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Review of LoRaWAN: Performance, Key Issues and Future Perspectives

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ABSTRACT

In the last few years, the Low-powered wide area networks (LPWAN) have gained popularity and massively deployed, especially in smart cities and agriculture, due to their advantages, such as energy efficiency, extensive coverage, and low cost. The long-range wide area networks (LoRaWAN) protocol is a new technology. It attracts the attention of many research centers worldwide as it allows data transmission at a low cost across long distances. This article reviews the performance of LoRa and LoRaWAN for both investigations in indoor and outdoor environments. Moreover, a performance analysis of this technology is made by focusing on five main indicators, which are coverage, time on air (TOA), packet error rate (PER), received signal strength indication (RSSI), and signal-to-noise ratio (SNR) while considering technical characteristics is included. The investigation settings were divided into two categories: simulation and testbed in a real-world application. Consequently, a table of summary of indicators used by the researcher was made to make it easier for other researchers to find references for their topics relevant to this review. Next, the identified key issues and solutions are discussed in this review. The issues discussed significantly affect the performance of various monitoring technologies regarding energy management, quality of service, coverage, signal interference, and data handling. Finally, this review will discuss the future perspective, provide valuable suggestions for future research works, and lead toward improving current LoRaWAN technology.

Keywords: LPWAN; LoRaWAN; Performance; Indooor &Outdoor Environment; Issues; Future Directions

INTRODUCTION

As IoT technologies evolved, remote sensing systems have recently become necessary for many situations and applications. Furthermore, the revolution in semiconductors and microelectronics drives the development of high-performance and cost-effective modules. It fulfills the possible requirements for diverse remote sensing applications (Balaji et al. 2019).

The LPWAN technological landscape of today is quite diverse and comprises several technologies, including Sigfox, LoRa, LTE-M from the 3GPP, NB-IoT, and Weightless. Long Range Wide Area Networks (LoRaWAN) are among the most popular LPWAN technologies, with over 700 million connections anticipated by 2023 (Chaudhari et al. 2020).

The arrangement of this review is organized as follows. After this short introduction, Section 2 provides an overview of LoRaWAN, focusing on its physical and Media Access Control (MAC) layers. Next, section 3 reviews the past study regarding the performance analysis of LoRaWAN by concentrating on five indicators which are coverage, time on air (TOA), packet error rate (PER), received signal strength indication (RSSI), and signal-to-noise ratio (SNR).

Furthermore, section 4 provides a summary table of findings for performance analysis of LoRa and LoRaWAN.

Section 5 discusses several key issues and solutions of LoRaWAN technology. Next, section 6 discusses the future perspective and provides valuable suggestions for future research works. Finally, Section 7 summarizes and concludes this review.

OVERVIEW OF LORAWAN

Semtech Corporation has a patent for the LoRa modulation, and the first version was made available in 2015. LoRa defines the physical layer, whereas LoRaWAN describes the communication protocol and system architecture. End nodes can communicate with a gateway using the LoRa modulation with the LoRaWAN's medium access control mechanism.

LoRaWAN is one of the most popular low-power area network technologies. This technology has great potential for implementation in numerous Internet of Things applications due to its low cost, low power consumption, and wide network coverage.

LORA

At the physical layer, the spread spectrum modulation method known as the chirp spread spectrum modulates LoRa. It is a dated modulation method first employed for military communication in 1940. Compressed high-intensity radar pulse is what the name "chirp" stands for. It states that the signal frequency increases and decreases during the modulation process. This modulation strategy enables long-distance communication since it can overcome noise and interference.

LoRa offers kilometers of communication range, longer battery life, resistance to multi-path, and high interference levels by utilizing unlicensed (ISM) frequencies. This approach offsets time and frequency so that the transmitter and receiver are identical.

The modulation robustness may be tuned using the spreading factor (SF) option, which accepts integer values between 7 and 12. The data rate and SF are correlated. Higher SF makes the transmitted signal more reliable and extends the coverage area in exchange for a reduced data rate and longer transmission times.

LORAWAN

LoRaWAN defines the network architecture on top of the physical LoRa and MAC layers. Due to the deployment of thousands of end nodes, wide-ranging access is necessary to maximize concurrent transmissions and eradicate packet collisions.

The LoRaWAN MAC allocates airtime across end nodes to coordinate the networks and manage packet collisions. The end nodes can forward data packets after waking up with the aid of the Aloha MAC.

LoRaWAN introduces three operating modes: class A (the default), class B, and class C. These options define the connection parameters for wireless end nodes. The end node can jitterlessly arrange an up-link transmission for Class A in accordance with their requirements. These devices allow for two-way communication. Devices referred to as Class A use the least amount of energy.

Class B devices may communicate in both directions and have an extra time period for data reception. Several reception slots enabled by a beacon message delivered by the gateway are also available for Class B devices.

Class C end nodes continuously sense the channel excluded when sending a frame. It must thus be linked to a power source. Class C hence has a high power consumption, no delay, and can transmit and receive multicast and unicast communications.

PERFORMANCE

The technology features of LoRa and LoRaWAN and the effectiveness of these technologies have been the subject of numerous investigations. Figure 1 shows the framework of the performance analysis of LoRa and LoRaWAN. The analysis is divided into two main categories, which are indoor and outdoor environments. The outdoor environment considers both testbed and simulation experiments, while the indoor environment considers only the testbed experiments.

The testbed is divided into two categories which are the development module and commercial devices. Development modules are modules fabricated by researchers. Most of the models were novel and fabricated primarily for the experiment. Whereas the other category is for commercially available devices.

On the other hand, newer simulator models can simulate and analyze this technology's performance. The simulation study carried out by researchers in this analysis is only for the outdoor environment.

The studies chosen for this analysis are primarily focused on five key indicators. These indicators were selected based on their prominence, as demonstrated by their utilization in previous studies. By incorporating these widely recognized indicators, we aim to ensure the comprehensive coverage of important aspects within the research and maintain consistency with established methodologies in the field. The five indicators used are coverage, time on air (TOA), packet error rate (PER), received signal strength indication (RSSI), and signal-to-noise ratio (SNR) (Lin & Hao 2021).

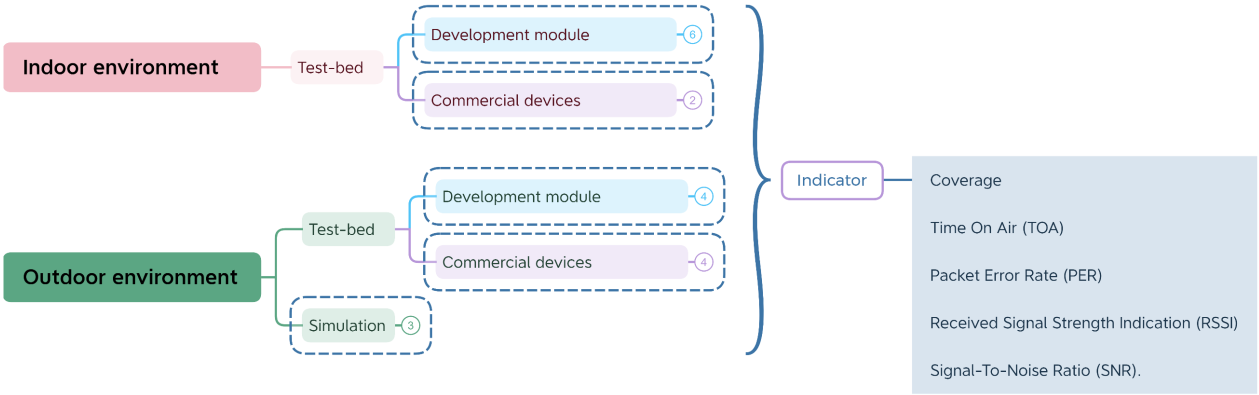

FIGURE 1. Framework for performance analysis of LoRa and LoRaWAN

INDOOR ENVIRONMENT

Figure 2 below shows the mind map of indoor environment studies. This analysis contains only studies that investigate the performance using a testbed. The performance of LoRa and LoRaWAN in the indoor environment with different objectives based on previous publications has been investigated. For example, Miles et al. (2020) examine the general performance evaluation of LoRa and LoRaWAN, while Harinda et al. (2022) investigate the feasibility of LoRa and LoRaWAN for indoor environments.

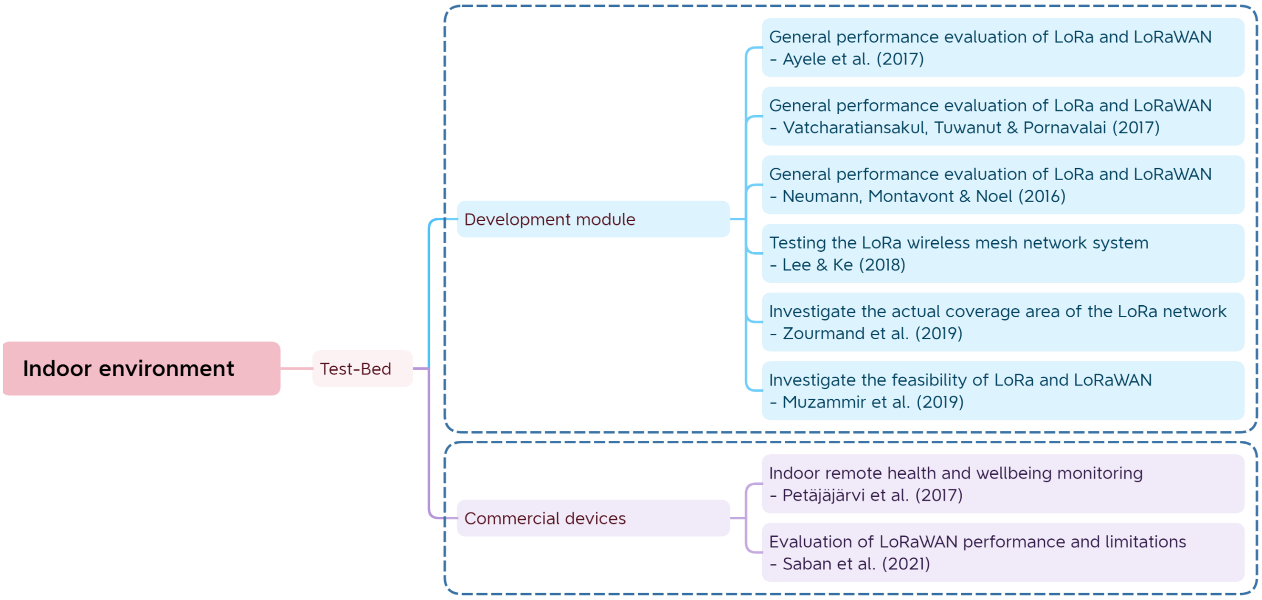

FIGURE 2. Mind map of indoor environment studies

DEVELOPMENT MODULE (INDOOR ENVIRONMENT)

Ayele et al. (2017) observed the LoRa radio's performance study for indoor IoT applications. The examination of LoRa radio RSSI values indicated that LoRa gives protection against multi-path and signal fading, especially at larger spreading factors, because of the broadband chirp pulses and greater sensitivity of the LoRa modulation (SF). The received signal is stronger and closer to the gateway for a low spreading factor system. Furthermore, when the SF is raised, the PER falls off at the price of a lower effective bit rate, making it unsuitable for high-throughput IoT applications. And interference levels are notably high in areas distant from the doorway. End nodes ought to communicate at high spreading factors as a result.

According to Vatcharatiansakul, Tuwanut & Pornavalai (2017), based on evaluating LoRaWAN's experimental performance inside King Mongkut's Office of Learning Ladkrabang, Bangkok. While the gateway is situated on the sixth level of the central library, there are four end-device sites at a distance of 55, 95, 120, and 150 meters. The gateway can only receive packets from two of the four sites, at a distance of 55 and 120 meters, with a corresponding packet loss of 56% and 94%.

Neumann, Montavont & Noel (2016) have evaluated how well LoRaWAN unconfirmed uplink data frames function indoors. In order to determine if LoRaWAN technology might cover a whole building, the researchers evaluated the signal strength collected from several areas. Regarding the wall composition, there was no discernible difference in the transmission quality or packet loss between the lab levels and the rooms. The only thing affected in the basement was the communications. In conclusion, LoRaWAN can offer reliable indoor connections for low-cost remote sensing applications.

An indoor wide-area LoRa mesh networking system for IoT application monitoring was presented by Lee & Ke (2018). The researchers presented an indoor wide-area LoRa mesh networking system for IoT application monitoring. They placed 19 LoRa mesh networking devices over an area that measured 800 m by 600 m, together with a packet gateway that collected data every minute. The star-network design of LoRa was used, which was reported to have a 41.3 percent of packet error rate (PER). The LoRa mesh networking technology produced an average PER of 11.51 percent under similar scenarios. The proposed LoRa mesh network may significantly lower PER without requiring an additional gateway, according to data comparison between the network and the LoRa PHY one-hop wireless network.

A study by Zourmand et al. (2019) demonstrates the characteristic of LoRa, such as the spreading factor, bandwidth, and performance of the LoRa network in indoor and outdoor scenarios and its actual coverage area. The devices were tested in various places for the indoor environment. The path loss and distance from the gateway influence the efficacy of the LoRa network performance. Additionally, with a spreading factor of 9, a single LoRa gateway on the middle floor of the building could manage LoRa end nodes across the campus. In contrast, three hundred thirty meters is the maximum coverage distance in outdoor situations, with a signal SNR of -16.75 dB and an RSSI of -130 dBm. Furthermore, the signal's quality degrades the farther the end nodes are from the gateway. Test results reveal that the communication system begins to function below the noise floor more than 120 meters from the gateway.

Muzammir et al. (2019) examined the performance of LoRaWAN to determine if LoRaWAN is practical for indoor applications. The investigation uses a multichannel LoRa gateway and several LoRa end nodes. The LoRa infrastructure was located on several floors of Tower 2 of the Engineering Complex at Universiti Teknologi MARA in Shah Alam. At 125 kHz of bandwidth, the measurement for SF varies from 7 to 12. Time on air (TOA) increases gradually as SF increases.

COMMERCIAL DEVICES (INDOOR ENVIRONMENT)

According to Petäjäjärvi et al. (2017), The main objective of the study is to evaluate LoRa LPWAN technology for remote indoor health and wellness monitoring. It was accomplished since a single gateway could cover the whole campus of the University of Oulu in Finland with a transmit power SF of 12 to 14 dBm. In this instance, the average recorded packet success delivery ratio was 96.7 percent.

A study by Saban et al. (2021) demonstrate that LoRa performs better outside than indoors. The signal quality received by the end-node devices can be improved by elevating the gateway to have a direct line of sight with the end node, making it possible to cover greater distances. The researcher observed that when the measuring point moved further from the floor where the LoRa gateway was positioned, the signal quality began to deteriorate noticeably. Due to the high noise and dense materials used to construct the building walls, windows, etc., it was difficult to travel three blocks from the entryway in this setting. End nodes successfully forwarded 100% of the packets to every level in the block where the gateway was located. As a result, a LoRa network can effectively serve small buildings.

OUTDOOR ENVIRONMENT

Figure 3 below shows the mind map of outdoor environment studies. This analysis contains the test bed (development module and commercially available devices) and simulation settings.

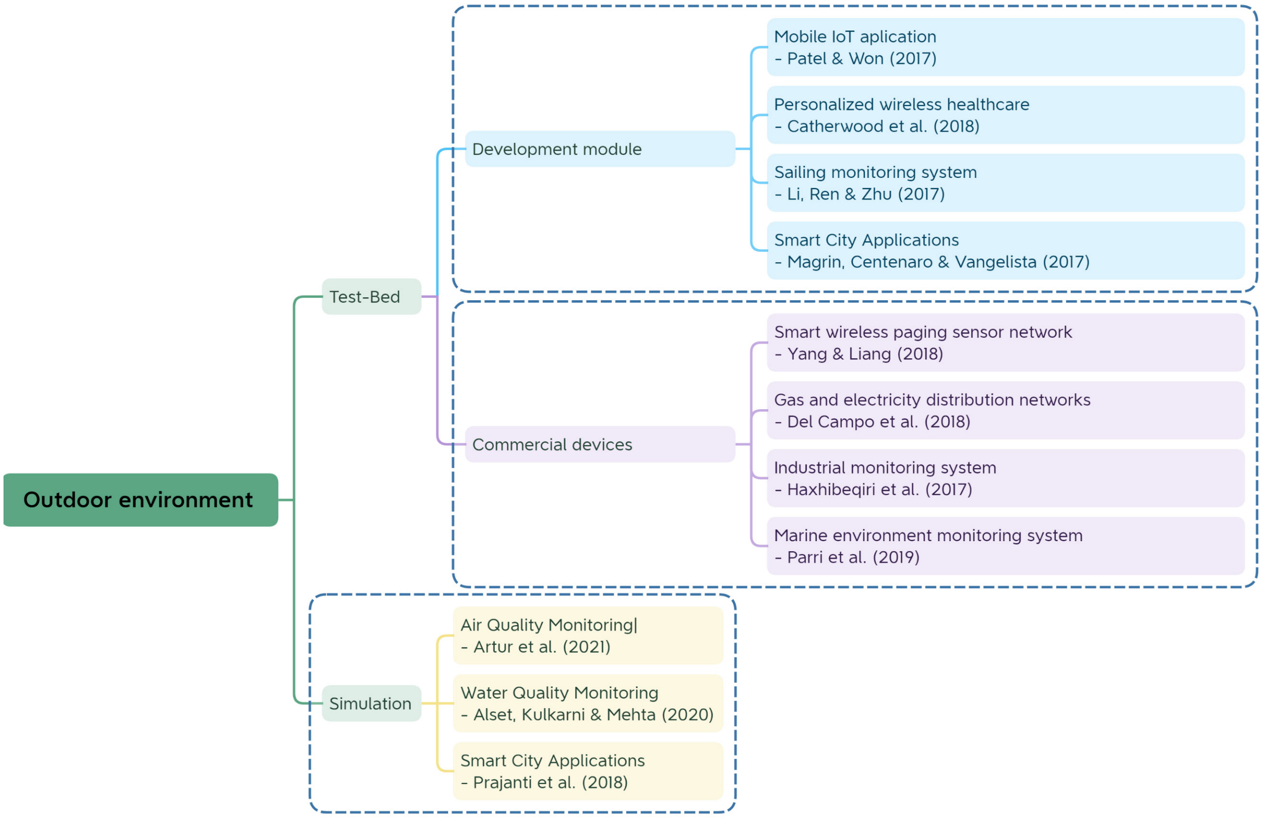

FIGURE 3 Mind map of outdoor environment studies

DEVELOPMENT MODULE (OUTDOOR ENVIRONMENT)

According to experimental findings by Patel & Won (2017), to determine whether LPWAN would be suitable for mobile IoT, the study examined the relationship between mobility and LPWAN performance. Even with little human movement, LoRaWAN performance is surprisingly sensitive to motion. Moving farther away from the gateway, driving faster, and placing the terminal node outside dramatically worsen the effect of mobility. The outcome demonstrates that SF 7 is ideal for implementing the system since it ensures minimal packet losses. As expected, the signal-to-noise ratios, RSSI standard deviations, and mean values are all within acceptable limits. Compared to higher SFs for the same packet length, SF 7 uses less power.

Catherwood et al. (2018) have conducted IoT-based personalized wireless healthcare solution trials in the community. The system is paired with an 868 MHz LoRaWAN-enabled customized monitor and showed good promise, with UTI test results correctly identified and sent to a distant secure cloud server in every instance. Radio path losses in the tests ranged from 119 to 141 dB at distances of 1.1 to 6.0 km.

LoRaWAN is an excellent choice for long-range and broad coverage. The study conducted by (Li, Ren & Zhu 2017) in Rio sailing venue for two cases. With the gateway and sink nodes totally on the water, Case 1 indicates that LoRa has strong mobility performance with an average speed of 20 km/h. Case 2 shows how well a LoRa system performs regarding low power consumption, wide coverage, and reliable transmission. In this instance, the gateway was installed on the land, whereas the sink nodes were on the sea. This shows that the LoRa technology used by the system can function with a low packet loss rate of less than 5% and a range extension of more than 2 km on flat terrain. The packet loss rate for LoRa technology might exceed 20% in some areas due to obstacles like high buildings and trees.

A study conducted by Magrin, Centenaro & Vangelista (2017) attempted to develop a basic cover design for the city of Padova, which spans a region of around 100 km2. The outcome reveals that 30 gateways—less than half the number of sites installed by one of Italy's largest cellular operators—are sufficient to cover the whole municipality.

COMMERCIAL DEVICES (OUTDOOR ENVIRONMENT)

Yang & Liang (2018) demonstrate an innovative packet transmission model for a real-time senior care application supported by a smart LoRaWAN-based wireless paging sensor network (WPSN). The model examines the effectiveness of star topology communication on the Markov discrete-time M/M/1 queuing system for senior care. The approach aims to balance the network load on nodes, decrease time delay and energy consumption, and promote software-defined radio. The successful delivery rate, packet delay, and traffic load of the suggested wireless passive sensor networks are simulated and empirically examined in an elder care application. The innovations put forward in this paper might serve as a guide for creating wireless passive sensor networks.

A study conducted by Del Campo et al. (2018) aims to enhance maintenance procedures in gas and electricity distribution networks by implementing a monitoring system. The researchers assessed the LoRa communication range in suburban areas (up to 10 km) while considering different topography at various electrical network sites. According to the results of the experiments, the line of sight has the most significant impact, and buildings and dense vegetation adjacent to communication nodes decrease the range.

According to Haxhibeqiri et al. (2017), researchers have determined that SF 7 can cover the 34,000 m2 of indoor industrial area. The RSSI values at each measurement site, which were all above -100 dBm, several measuring sites recorded negative signal-to-noise ratio values. For outdoor measurement sites, up to 6% of packets are received with the wrong CRC while communicating only with SF 12 at the farthest measuring point, 400 m away. The average SNR values were peaking at negative 16.4 dB. Network scalability may be accomplished by considering the end nodes' data rate in this scenario, where 75% of nodes send a 20-byte packet per hour and 25% complete it every five minutes. A network design like this may accommodate up to 6000 end nodes with packet loss rates of about 10%.

Parri et al. (2019) deployed transmitting devices in the middle of the ocean and the gateway on land. The researchers demonstrated that a LoRaWAN network could gather data in marine environments. The link's feasibility was shown by covering the 8.33 km distance between the facility and the offshore breeding cages. Additionally, the testing demonstrated that SF 7 is the best SF to employ when the full system is installed in the future since it guarantees less packet loss and respectable mean values and standard deviations for RSSI and SNR.

SIMULATION (OUTDOOR ENVIRONMENT)

Artur et al. (2021) investigated the deployment of LoRaWan devices for monitoring air quality using Network Simulator 3 (NS-3). The study considered the distance between nodes, antennas, and other spreading components. A real-world situation in the Brazilian city of Teresina is also used to obtain data on RSSI, Latency, SNR, and Packet Error Rate (PER). Additionally, a simulation is run to look at the energy use in the lifetime of the sensor nodes. The results show that the LoRaWAN technology has shown to be a useful option, being able to communicate at distances of up to 2000 meters with a packet loss rate of 0.3%, a low SNR, and a latency of only 23ms. With a node lifespan of 2081 days, up to 12000 packets may be transmitted, consuming a total of 0.0105 mWh.

Alset, Kulkarni & Mehta (2020) investigated the transmission of water quality values utilizing the LoRa frequency spectrum at 433 MHz, 865 MHz, and 915 MHz in the MATLAB/Simulink environment. These frequencies were evaluated based on power consumption and data-packet loss across various transmission distances. This comparison could facilitate choosing the best LoRa module for a specific application. The distance between the transmitter and receiver influences packet data loss. The receiver's sensitivity will be improved by using bigger SF values to increase coverage while reducing the data bit rate. Depending on the distance between the LoRa transmitter and receiver, the optimal SF value is selected to balance power consumption and data-packet loss.

A simulation study conducted by Prajanti et al. (2018) uses an NS3 simulator to simulate the deployment of LoRaWAN for smart city applications in the Jakarta region. On its 662,33 km2 of land, Jakarta has many structures, particularly high-rise structures. Their simulation findings with different gateway radiuses show that the highest performances are attained in radii as small as 3000 m and as large as 6500 m. The maximum number of end nodes that each gateway may support is 3000. Twenty-six estimated gateways can support up to 78,000 end nodes in Jakarta.

SUMMARY OF FINDINGS FOR PERFORMANCE ANALYSIS

Based on the studies discussed above, Table 1 summarises the findings of the studies for performance analysis of LoRa and LoRaWAN. The table was categorized into three settings: commercial devices, development module, and simulation. In addition, the papers studied are also divided into two color codings. In this case, the blue shaded rows represent the study done in the indoor environment, while the green shaded area represents the outdoor environment investigation.

Furthermore, this table also summarizes the highlighted five primary indicators, which are coverage, time on air (TOA), packet error rate (PER), received signal strength indication (RSSI), and signal-to-noise ratio (SNR), which were highlighted alongside summary remarks of the related references.

TABLE 1. Summary of findings for performance analysis of LoRa and LoRaWAN

No	Settings	Reference	Coverage	TOA	PER	RSSI	SNR
1.	Commercial devices	Petäjäjärvi et al. (2017)	✓		✓	✓	
2.		Saban et al. (2021)	✓		✓	✓	✓
3.		Yang & Liang (2018)		✓	✓		
4.		Del Campo et al. (2018)	✓		✓	✓	✓
5.		Haxhibeqiri et al. (2017)	✓	✓	✓		✓
6.		Parri et al. (2019)	✓		✓	✓	✓
7.	Development module	Lee & Ke (2018)	✓	✓	✓	✓	✓
8.		Ayele et al. (2017)	✓	✓	✓	✓	
9.		Zourmand et al. (2019)	✓		✓	✓	✓
10.		Muzammir et al. (2019)	✓		✓	✓	
11.		Vatcharatiansakul, Tuwanut & Pornavalai (2017)	✓	✓	✓		✓
12.		Neumann, Montavont & Noel (2016)		✓	✓	✓	✓
13.		Patel & Won (2017)	✓		✓		
14.		Catherwood et al. (2018)	✓		✓	✓	✓
15.		Li, Ren & Zhu (2017)	✓	✓	✓		
16.		Magrin, Centenaro & Vangelista (2017)	✓				
17.	Simulation	Artur et al. (2021)	✓		✓	✓	✓
18.		Alset, Kulkarni & Mehta (2020)			✓	✓	
19.		Prajanti et al. (2018)	✓		✓		

KEY ISSUES AND SOLUTIONS

The primary goal of LPWAN technology development is efficient data transmission over long distances. Apart from that, the technology also has to be reliable, secure, and efficient. However, several issues significantly affect the performance of various monitoring technologies regarding energy management, quality of service, coverage, signal interference, and data handling. The identified key issues and solutions are discussed in the following section.

ENERGY MANAGEMENT

Since the LoRaWAN is a critical low-powered device for its application, the wireless sensor network is usually placed in a hard-to-reach area, making battery replacement challenging. This situation may cause trouble for a necessary application that needs data in real-time consistently. Thus power consumption management is essential for proper operation, as batteries are large, bulky, and have a short lifespan. Batteries are also highly harmful to the environment and matter. Two studies confronted this problem by creating novel solutions as non-traditional ways of powering devices.

Asenov (2020) proposes a technique for deploying end nodes without batteries for Internet of Things applications. The fundamental feature is low energy consumption that only enables supercapacitor and solar harvesting energy. In addition, Mulders et al. (2019) also investigate the feasibility of providing IoT nodes with power utilizing an autonomous vehicle that's primary objective is to recharge nodes.

As for energy efficiency, Kromes et al. (2019) find that nodes consume more energy when not in idle mode as the transmission cycle is not regulated. The researchers create an artificial neural network (ANN)-based algorithm that regulates the network nodes' transmission cycles. The system anticipates the nodes' data, allowing them to minimize data transfer and operate more in idle mode.

Furthermore, based on observation by Callebaut et al. (2020), the primary cause of energy consumption for the nodes is still wireless transmission, which affects their autonomy. The researchers are testing massive MIMO technology to enable low-energy devices with strong coverage at sub-GHz frequencies and boost system stability.

QUALITY OF SERVICE

QoS (Quality of service) refers to the level of reliability and predictability of the network's performance. In LoRaWAN, QoS is typically measured in terms of the following parameters:

1. Reliability: The network can deliver data packets without loss or corruption. LoRaWAN provides reliability by implementing a range of error detection and correction mechanisms.

2. Latency: The time required for data to be sent between a device, the network, and back to devices. Low latency is desirable for many applications, particularly those needing real-time data processing.

3. Throughput: The amount of data transmitted over the network over time. High throughput is desirable for applications that require large amounts of data to be transmitted quickly.

4. Availability: The network's ability to maintain a connection with devices over time. LoRaWAN provides availability by implementing adaptive data rate mechanisms, which adjust the data rate based on the quality of the connection.

Overall, QoS is an essential consideration for any LoRaWAN deployment, as it directly impacts the performance and reliability of the network. Many research has been done to improve the QoS. For example, Sallum et al. (2020) investigate the viability of enhancing LoRa QoS through improved radio resource management. The Data Extraction Rate (DER), packet collision rate, and energy consumption in LoRa networks are improved by fine-tuning specific radio parameters using Mixed Integer Linear Programming (MILP).

In addition, it is worth noting that Vangelista & Cattapan (2021) develop a DloRa modulation with a bandwidth and numerology compatible with the conventional LoRa modulation. DLoRa employs an immediate lowering frequency in the chirps instead of the typical LoRa modulation, which uses an increasing instantaneous frequency. It has been demonstrated that this new modulation makes it possible to lower the collision probability.

COVERAGE

The term "coverage" describes the maximum distance across which data may be sent between two sites when it is done so using a certain form of communication, such as radio waves, cable connections, or optical signals. The signal intensity, frequency, transmission medium, and any interference from other devices or environmental elements are just a few of the variables that might affect the transmission range.

Without needless repeats, stable and energy-efficient communication with adequate coverage and capacity must be ensured by the LoraWAN gateway. A study by Turˇ (2022) seeks to improve the communication range by adding two or more concentrators. The results showed a significant increase in the likelihood of messages being successfully received on the gateway.

Also, another problem for LoRaWAN devices is low flexibility levels and difficulty deploying a gateway. For example, in a remote area that has no internet connectivity. Human intervention is needed to retrieve the data, and hence, the efficiency is reduced. Li et al. (2021) investigated using an energy-constrained Unmanned Aerial Vehicle (UAV), in which the sensory data is stored in devices, even though the devices are possibly not within the transmission range.

Moreover, LoRaWAN operates in the unlicensed ISM (Industrial, Scientific, and Medical) radio bands, which have limited range and can be affected by interference from other wireless devices. In some cases, the LoRaWAN coverage may be limited due to physical obstacles or environmental conditions, such as buildings or terrain. For example, when it comes to an ecosystem as complicated as a Smart City, the landscape of the IoT system is overly diversified.

These issues can be solved by employing a LoRaWAN device to communicate with multiple Radio Access Technologies (RATs) simultaneously or seamlessly. Multi-

RAT enables IoT devices to communicate with multiple communication technologies, such as cellular networks or satellite networks, which can extend their coverage beyond the LoRaWAN network. This can be especially useful in areas where the LoRaWAN coverage is weak or unavailable or in remote or rural areas where other networks are the only option. Stusek et al. (2020) proposed using multi-RAT options at a single ED and the dynamic switching between them by employing reinforcement learning (RL) algorithms for better coverage of LoRaWAN.

SIGNAL INTERFERENCE

Numerous independent LoRa networks have been set up close to one another. Neighboring networks could interfere with this situation. Signal interference can significantly impact the performance and reliability of LoRaWAN networks, especially in dense urban areas or environments with many wireless devices. To mitigate the impact of signal interference, LoRaWAN networks can use several techniques, such as frequency hopping, spreading codes, and adaptive modulation, which can reduce interference effects and improve the overall network performance and reliability.

Additionally, It is possible to use directional antennas and several gateways to reduce interference between nearby networks. Directional antennae increase signal strength at receivers without raising the cost of transmission energy. For the LoRa network, the interference is often caused by simultaneous transmission with the same spreading factor (co-SF) and a different spreading factor (inter-SF).

To mitigate the interference in the network, Mahmood et al. (2019) proposed the poisson point process to model the interference. The suggested scheme determines the width and bounds of SF zones by considering each area's success probabilities and device density (SPD). The proposed SPD scheme has a 13.20 percent higher success probability under joint co-SF and inter-SF interference.

DATA HANDLING

Data handling in LoRaWAN refers to transmitting, receiving, processing, and storing data generated by LoRaWAN devices. LoRaWAN also presents some challenges in data handling. Here are some of the main issues of data handling in LoRaWAN:

1. Limited Bandwidth: LoRaWAN uses a narrow radio spectrum band, limiting the amount of data that can be transmitted. As a result, data must be sent in small packets, and larger data sets must be broken up into smaller chunks.
2. Delayed Transmission: LoRaWAN is made for low-power, long-range communication, which permits delayed data transfer. This latency may impair real-time applications and make it challenging to synchronize data across numerous devices.

LoRaWAN protocol has built-in ADR (Adaptive Data Rate) functionality. The ADR algorithm ensures the device maintains a reliable connection to the gateway while consuming the least amount of power possible to send data (Kufakunesu et al. 2020).

ADR is a crucial component of LoRaWAN that aids in streamlining the data transmission procedure and enhancing the functionality of IoT applications. ADR assists in addressing the issues of constrained bandwidth, delayed transmission, security, and scalability by automatically altering the data rate, transmit power, and other factors (Kufakunesu et al. 2022).

Based on the wireless channel's quality, ADR can modify the data transmission rate of a LoRaWAN device. This means that when the channel is clear, the device can transmit at a higher rate, and when the channel is noisy or congested, the device can transmit at a lower rate. By adapting to the network conditions, ADR can help to optimize data transmission and reduce the impact of limited bandwidth.

Next, ADR can change a LoRaWAN device's power level based on the distance from the gateway. The transmission latency decreases when the device is near the gateway because it may broadcast at a lower power level. The transmission range is increased when the device is distant from the gateway because it may broadcast at a greater power level. ADR may reduce transmission latency by adjusting to the gateway's distance.

FUTURE PERSPECTIVE

Overall, the future of LoRaWAN looks promising as the developments of these technologies continue to unfold. LoRaWAN is likely to play an increasingly important role in the growth of IoT. This section will discuss the future perspective and provide useful suggestions for future research works.

1. Improvement of network performance: Although the LoRaWAN network performance is among the best in LPWAN technology, with the increased adoption of this technology, LoRaWAN will need to improve

capacity and enhance data handling abilities. The improvement of network performance will be made possible by the development of sophisticated data processing techniques like ADR. Since ADR is only fundamental as it only considers distance and RSSI to determine the right settings, future research is needed to enhance this technique. Furthermore, employing machine learning techniques to predict and manage traffic may help networks function better.

2. Advanced simulation platforms: Few simulations of LoRaWAN can simulate devices' performance and energy consumption. It should be noted that the currently available simulators may not encompass all of the crucial parameters. Hence, the accuracy of the result may be inaccurate. Therefore, an advanced simulation platform is essential for accurate evaluation.

3. Integration with other technology: LoRaWAN has the potential to be combined with other wireless technologies, like Bluetooth and Wi-Fi, to form hybrid networks that can provide the benefits of both technologies. Integrating with other technologies makes IoT applications even more flexible and scalable. Furthermore, if LoRaWAN is integrated with blockchain technology, it could create secure and decentralized IoT networks (Shahjalal et al. 2022).

4. Increase geographical reach: As the adoption of LoRaWAN continues to rise, there is a growing need to extend network coverage to reach new geographical areas. This can be achieved by deploying additional gateways and developing new infrastructure. To meet this demand, there will likely be increased investment in network expansion. Furthermore, advancements in satellite-enabled LoRaWAN solutions could offer a viable option for expanding network coverage to remote and isolated areas. The availability of such solutions would enable the deployment of LoRaWAN networks in previously unreachable locations, facilitating the integration of new use cases and supporting the growth of the IoT ecosystem.

5. The lifespan of the end node: Despite LoRaWAN modules offering a very low energy consumption, the deployed nodes with a limited power supply were using an inefficient microcontroller. Thus, it will lower the lifespan of end nodes. A shorter lifespan of end nodes requires regular changing of batteries and could increase maintenance costs for the overall network. New research on developing optimized microcontrollers specifically for LoRaWAN modules would be beneficial (Ansari et al. 2021).

CONCLUSION

This review of LoRa and LoRaWAN technology has discussed their performance in indoor and outdoor environments. The study parameter concentrated on five indicators which are coverage, time on air (TOA), packet error rate (PER), received signal strength indication (RSSI), and signal-to-noise ratio (SNR). The year of studies picked they were ranged from 2017 to 2021.

The investigation settings were divided into two categories: simulation and test bed in a real-world application. The testbed investigation is divided into the development module and commercial devices. Development modules are modules fabricated by researchers. Most of the models were novel and fabricated primarily for the experiment. At the same time, the others are commercially available devices.

Consequently, a table of summary of indicators used by the researcher was made to make it easier for other researchers to find references for their topics relevant to this review. Hopefully, this review can lead to a better understanding of LoRaWAN performance for indoor and outdoor environments.

Next, this review discusses the key issues and solutions that have been identified. These issues significantly impact the performance of various monitoring technologies, including energy management, quality of service, coverage, signal interference, and data handling. Additionally, this review provides insights into future perspectives, valuable suggestions for future research, and guidance toward improving LoRaWAN technology.

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DECLARATION OF COMPETING INTEREST

None.

REFERENCES

Alset, U., Kulkarni, A. & Mehta, H. 2020. Performance Analysis of Various LoRaWAN Frequencies for Optimal Data Transmission of Water Quality

Parameter Measurement. *2020 11th International Conference on Computing, Communication and Networking Technologies, ICCCNT 2020* 2–7.

Ansari, S., Ayob, A., Hossain Lipu, M.S., Md Saad, M.H. & Hussain, A. 2021. A review of monitoring technologies for solar pv systems using data processing modules and transmission protocols: Progress, challenges and prospects. *Sustainability (Switzerland) 13*(15).

Artur, A.F., Silveira, J.D.F., Moura, M.C.L., Dos Reis, J. V., Rabelo, R.A.L. & Rodrigues, J.J.P.C. 2021. Performance analysis of LoRaWAN in an air quality monitoring applications for smart cities. *2021 6th International Conference on Smart and Sustainable Technologies, SpliTech 2021* 15–20.

Asenov, S. 2020. Battery Free Wireless LoRaWAN End Sensor Node for IoT Applications 2020–2023.

Ayele, E.D., Hakkenberg, C., Meijers, J.P., Zhang, K., Meratnia, N. & Havinga, P.J.M. 2017. Performance analysis of LoRa radio for an indoor IoT applications. *Internet of Things for the Global Community, IoTGC 2017 - Proceedings* 1–6.

Balaji, S., Nathani, K. & Santhakumar, R. 2019. IoT Technology, Applications and Challenges: A Contemporary Survey. *Wireless Personal Communications 108*(1): 363–388.

Callebaut, G., Gunnarsson, S., Guevara, A.P., Tufvesson, F., Pollin, S., Van Der Perre, L. & Johansson, A.J. 2020. Massive MIMO goes Sub-GHz: Implementation and Experimental Exploration for LPWANs. *Conference Record - Asilomar Conference on Signals, Systems and Computers 2020-Novem*(732174): 1101–1105.

Catherwood, P.A., Steele, D., Little, M., McComb, S. & McLaughlin, J. 2018. A Community-Based IoT Personalized Wireless Healthcare Solution Trial. *IEEE Journal of Translational Engineering in Health and Medicine 6*(May): 1–13.

Chaudhari, B.S., Zennaro, M. & Borkar, S. 2020. LPWAN technologies: Emerging application characteristics, requirements, and design considerations. *Future Internet 12*(3): 1–25.

Del Campo, G., Gomez, I., Calatrava, S., Martinez, R. & Santamaria, A. 2018. Power distribution monitoring using lora: Coverage analysis in suburban areas. *International Conference on Embedded Wireless Systems and Networks* 233–238.

Harinda, E., Wixted, A.J., Qureshi, A.U.H., Larijani, H. & Gibson, R.M. 2022. Performance of a Live Multi-Gateway LoRaWAN and Interference Measurement across Indoor and Outdoor Localities. *Computers 11*(2): 1–23.

Haxhibeqiri, J., Karaagac, A., Van Den Abeele, F., Joseph, W., Moerman, I. & Hoebeke, J. 2017. LoRa indoor coverage and performance in an industrial environment: Case study. *IEEE International Conference on Emerging Technologies and Factory Automation, ETFA* 1–8.

Kromes, R., Russo, A., Miramond, B. & Verdier, F. 2019. Energy consumption minimization on LoRaWAN sensor network by using an Artificial Neural Network based application. *SAS 2019 - 2019 IEEE Sensors Applications Symposium, Conference Proceedings*.

Kufakunesu, R., Hancke, G. & Abu-Mahfouz, A. 2022. A Fuzzy-Logic Based Adaptive Data Rate Scheme for Energy-Efficient LoRaWAN Communication. *Journal of Sensor and Actuator Networks 11*(4).

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): 1–25.

Lee, H.C. & Ke, K.H. 2018. Monitoring of Large-Area IoT Sensors Using a LoRa Wireless Mesh Network System: Design and Evaluation. *IEEE Transactions on Instrumentation and Measurement 67*(9): 2177–2187.

Li, L., Ren, J. & Zhu, Q. 2017. On the application of LoRa LPWAN technology in Sailing Monitoring System. *2017 13th Annual Conference on Wireless On-Demand Network Systems and Services, WONS 2017 - Proceedings* 77–80.

Li, Y., Liang, W., Xu, W., Xu, Z., Jia, X., Xu, Y. & Kan, H. 2021. Data Collection Maximization in IoT-Sensor Networks Via an Energy-Constrained UAV. *IEEE Transactions on Mobile Computing X*(X): 1–16.

Lin, K. & Hao, T. 2021. Experimental Link Quality Analysis for LoRa-Based Wireless Underground Sensor Networks. *IEEE Internet of Things Journal 8*(8): 6565–6577.

Magrin, D., Centenaro, M. & Vangelista, L. 2017. Performance evaluation of LoRa networks in a smart city scenario. *IEEE International Conference on Communications*.

Mahmood, A., Sisinni, E., Guntupalli, L., Rondon, 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.

Miles, B., Bourennane, E.B., Boucherkha, S. & Chikhi, S. 2020. A study of LoRaWAN protocol performance for IoT applications in smart agriculture. *Computer Communications 164*: 148–157.

Mulders, J. Van, Crul, S., Leenders, G., Thoen, B. & Der Perre, L. Van. 2019. Bringing Energy to IoT Nodes: An Unmanned Vehicle for Wireless Power Transfer. *SAS 2019 - 2019 IEEE Sensors Applications Symposium, Conference Proceedings* 1–5.

Muzammir, M.I., Abidin, H.Z., Abdullah, S.A.C. & Zaman, F.H.K. 2019. Performance analysis of LoRaWAN for indoor application. *ISCAIE 2019 - 2019 IEEE Symposium on Computer Applications and Industrial Electronics* 156–159.

Neumann, P., Montavont, J. & Noel, T. 2016. Indoor deployment of low-power wide area networks (LPWAN): A LoRaWAN case study. *International*

Conference on Wireless and Mobile Computing, Networking and Communications.

Parri, L., Parrino, S., Peruzzi, G. & Pozzebon, A. 2019. Low power wide area networks (LPWAN) at sea: Performance analysis of offshore data transmission by means of loRaWAN connectivity for marine monitoring applications. *Sensors (Switzerland) 19*(14).

Patel, D. & Won, M. 2017. Experimental Study on Low Power Wide Area Networks (LPWAN) for Mobile Internet of Things. *IEEE Vehicular Technology Conference 2017-June*: 0–4.

Petäjäjärvi, J., Mikhaylov, K., Yasmin, R., Hämäläinen, M. & Iinatti, J. 2017. Evaluation of LoRa LPWAN Technology for Indoor Remote Health and Wellbeing Monitoring. *International Journal of Wireless Information Networks 24*(2): 153–165.

Prajanti, A.D., Wahyuaji, B., Rukmana, F.B., Harwahyu, R. & Sari, R.F. 2018. Performance Analysis of LoRa WAnTechnology for Optimum Deployment of Jakarta Smart City. *2018 2nd International Conference on Informatics and Computational Sciences, ICICoS 2018* 54–59.

Saban, M., Aghzout, O., Medus, L.D. & Rosado, A. 2021. Experimental analysis of IoT networks based on LOra/LoRAWAN under indoor and outdoor environments: Performance and limitations. *IFAC-PapersOnLine 54*(4): 159–164.

Sallum, E., Pereira, N., Alves, M. & Santos, M. 2020. Improving quality-of-service in LOra low-power wide-area networks through optimized radio resource management. *Journal of Sensor and Actuator Networks 9*(1): 1–26.

Shahjalal, M., Islam, M.M., Alam, M.M. & Jang, Y.M. 2022. Implementation of a Secure LoRaWAN System for Industrial Internet of Things Integrated With IPFS and Blockchain. *IEEE Systems Journal 16*(4): 5455–5464.

Turˇ, F. 2022. LoRaWAN Base Station Improvement for Better Coverage and Capacity 1–11.

Vangelista, L. & Cattapan, A. 2021. Extending the Lora modulation to add parallel channels and improve the LoRaWAN network performance. *2021 11th IFIP International Conference on New Technologies, Mobility and Security, NTMS 2021*.

Vatcharatiansakul, N., Tuwanut, P. & Pornavalai, C. 2017. Experimental performance evaluation of LoRaWAN: A case study in Bangkok. *Proceedings of the 2017 14th International Joint Conference on Computer Science and Software Engineering, JCSSE 2017* 7–10.

Yang, G. & Liang, H. 2018. A Smart Wireless Paging Sensor Network for Elderly Care Application Using LoRaWAN. *IEEE Sensors Journal 18*(22): 9441–9448.

Zourmand, A., Kun Hing, A.L., Wai Hung, C. & Abdulrehman, M. 2019. Internet of Things (IoT) using LoRa technology. *2019 IEEE International Conference on Automatic Control and Intelligent Systems, I2CACIS 2019 - Proceedings* (June): 324–330.