which is connected to the LoRa gateway and located 8 m above ground level. This LoRa network is estimated to achieve 14.6 km distance coverage, but the testing shows that it can reach up to 8 km only in an urban area. This LoRa network can be further improved in terms of packet loss and real-time data transmission. Davoli *et al.* [28] also employed DJI Phantom 4 Pro as a LoRa node by installing a TTGO T-Beam LoRa board under the UAV frame to collect the GNSS latitude, longitude, and altitude and transferring it to multiple LoRa gateways through an 868 MHz LoRa channel frequency. The UAV was maintained in a hovering state at an altitude of 100 m and the LoRa system was powered by a 3.7 V 3500 mAh MR18650 Li-ion battery. The LoRa module was already equipped with a board, so no additional board was required. Other hardware employed by other researchers can be observed in Table 6 [47], [48], [55]–[61].

B. UAV-BASED LoRa GATEWAY

A UAV-based LoRa gateway is typically used for data collection from ground LoRa nodes [43], [45], [62]–[66] and to increase the communication ranges [29], [67]. It consists of at least two different wireless interfaces for backhaul and fronthaul connectivity. The fronthaul connectivity employs LoRa radio technology to communicate with the LoRa node, whereas the backhaul connectivity uses 4G or WiFi as a channel to establish communication between the LoRa gateway and LoRa network server, which is discussed in a later section of the manuscript. Sunnyeo *et al.* [68] applied the 3DR IRIS+, a quadcopter-type UAV as a LoRa gateway to help farmers obtain environmental data over a large

TABLE 6. **Hardware applied by other researchers for UAV-based LoRa nodes.**

References	Publication Year	Board	UAV Type	LoRa Module	Sensors	Battery	Frequency Channel
[55]	2018	Raspberry Pi	Not specified	Semtech SX1272	Thermometer and magnetometer	Not specified	Not specified
[56]	2019	RN2903 Mote board	Quadcopter (DJI Phantom 4 Pro)	LoRa Technology Evaluation Kit–900 by Microchip Technology	No sensors involved	Not specified	902 to 928 MHz.
[57]	2019	Raspberry Pi	Quadcopter	Acsip S765	No sensor	Not specified	920-925 MHz
[58]	2019	Raspberry Pi	Not specified	Dragino LoRa	Humidity sensors and anemometers	Not specified	Not specified
[47]	2020	Leafony	Not specified	LoRa ES920LR	Pulse sensor	Not specified	920 MHz
[48]	2020	Arduino Nano	Quadcopter (3DR IRIS+)	LoRa SX1278	Gas sensors (LPG, methane, and carbon monoxide)	Not specified	433MHz
[59]	2020	Arduino Mega R3	Quadcopter (DJI Inspiron 1 V2.0)	Dragino LoRa	MH-Z14A CO_2 sensor, a TGS2600 CH_4 sensor, a DHT22 temperature, and humidity sensor	5000 mAh USB rechargeable battery	Not specified
[60]	2020	STM32L452 microcontroller	Not specified	Semtech SX-1261 IC	GNSS	3.7 V Li-ion rechargeable battery	868 MHz
[61]	2021	Waspmote board and Raspberry Pi Hat	Hexacopter (Typhoon H Pro)	LoRa Hat	Gas sensors and temperature and humidity sensor	Not specified	868 MHz

agricultural field and dangerous areas. Dragino LG01 is installed on the UAV to communicate with the LoRa node, which consists of Arduino UNO as the mainboard, micro sd module, sensors, and LoRa Shield v1.4 of Dragino. Based on the experiment in the parking building, it was found that LoRa communication was possible up to 15 m vertically and 500 m horizontally. However, the performance was poor in a low-temperature environment, and due to UAV battery limitations, the number of tests was limited. Escolar *et al.* [69] utilized a UAV as a mobile gateway to send the hyperspectral and photonic sensor data installed on the target crop field to the server for further analysis. An Adafruit Feather M0 microcontroller and RFM95 LoRa module were equipped with a UAV for communication, whereas a photovoltaic solar panel (PV) and a lithium rechargeable battery, which has a capacity of 2000 mAh, were installed as a power supply. This work discusses only the real-time deployment of UAV-based LoRa gateway architecture, and there is no further analysis of the influence of UAV height on LoRa performance. Wang *et al.* [70] also employed a LoRa gateway on a UAV staying at 60 m height, whereas another UAV carrying the LoRa module was flying at 70 km/h towards the LoRa gateway from 10 km distance along the line-of-sight motorway. The LoRa module used was Acsip EK-S76GXB. No discussion on the board and type of UAV used by the authors is available. Other controller modules applied are listed in Table 7 [13], [29], [44], [49], [71]–[79].

C. LoRa NETWORK SERVER

Backhaul connectivity in the LoRa communication network includes Wi-Fi, 4G/LTE, and Ethernet. Depending on the deployment environment, a reliable connection can be established from the gateway to the LoRa network server via one of the communication modules. However, performance comparisons between these communication modules in LoRa network applications are not widely discovered by researchers. Table 8 summarizes the backhaul communication modules integrated by the researchers in the LoRa network applications.

1) Wi-Fi

Wi-Fi, also known as 802.11b, is a wireless Ethernet standard designed to support local area networks (LANs) [80]. It works by using radio frequencies to send and receive signals between devices in the gigahertz range. Among the advantages of Wi-Fi are a nearly constant affiliation experienced by the users connected to a wireless network that can be maintained with their desired network as they

TABLE 7. Hardware applied by other researchers for UAV-based LoRa gateway.

References	Publication Year	Board	UAV Type	LoRa Module	UAV Height	Frequency Channel
[49]	2017	BeagleBone Black (BBB)	Fixed-Wing (Delta Wing)	LoRa SX1276	30 m	433 MHz
[71]	2018	Not specified	Quadcopter (Holy Stone HS100)	SemTech SX1276	Not specified	Not specified
[72]	2018	Adafruit Feather M0	Quadcopter	RFM 95 LoRA	30 m to 40 m	900 MHz
[13]	2019	Rak2245 Pi-Hat board equipped with Raspberry Pi	Not specified	Semtech SX1301	Currently at simulation / preliminary stage	868 MHz
[73]	2019	Raspberry Pi 3 and Arduino M0	Quadcopter	LoRa Beacon	200m	433 MHz
[74]	2019	Raspberry Pi	Quadcopter (Intel Aero Drone)	Pycom LoRa	Indoor	Not specified
[75]	2019	ESP32 board	Not specified	RFM95 LoRa	Currently at simulation / preliminary stage	868 MHz
[29]	2020	Raspberry Pi 3	Quadcopter	iC880A-SPI - LoRaWAN Concentrator	60m	868 MHz
[76]	2020	Raspberry Pi	Quadcopter	MultiTech MultiConnect Conduit LoRa	10m	Not specified
[44]	2020	Not specified	Not specified	Not specified	60m	Not specified
[77]	2020	Raspberry Pi 3	Quadcopter (RE470)	RAK-831 Multi-channel LoRa with Semtech SX1272	Not specified	Not specified
[78]	2020	Raspberry Pi 3B+	Not Specified	Waspmote embedded with SX1272 LoRa	Not specified	Not specified
[79]	2020	FETMX6DL-C core board	Hexacopter (DJI Matrice 600 Pro)	Not specified	50 m	433 MHz

move from place to place and a low cost for the initial setup of an infrastructure-based wireless network. There are also many Wi-Fi devices available on the market that can be incorporated into a UAV-based LoRa communication network. The limitation of using the Wi-Fi technique is the shared frequency specification of 802.11b with many microwave ovens, Bluetooth, and cellular phones [81]. Thus, it is up to WiFi users to choose an access point that is not close to one of the devices mentioned due to the incoming interruption as it might cause a loss of signal.

2) 4G/LTE

LTE is a type of fourth-generation (4G) mobile communication technology that has been commercially available for almost 9 years [82]. It is an improvement over third-generation (3G) mobile network technology, with the objective of improving the capacity and speed, as well as reducing the latency of mobile networks. It works by moving large packets of data to an internet protocol system (IPS) and streamlines the service. 4G/LTE offers a higher bit rate, lower latency, longer range or coverage, and better security than its predecessors and Wi-Fi [83]. However, the number of available 4G/LTE products is limited.

3) ETHERNET

Ethernet is a fixed-line network that is fast and easy to install [84]. It works by using specialized Ethernet cables that connect one or multiple devices to a central hub or router for networking. Compared to Wi-Fi communication, it is more secure and consumes less power [85]. The limitation of Ethernet is the number of connections that are established. A single Ethernet cable can be applied to only a single device, which means that more cables are required for multiple device connections. It is also designed for short-distance communication.

TABLE 8. **Several communication techniques used by researchers to communicate with a LoRa network server.**

Backhaul Communication	References
MQTT	[53]
IEEE 802.11s	[28]
ES920GW as an Internet Gateway	[47]
4G/LTE	[29], [57], [70], [76], [77], [79]
Wi-Fi	[44], [68], [73], [74]
Virtual Ethernet	[49]

V. UAV-BASED LoRa COMMUNICATION PERFORMANCE

The performance of LoRa network communication can be measured by various indicators, including the communication range between LoRa modules, packet loss rate, RSSI, and SNR. The packet loss rate, P_{recv}, is the percentage of sent packets, P_{sent}, that did not actually reach the receiver and can be determined as follows [86]:

$$P_{\text{loss}} = 1 - \frac{P_{\text{recv}}}{P_{\text{sent}}} \times 100 \tag{5}$$

where P_{recv} is all the packets received by the receiver. RSSI can be defined as the measurement of the power present in a received radio signal and measured in decibel milliwatts (dBm). It is usually represented in negative dBm, where a value closer to 0 dBm corresponds to a better signal. According to [87], an RSSI of −60 dBm is considered acceptable, whereas −100 dBm is considered poor. SNR is the ratio of a signal's power to the power of the noise, where a value greater than 0 indicates that the received signal operates above the noise floor [88]. SNR can be calculated as follows:

$$\text{SNR} = \frac{P_{\text{signal}}}{P_{\text{noise}}} \tag{6}$$

where P_{signal} is the power of the signal and P_{noise} is the measured power of the noise. SNR is a unitless ratio, but typically it is converted to dB.

Yuan *et al.* [89] found that the reliability of the LoRa communication network in terms of data rate decreases linearly from 100% to 20% as the communication distance increases to 2.5 km. The 100% network reliability (0% packet loss rate) can be achieved at a distance of up to 320 m. This proves the superior performance of LoRa compared to WiFi, where its reliability decreases sharply from 100% to 0% at 40 m to 320 m, respectively. However, the results show that LTE networks in urban areas offer 100% communication reliability within the range of 1.28 km. Thus, the LTE communication approach is preferable when cellular coverage is available, whereas LoRa is recommended when there is no cellular network support, as in rural areas. Wang *et al.* [70] tested the performance of LoRa communication using UAVs deployed at high speed. LoRa communication was successful over a range of 4.1 km. However, the expected range for successful communication was 10 km due to the line-of-sight path. This is due to the usage of a 0 dBi short antenna on the UAV, and the LoRa performance can be improved by deploying a more powerful UAV that can carry an 8 dBi or higher long antenna. A set of UAV-based LoRa gateways was deployed by Saraereh *et al.* [44] for disaster management applications that can communicate with the base station via WiFi. Based on real-time testing, packet loss rates of less than 10% and between 10% and 20% were achieved by deploying 12 UAVs and 8 or 10 UAVs, respectively. However, there are still unnecessary movements and transmissions that can be reduced to improve the LoRa communication performance. Other LoRa performances based on the real-time deployment conducted by other researchers are listed in Table 9.

VI. DISCUSSION

The objective of this study is to evaluate the current state of the art in the use of UAVs in the LoRa communication network. The analysis is based on the selected UAV-based LoRa-related studies. The authors also want to answer several research questions mentioned in the introduction section. To answer RQ1, Fig. 6 illustrates the distribution of selected research articles by (a) publication year, (b) application domain, (c) type of UAV applied, and (d) country. Fig. 6(a) demonstrates that the trend of using LoRa with UAVs is a new research scope, as the first reported application based on our findings was in 2016. Since then, this research area has continued to increase and reached a peak in 2019 and 2020. This number is expected to grow, as many research perspectives regarding UAV-based LoRa have not yet been explored. Based on Fig. 6(b), most of the works related to UAV-based LoRa focus on the technical evaluation domain, where the ability of LoRa to transmit data with the help of UAVs is tested, either by simulation or real-time deployment. For real-time applications, UAV-based LoRa technology is mostly applied in environmental monitoring tasks, where relevant sensors are attached to the UAV. It can also be observed in Fig. 6(c) that most of the UAV-based LoRa prototypes built are based on quadcopter-type UAVs, and there is no reported usage of octocopter-type UAVs. Fig. 6(d) reveals the country of origin for all the selected research articles, with Italy as the largest contributor to the largest number of papers for a single country.

Through this review, it was discovered that UAVs have been utilized as LoRa nodes and LoRa gateways in IoT applications such as traffic monitoring, air quality monitoring, agricultural data collection, and forestry monitoring. For the research question regarding the UAV-based LoRa communication network set up (RQ 2), as a LoRa node, multiple sensors will be installed on the UAV for data collection, and these data will be sent to the fixed or ground LoRa gateway, whereas the UAV carrying LoRa Gateway will fly according to the predetermined paths to collect all the data from the

TABLE 9. UAV-based LoRa communication performance based on the real-time deployment.

References	Publication Year	LoRa Performance
[49]	2017	LoRa communication signal was lost at approximately 4 km in range, compared to the expected range of 5 km. This is because part of the sensor node was submerged in the sea and creates interference
[54]	2018	The proposed LoRa system can achieve up to 8 km coverage in an urban area and 5% packet loss rate if the lowest SF is used
[55]	2018	For the 10km line-of-sight range, the SNR and RSSI achieved by the proposed LoRa communication are 3 dBm and -106 dBm, respectively
[68]	2018	Testing at the tree farms showed that LoRa communication can be successfully achieved when a UAV is at a height of 20 m, but the proposed system did not work very well in the low outside temperature (early winter weather)
[71]	2018	By applying the proposed LoRa communication, testing showed that the median errors of 1.2326 mm and 0.0164 radians are obtained for UAV location and orientation, respectively
[72]	2018	For the non-line-of-sight testing, the packet loss rate is 5%. However, unstable and unpredictable data are obtained for the line-of-sight testing
[56]	2019	It was observed that the UAV's height greatly influences the RSSI in the suburban environment compared to urban areas. In a suburban area, the RSSI at 50 m UAV height is always better than the RSSI at 25 m UAV height, whereas there is no significant effect on the RSSI at different UAV heights in the urban areas
[57]	2019	The RSSI of the proposed UAV-based LoRa communication acquired are -90 dBm and -100 dBm for the 5 km and 10 km range, respectively
[73]	2019	The proposed LoRa system achieved an RSSI average of approximately -83 dBm over a 6 km range
[47]	2020	It was found that the RSSI on the ES920LR generally decreases in accordance to the distance or time on air (ToA) and the ES920LR loses the LoRa signal at a distance of 1 km in the full obstacle situation
[59]	2020	The proposed UAV-based LoRa communication was successfully at the range of about 1 km and RSSI of roughly -95 dBm was obtained
[76]	2020	High localization precision of 12 m was achieved using UAV-based LoRa communication, which is ten times better than the LoRa-only system
[78]	2020	LoRa communication performed best when kept under concrete pieces with an RSSI value of approximately -100 dBm and performed worst when covered with a wooden or glass box
[79]	2020	The proposed LoRa communication achieved RSSI values of -60 dBm and -70 to -90 dBm when in the range of 1 km and 1.5 km to 2.5 km, respectively
[28]	2021	The proposed LoRa system can achieve between 30 km to 60 km coverage with less than a 5% packet loss rate. However, an indoor LoRa gateway, located 4 km from the LoRa node, produced a high packet loss rate
[61]	2021	There are only 1% to 2% discrepancies between the data measured using the proposed UAV-based LoRa device and the data obtained from the government-operated air quality station, which implies that this low-cost device can be an alternative in air quality monitoring tasks

ground or fixed LoRa nodes. Both roles require the application of a board (Raspberry Pi, Arduino, etc.) to interact with the LoRa devices. This UAV-based LoRa communication network is expected to be incorporated more, especially in precision agriculture areas. This is due to the future of agriculture, where connected farmers will be able to monitor and analyze their crops without physical examination, in terms of soil moisture, mapping, and pesticide control. However, one must follow a specific frequency channel when operating UAVs.

For the research question regarding the reported ranges of UAV-based LoRa communication achieved during its real-time deployment (RQ 3), the successful communication ranges obtained are between 1 km and 60 km and at an altitude of up to 100 m. Work conducted by Davoli *et al.* [28] achieved the highest communication ranges, where most of the grounded LoRa gateways, located within a radius between 30 km and 60 km from the UAV-based LoRa node, can receive messages. To answer RQ 4, there are several indicators to measure the LoRa performance, such as RSSI, packet loss rate, and SNR. The best RSSI, packet loss rate, and SNR were obtained by Zhang *et al.* [79] (−60 dBm), Yuan *et al.* [89] (0%), and Godot *et al.* [55] (3 dBm), respectively.

Most of the real-time deployments of LoRa using UAVs reported in this study are limited by the UAV's payload and flying time. This is due to the usage of quadcopter, which can

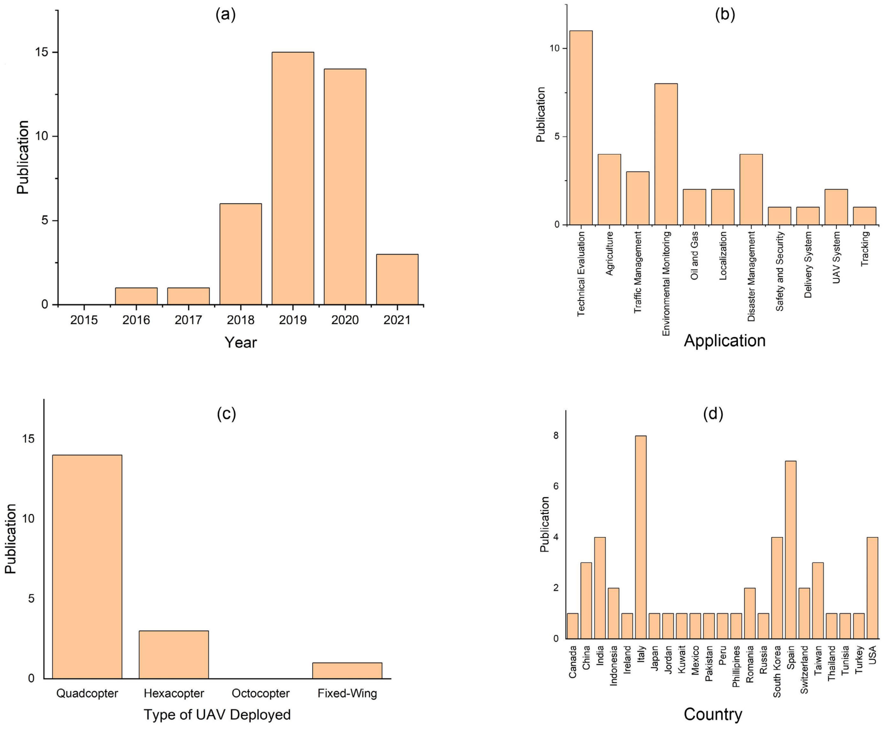

FIGURE 6. Distribution of chosen research articles by (a) publication year, (b) application domain, (c) type of UAV applied, and (d) country.

only carry a low payload, and thus, only a limited number of sensors can be used. A more powerful antenna also cannot be equipped with the quadcopter due to its high weight, which in turn will lower the LoRa communication range. A fixed-wing UAV can be employed to increase the flying time so that more testing can be conducted. An octocopter-type UAV can also be used to carry more payloads, such as a larger antenna. Although payload specifications have a substantial impact on UAV-based LoRa performance, most of the presented works did not fully disclose their payloads. In addition, some authors set the transmission power to the maximum value. This might waste the battery life, as nodes closer to the gateway can use less transmission power. Overall, the findings obtained from this study provide a reliable view and guidance on LoRaWAN performance, especially on the behavior of LoRa in a real environment and how various environmental factors affect its performance. This accounts for a vital preparation toward the real-time deployment of UAV-based LoRa. For example, it is noted that LoRa performs better in rural environments than in urban areas. In addition, poorer LoRa communication is established when it is deployed in a low-temperature environment. Table 10 shows the technology readiness level (TRL) of each proposed UAV-based LoRa communication network reported in this study. It represents the maturity of the proposed technologies towards full economic operation. Most of the reported UAV-based LoRa communication technologies are in TRLs 6 and 7, in which these technologies fall under sustainable goal development (SGD) 9. Several improvements in terms of energy consumption and demonstrations involving final developed technology are required to improve its maturity for commercialization purposes.

TABLE 10. The TRL of each UAV-based LoRa communication network studies reported in this manuscript.

TRL	Description	Related Studies
1-3	Protoype development	[13], [44], [75]
4	Prototype basic validation in a laboratory environment	[69], [71], [74], [78]
5	Prototype basic validation in a relevant environment	[47], [54], [67], [70]
6–7	Prototype demonstration in a relevant and operational environment	[28], [29], [49], [53], [55]–[60], [68], [72], [73], [76], [77], [79]
8	Actual technology completed and qualified through test and demonstration	[48], [61]

Regarding RQ 5, in the future, advanced AI algorithms such as deep learning can be incorporated into the UAV-based LoRa prototype to perform crucial analysis and decision-making onboard the UAV and produce results in real-time. This, however, requires more hardware, which in turn requires a more powerful UAV such as fixed-wing and octocopter. In terms of analyzing the LoRa communication performance, a study where the LoRa devices are not in the line-of-sight is very limited and needs further testing. Additionally, as mentioned before, the performance comparison of different backhaul connectivity technologies in the LoRa network can be explored by the researchers, as the study regarding this scope has not yet been reported.

VII. CONCLUSION

In this manuscript, the authors presented a systematic review of the real-time deployments of the UAV-based LoRa communication network. The authors systematically reviewed the role of UAVs as the LoRa node and LoRa gateway and discussed the LoRa performance in a real environment. This performance was measured in terms of packet loss rate, communication range, RSSI, and SNR. The research questions regarding the publication trend of the UAV-based LoRa communication network (RQ 1), the LoRa communication setup for the UAV including the hardware (RQ 2), the maximum LoRa communication ranges that can be achieved (RQ 3), and how its performance is determined (RQ 4) were successfully answered. Further works include utilizing a fixed-wing UAV or octocopter for the mobile platform and testing LoRa communication without line-of-sight features and in different weather conditions (RQ 5).

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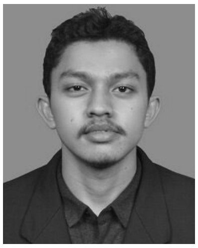

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