ISSN (e) 3007-3138 (p) 3007-312X
Volume 3, Issue 8, 2025

PERFORMANCE EVALUATION OF LORAWAN UNDER DIVERSE NETWORK SETTINGS: CURRENT APPLICATIONS AND FUTURE PROSPECTS

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DOI: https://doi.org/10.5281/zenodo.16881310

Keywords
WSN, LDCNs, LoRaWAN, ALOHA, LBT

Article History
Received: 12 May, 2025
Accepted: 01 July, 2025
Published: 15 August, 2025

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Abstract
LoRaWAN (Long Range Wide Area Network) is widely recognized as a leading communication protocol for the Internet of Things (IoT). It is designed for long-range, low-power, and low-data-rate wireless communication. LoRaWAN is particularly suitable for Wireless Sensor Networks (WSNs) operating over Wide Area Networks (WANs). These characteristics make it ideal for smart cities, industrial monitoring, precision agriculture, and other large-scale IoT applications. The performance of LoRaWAN largely depends on the Media Access Control (MAC) techniques it employs. Two major MAC techniques are ALOHA and Listen Before Talk (LBT). ALOHA uses random access without carrier sensing. LBT, on the other hand, senses the channel before transmission. Each has advantages and limitations that impact performance under different network conditions. This study evaluates the performance of LoRaWAN and presents a detailed comparison between ALOHA and LBT in the context of LoRaWAN. All the simulations are conducted using OMNeT++ with a network of 100 nodes. The evaluation focused on three key performance metrics: Packet Loss Ratio (PLR), End-to-End Delay, and Power Consumption. The results show that ALOHA is more energy-efficient. It avoids channel sensing, which reduces power usage. However, it leads to higher packet collisions, especially in dense networks. This causes significant packet loss and communication overhead. LBT, in contrast, offers better reliability. It senses the channel before transmitting, which reduces collisions and improves delivery. But this also increases energy consumption due to constant listening. This trade-off is important for designing efficient LoRaWAN-based systems. The choice between ALOHA and LBT should consider the network size, density, and energy constraints. Additionally, this study highlights current and future applications of LoRaWAN. It emphasizes the protocol's potential as a backbone for next-generation IoT systems that demand scalable, reliable, and energy-aware communication.

1. Introduction

The term Wireless Sensor Network (WSN) denotes autonomous networks composed of heterogeneous communication nodes that are mutually configured to perform specific objectives. Communication entities, sensors, actuators, transceivers, transmission channels, and communication protocols are some core components of WSN. The applications of WSN are continuously expanding in various cutting-edge domains, including Internet of Things (IoT), smart homes, smart industry, smart agriculture, smart healthcare, smart transportation, and smart education. However, IoT-based Long Distance Communication Networks (LDCNs) have become increasingly important because of their multi-dimensional applicability [1]. There exists a variety of communication protocols responsible for governing the data exchange among IoT-based LDCNs; however, Long Range Wide Area Network (LoRaWAN) have gained significant popularity. LoRaWAN is a widely spreading potential communication protocol that provides instant and reliable communication across extended-range networks. Efficient communication with less consumption of network resources over an extensive transmission range is the core strength of LoRaWAN [2].

Long-distance communication demands high energy for transmission, and energy is the core issue in resource-constrained networks. The LoRaWAN protocol aims to ensure good communication with nominal consumption of network resources. The architectural structure of the LoRaWAN protocol is fascinating and unique. It involves the Media Access Control (MAC) mechanism, and there are two primary MAC techniques named ALOHA and LBT. In ALOHA, each communication node sends data in the network without hesitation. However, in LBT, the transmission node has to sense the channel before transmitting a data packet in the network. LBT is also called a polite spectrum access technique in simple words [3]. LoRaWAN has to adopt one of those MAC techniques to perform its applications. As the applications of LoRaWAN are increasing, there must be an appropriate investigation for the selection of suitable MAC techniques for this purpose. In LoRaWAN, two standard MAC techniques, ALOHA and LBT, act as a game-changer in good communication. ALOHA does not involve any carrier sense mechanism, and it is famous for instant communications. However, the LBT consists of a carrier sense mechanism, and it offers relatively slow communication. On the other hand, the communication quality is high in LBT because it is compatible with communication issues such as noise and resonance [4].

The LoRaWAN protocol can be implemented in several network topologies and configurations. In a star topology, transmission can be achieved using just one base station. Due to its simplicity and ability to minimise the power consumption of remote sensors, wireless sensor networks benefit from this network model. Low-latency communications between the remote node and the base station can also be achieved using this technique [5]. One node administers a less strong network than others since the base station must be within the radio transmission range of all other nodes. The ease of wireless sensor networks and their ability to keep the power consumption of remote nodes to a minimum are also advantages. Remote nodes can communicate with the base station using low-power methods. Because the base station must be within the radio transmission range of all nodes, it is less trustworthy than the others because it controls the entire network. An internal mesh network communicates using radio waves in a mesh system. To put it another way, a node can send a message to another node that is not within its radio communication range by using an intermediary node. The redundancy and scalability offered by this network configuration are two of its main benefits. Nodes can communicate with each other even if a single one fails, as long as the other nodes are within range. Adding more nodes to the system expands the network's coverage because the distance between nodes isn't a factor. The multi-hop communication nodes in this network have a disadvantage in terms of power consumption, which commonly affects battery life [6].

A mesh topology employs radio waves to transmit data from one node to another inside the network. In other words, a node can use an intermediate node to forward a message to another node that is not within its radio communication range, enabling what is referred to as "multi-hop" communications. Two advantages of this network arrangement are redundancy and scalability. Even if a single node fails, contact with any other node within its range is still possible if the other nodes remain within range. Additionally, the network's capacity is not constrained by the distance between individual nodes; it may be expanded by adding additional nodes to the system [7]. This network type has a disadvantage in power consumption for the nodes that perform multi-hop communications, frequently reducing battery life. Combining a star network with a mesh network provides a flexible and robust communication system while also minimizing the power consumption of wireless sensor nodes. Messages can't be forwarded from low-power sensor nodes in this network configuration. As a result, just the absolute minimum amount of power is used. As a result, other nodes on the network can relay messages from low-power nodes to others on the web via multi-hop capabilities. Nodes having multi-hop capabilities tend to be more powerful and, if possible, connected to the power grid. ZigBee, a mesh networking standard in development, uses this design. It is impossible to forward messages from low-power sensor nodes in a network topology [8]. As a result, there is little power consumption. A sample LoRaWAN architecture is shown in Figure 1.

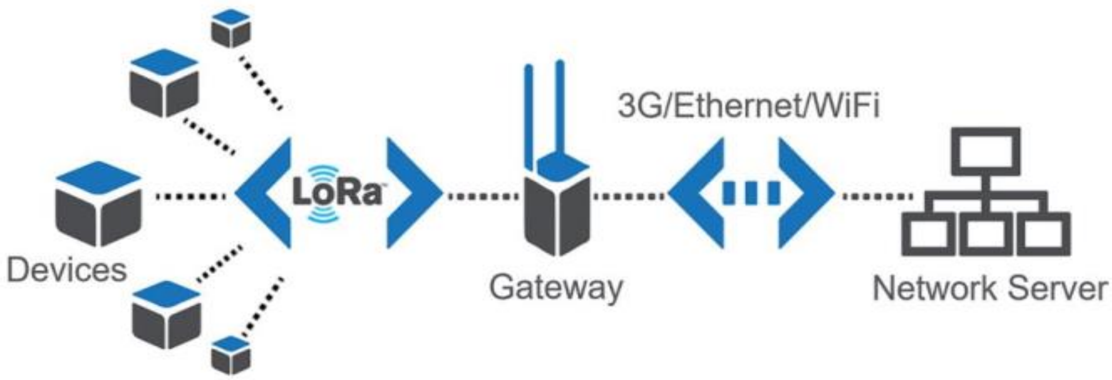

Figure 1: Communication architecture of LoRaWAN protocol

Radio technologies such as LoRaWAN are straightforward at their most fundamental level. The LoRaWAN network is best compared to a cellular network in terms of functionality. LoRa-based devices are equipped with a module that communicates with a gateway, which is central in the local area. The gateway serves as a communication channel between the devices and the server. Another way of putting it is that the network server eliminates duplicate data packets, verifies data integrity, and performs security checks on the information. Nodes in a star design are not required to constantly watch their surroundings for messages from other nodes, as is the case with different types of architecture. The LoRaWAN protocol is affected by a vast range of challenges that need to be addressed [9]. One significant issue is energy challenges, as energy is the core concern in resource-constrained networks. The second one is reliable communication that is required in every application area. LoRaWAN deals with long-distance communications, so many possible external factors are more likely to affect the communication stream of LoRaWAN. Channel breakage may also occur in long-distance communication. That is another significant challenge to the efficiency of this protocol and demands specific considerations [10].

A. Research Problem

LoRaWAN is increasingly positioned as a leading protocol for long-range, low-power communication in IoT environments. Its reliance on the ALOHA-based MAC technique has facilitated wide deployment due to its simplicity and minimal coordination overhead. However, as IoT networks grow in scale and complexity, this reliance prompts critical concerns regarding their long-term effectiveness and adaptability. In parallel, LBT has emerged as an alternative MAC approach, yet the implications of adopting LBT over ALOHA in the context of LoRaWAN remain insufficiently understood. There is a clear need for a more rigorous and comparative understanding of these two MAC techniques, particularly in how they shape the operational behaviour and deployment flexibility of LoRaWAN. The widespread assumption that LoRaWAN is an optimal solution for long-range communication must be examined through a more critical and systematic lens. Its practical applicability, efficiency, and overall validity across varied deployment environments and use cases require thorough investigation. Furthermore, LoRaWAN's growing adoption across domains such as smart infrastructure, industrial systems, and environmental monitoring necessitates a deeper exploration of its current capabilities and future potential. Clarifying these aspects will contribute to a more grounded and forward-looking understanding of LoRaWAN's role in the next generation of IoT communication networks.

B. Research Contributions

1. This research evaluated the performance of LoRaWAN under various performance parameters such as Packet Loss Ratio (PLR), End-to-End Delay, and Power Consumption
2. The performance of famous MAC techniques ALOHA and LBT is thoroughly examined in the context of LoRaWAN context.
3. A detailed outlook about the current applications of LoRaWAN is provided along with a comprehensive overview of prospects.

2. Literature Review

LoRaWAN works on the core fundamentals of the MAC mechanism. It involves different MAC techniques that incorporate its functionalities strategically. Researchers in [11] have conducted an in-depth analysis of the LoRaWAN protocol. Various device characteristics, such as packet error rate (PER), throughput, latency, and energy consumption, were studied in the context of various payload sizes and end device counts. Furthermore, a backlog and non-backlog study under the slotted Aloha LoRaWAN environment is carried out. With regards to PER and throughput, the simulation reveals good results. Experimental evaluations have shown an increase in latency. Researchers in [12] have investigated the performance and energy consumption of LoRaWAN-Aloha and LoRaWAN-CSMA/CA networks under various networking conditions. The simulation results allowed them to evaluate and compare the collision ratio and energy consumption per node between CSMA and Aloha systems. The performance evaluation reveals that, when compared to LoRaWAN-Aloha, the LoRaWAN-CSMA/CA could be a better choice for large IoT networks with high scalability requirements, according to the findings. LoRaWAN Aloha, on the other hand, will perform better. The LoRaWAN protocol is tested under both channel-aware and channel-oblivious jamming situations. The authors in [13] proposed several different approaches for improving the performance of LoRaWAN networks. The second contribution consists of offering a dynamic sharing mechanism to improve the management of the duty cycle's utilisation (Dynamic Duty-Cycle). The final contribution consists of proposing a deterministic access technique to replace Aloha in the future. Our experiments demonstrated that our proposed solutions provide better results in Packet Delivery Ratio (PDR) and energy consumption than the standard LoRaWAN solution in a mobile environment. The authors in [14] presented a new scheduling scheme for LoRaWAN that we believe will improve the network's performance. To do this, a Gateway is used to construct a temporal map of all transmissions from the Internet of Things devices, which may then be used to schedule messages and avoid clashes. The LoRaWAN protocol is well suited for transmitting data that only comprises a few small data packets, such as sensor reading data. The system achieves reliability while performing the monitoring task thanks to an adaptive mechanism that takes advantage of the advantages of both protocols and combines them. The system has been evaluated in the context of a real-world deployment situation. Based on the results, it can be concluded that the proposed approach provides high reliability in terms of average latency and the total number of sensors' data gathered [15]. Researchers in [16] have paid close attention to the usage of LoRaWAN for the industrial paradigm because it can automate a wide range of farming applications known as Smart Farming (SF). A system of sensors and actuators strategically placed throughout a farm to provide farmers with periodic farm information such as temperature, soil moisture, light intensity, and water usage, among other things. Clustering-based methods effectively reduce energy consumption in WSN. It is now possible to build massive and adaptable IoT applications because of significant advancements in Low Power Wide Area Network (LPWAN) technology over the last several years. Exceptional results from a long-term measuring effort in the Czech Republic, the focus of the research findings [17], are the most significant contribution. Climate change has contributed to the increasing importance of climate monitoring, which has become increasingly important. It is necessary to conduct continuous monitoring of environmental parameters to determine the value of the atmosphere. The IoT technology has brought a revolution to any aspect of human life, transforming it into something digital and insightful. It is a collection of things that form a network capable of self-configuring itself. Because the IoT is the most advanced technology available, it can collect data from the sensor system [18]. Class A and Class B LoRaWAN MAC Layers should be updated, according to the authors, to remedy this issue. Rather than waiting until after the uplink operation has finished sending the channel parameters, the time frame for receiving these parameters has been changed. Suppose you're a small or medium-sized city with fewer than 500 sensors. In that case, you should expect a 20 per cent reduction in the rejected packet rate and the PER with our modification compared to LoRaWAN, based on simulations in Matlab. Thus, network infrastructure expenses are lowered due to the reduction of network gateways [19]. An analytical model for LoRaWAN Class B mode transmission is presented in [20], which is based on the M/G/1 queueing model. The authors concentrate on the latency, data throughput, and energy consumption associated with downlink frame transmission. Analysis of the analytical model resulted in the development of a cost function that considers both the average waiting time of a frame in a gateway and the average power consumption of an end device.

3. Research Methodology

LoRaWAN is a widely used communication protocol typically considered an ideal choice for long-range, wide-area networks. LoRaWAN incorporates the Adaptive Data Rate (ADR) mechanism to maximise the network's utilisation of the fastest feasible data rate while maintaining network reliability. Each end node can configure any available data rates and transmission power. The network nodes are more often situated over a long distance. Detection of a suitable communication gateway is a crucial task in LoRaWAN, and several selection criteria are involved for this purpose. An ideal gateway must ensure instant communication without creating interference or unnecessary channel occupancy and provide good communication of data packets. There exist a variety of customizable parameters, such as Transmission Power (TP), Carrier Frequency (CF), Spreading Factor (SF), and Bandwidth (BW), that must be taken into consideration before selecting a suitable MAC technique. Some specified terminologies used in the proposed framework and their detailed elaboration are given in Table 1.

Table 1: Common Terminologies in the Proposed Framework

Term	Elaboration
UTX	Uplink Transmission
DRX	Downlink Received
DRX Win	Downlink Received Window

DRX delay	Downlink Received delay
CCA	Clear Channel Assessment
MAX Signal Interval	Maximum Signal Interval
MIN Signal Interval	Minimum Signal Interval
AVG Signal Interval	Average Signal Interval

A. ALOHA

Although no carrier sensing mechanism is involved in ALOHA; however, a specific process is still followed to avoid probabilistic interference and overconsumption of network resources in one particular communications stream. For an endnote to transmit an uplink packet towards the network server, it must follow a specific procedure. Whenever a message is generated, the end-node strives to send it out as fast as possible. Each time an uplink transmission is completed, the end-node opens two downlinks receive windows, referred to as DRX Win-I and DRX Win-II, respectively. After the end of the uplink broadcast, the downlink receive delay for an expected approximate value is specified for each DRX window following the end of the transmission. Whenever the duration of a receive window is greater than or equal to the amount of time required for the radio transceiver of an end-node to detect a downlink message, i.e., to identify the Preamble, the receive window is regarded to be in use. If a preamble is caught during one of the receive window periods, the receiver remains active until it demodulates the downlink message. Suppose an end-node receives a message that that node has appropriately demodulated while in the first receive window; the second receive window will be activated immediately. To begin any receive window, the network server can broadcast downlink messages to one or more end-nodes that have been predetermined. It is only in the aftermath of transmission that the end-node can promote a new message after setting DRX delay values if it has received a downlink message in either the first or second receive window. Other than in this scenario, the UTX packet will be transmitted when the double receive window of the previous transmission has elapsed.

Algorithm I: Workflow of ALOHA in LoRaWAN

```
START
Send UTX packet
Open DRX Win-I
Open DRX Win-II
    Analyze customizable parameters
    Set DRX delays
    Set DRX delay-I (+/-10)
    Set DRX delay-II (+/-10)
    Identify Preamble
If
    Preamble received in DRX Win-1
Then
    Sense DRX
If
    Preamble received in DRX Win-II
    Wait until DRX is modulated
    Session expired
Start new session
    SET DRX delays
If
    DRX received in Win-I/Win-II
    SET DRX delays
Else if
     DRX-II is expired
     Send UTX packet
End
```

The entire process is specified in Algorithm I, as well as explained in Figure 2:

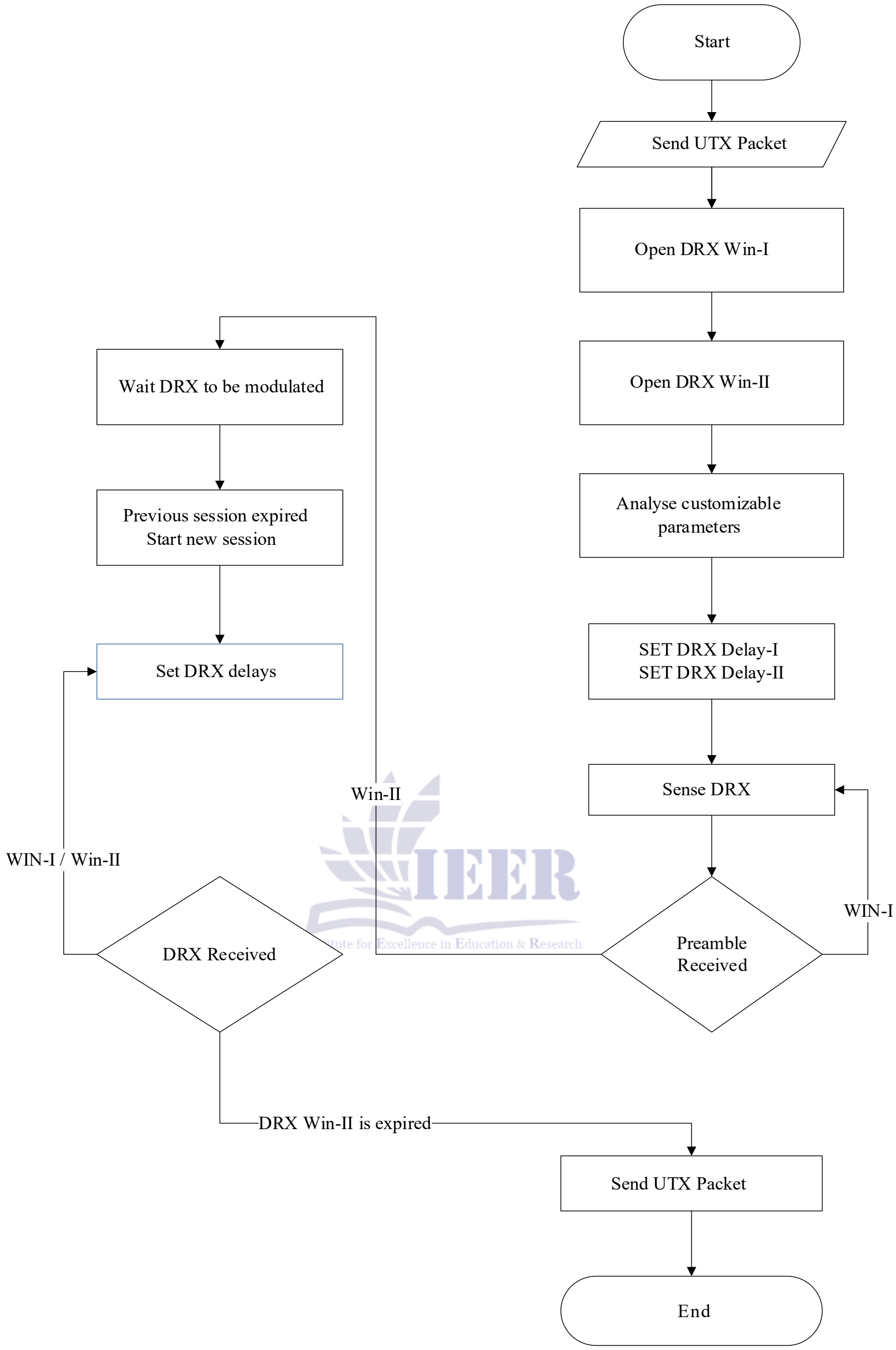

Figure 2: Workflow of ALOHA

B. LBT

The LBT is a polite spectrum analysis technique that encompasses an entirely converse mechanism and imposes that each device performs a Clear Channel Assessment (CCA) before transmitting a packet over the network. This mechanism helps a device check the availability of transmission channels to avoid communication interferences and collisions. At the start of a communication session, a CCA threshold is defined as a scale for feasible communication. As soon as the average signal level detected over the CCA listening interval is lower than the CCA threshold, the device starts transmitting the message. If this is not the case, the channel access, i.e., the message transmission, is delayed by a deferral interval to avoid mutual interference. A second possibility

ISSN (e) 3007-3138 (p) 3007-312X Volume 3, Issue 8, 2025

is that the device will switch to a different channel and restart the CCA before transmitting. The entire workflow is mentioned in Algorithm II, and is also depicted in Figure 3.

Algorithm II: Workflow of LBT in LoRaWAN

START
 Analyze customizable parameters
 Set CCA Threshold
 Set duration of CCA interval
 Perform CCA
 Count the MAX signal level in CCA interval
 Count MIN signal level in CCA interval
 Calculate AVG signal level in CCA interval
If
 AVG signal level in CCA interval < CCA Threshold
 Send UTX packet
If else
 Delay message transmission
 Sense some other channel
End

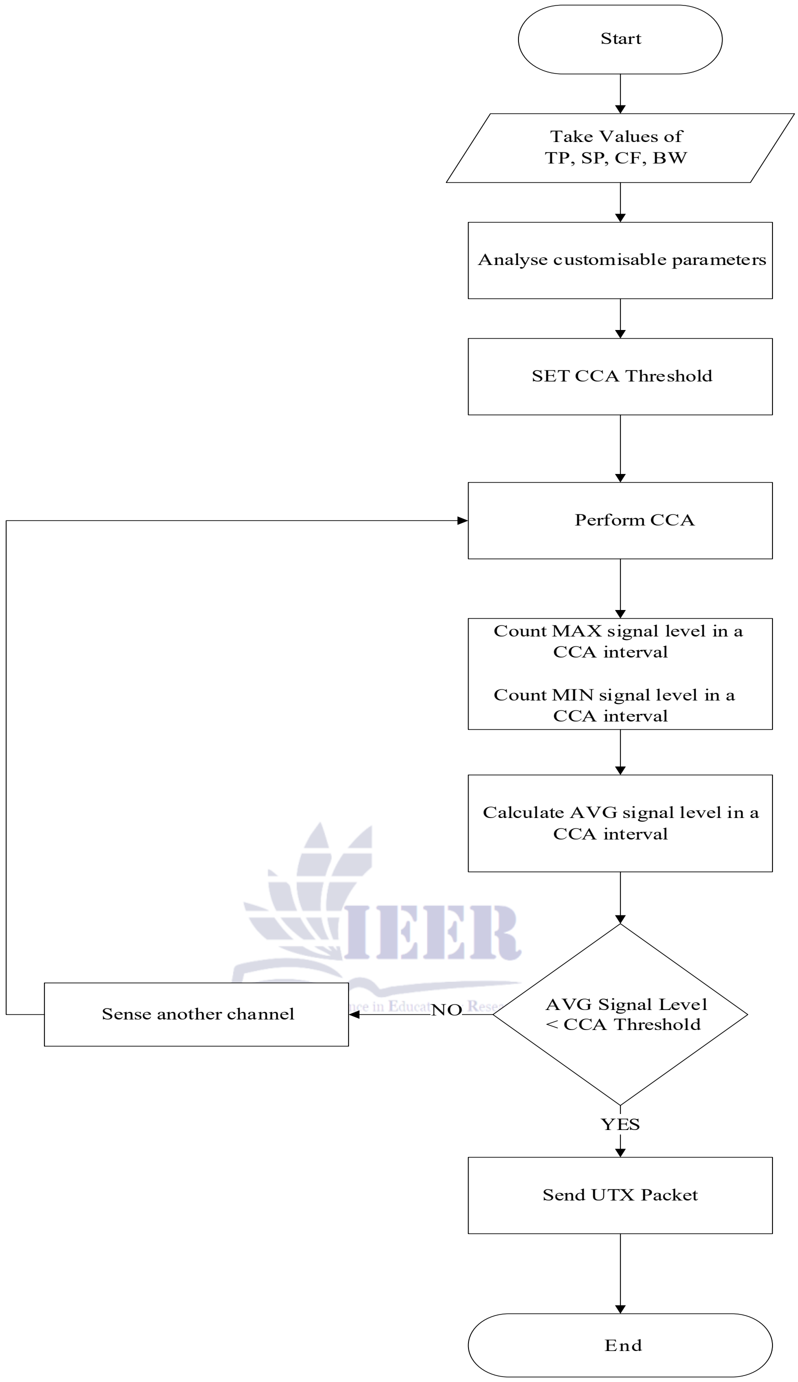

Figure 3: Workflow of LBT

C. Experimental Details

To evaluate the actual performance of LoRaWAN protocol under two famous medium access techniques, e.g. ALOHA and LBT, we have made a communication network of 100 nodes that are 500 X 500 area in a fixed star topology. All nodes are considered static, and both MAC schemes are tested on specific characteristics. We have acquired a frequency bandwidth of 125 kHz, where the application payload is defined as 20 bytes. The transmission power is 14dBm. Some specific parameters are taken into consideration for LBT, such as the minimum CCA interval is tuned for 160 microseconds. However, the CCA interval for overall transmission is adjusted to 220 microseconds. The maximum transmission gap is necessary to avoid communication conflict. When a specific sender node attempts to acquire a communication channel, the opening must be tuned to a reasonable threshold, which is 100 microseconds. All the simulations are performed in the OMNET++ simulator for a time duration of 3600s. OMNeT++ is a C++ simulation toolkit and framework primarily used to create network simulators. OMNeT++ includes an Eclipse-based integrated development environment, a graphical runtime environment, and several other features. Real-time simulation, network emulation, database integration, and other enhancements are available. All simulation parameters included in the experimental setup are listed in Table II.

Table II: EXPERIMENTAL SETUP

Parameters	Value
Communication Protocol	LoRaWAN
Communication standard	IEEE 802.15.4
MAC techniques used	ALOHA, LBT
Communication nodes	100
Simulator	OMNET++
Version	OMNET++ 5.6.2
Deployment area	500 X 500
Topology	Star
Topology structure	Static nodes
Frequency bandwidth	125 kHz
Application payload	20 bytes
CCA interval	220 ms
Transmission power	14dBm
Propagation Model	Lora Path Loss Oulu
Minimum CCA interval for LBT	160 ms
The minimum value of the deferral interval	CCA interval
Simulation duration	3600 Seconds

D. Performance Parameters

The performance of LoRaWAN is evaluated in a diverse range of performance parameters such as Packet Loss Ratio (PLR), End-to-End delay, Power Consumption, Convergence Time and Network lifetime. PLR can be calculated as the ratio of total packets delivered to complete packets sent from source to destination nodes in the network. Lack of completed network transmissions due to missing data packets is known as packet loss, and it can seriously impair real-time communications. Packet loss can be quickly evaluated from the command line using basic ping programs that can be found on the majority of computers. Packet loss ratio and frame loss rate are commonly used to express packet loss. It is the number of lost packets divided by the number of packages sent to get the packet loss ratio. Instead, the frame loss rate is the proportion of lost frames between the source and the destination. The term "end-to-end delay" refers to the time taken for a packet to transit from source to destination across a network. On the internet, packages must be fully received by a node, a router, before they can be routed to the next hop in the path toward their final destination. In other words, each router in the passage from source to destination affects the delay. A second is a standard unit of time for this measurement. Depending on the location of the communicating endpoints, the delay may vary slightly. The consumption of power is one of the most challenging criteria to meet when designing and implementing communicating sensor networks. The total power consumed during a communication session is calculated by aggregating the power taken by a node during sending, receiving, sleeping and receiving activities.

4. Results and Discussions

This section presents the performance analysis of LoRaWAN under diverse network settings. A comprehensive comparison is also conducted between the performance of ALOHA and LBT on a wide range of performance parameters. Firstly, both techniques are evaluated in terms of PLR, where it can be seen that when there were ten nodes in the network, the PLR was 7.65% for ALOHA and 7.29% for LBT. When we added ten more nodes in the network, the PLR was 11.4% for LBT; however, the ALOHA showed a slightly decreased PLR of approximately 10.23%. Similarly, in a network of 30 nodes, LBT shows a PLR of about 12.69% and ALOHA have delivered a PLR of 12.75%. The sequence goes on and on. The performance is further evaluated in a network of 40 nodes, where LBT seems to provide a PLR of about 14.3%. That PLR is comparatively low because the proposed ALOHA provides a PLR of 14.58%. The performance of both candidate technologies is evaluated in a network of 50 nodes, where LBT depicts a PLR of 15.4%. The ALOHA seems to beat LBT with the PLR of 16.75%. The performance comparison is visualised in Figure 4.

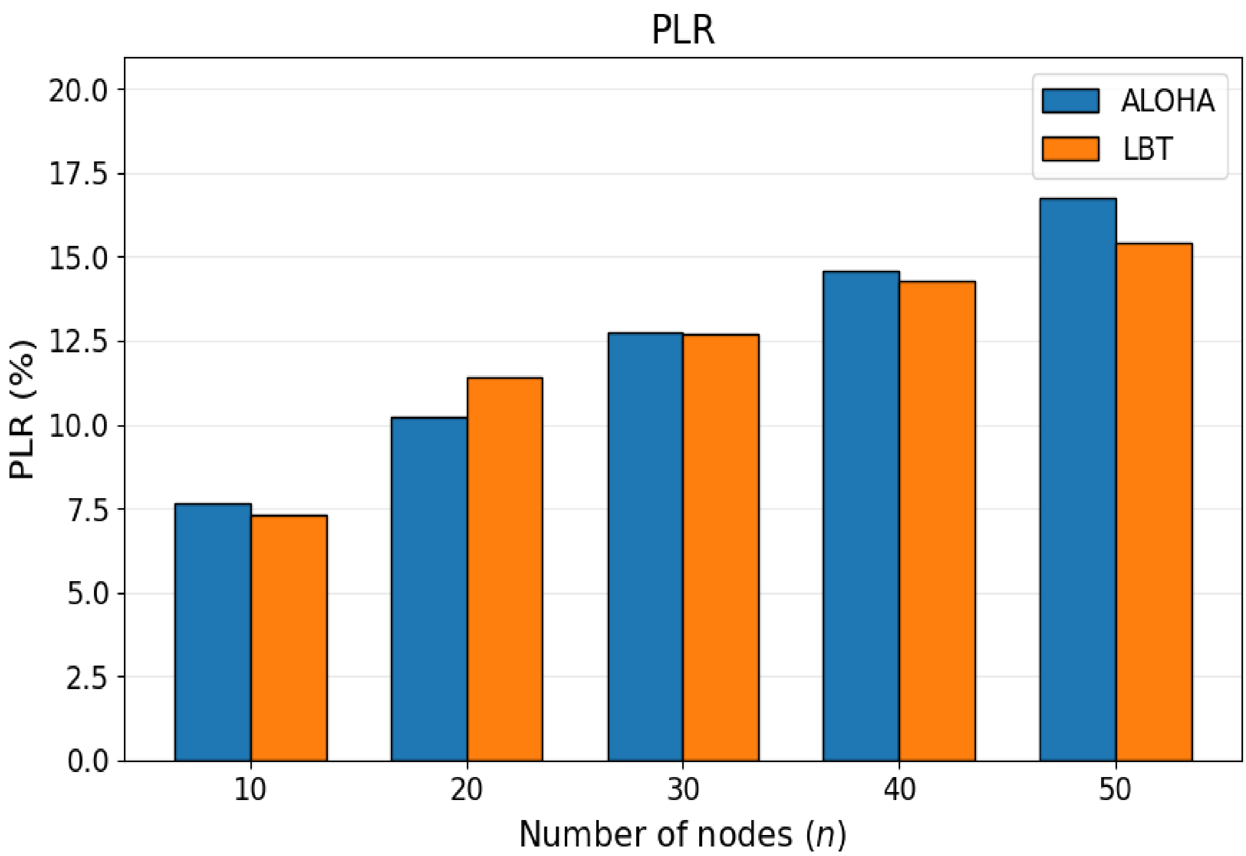

Figure 4: Performance comparison of ALOHA and LBT in terms of PLR (Nodes 1-50)

ALOHA and LBT were further evaluated in PLR when there were 60 nodes in the network; the PLR was 18.44% for ALOHA and 17.9% for LBT. When we added ten more nodes in the network, the PLR was 19.2% for LBT; however, the ALOHA shows a slightly increased PLR of approximately 19.31%. Similarly, in a network of 80 nodes, LBT shows a PLR of about 20.7% and ALOHA have delivered a PLR of 20.4%. The performance is further evaluated in a network of 90 nodes, where LBT seems to provide a PLR of about 23.9%. That PLR is comparatively low because the ALOHA provides a PLR of 22.6%. The performance of both candidate technologies is evaluated in a network of 100 nodes, where LBT depicts a PLR of 24.9%. The ALOHA seems to be beaten by LBT with the PLR of 23.8%, as shown in Figure 5.

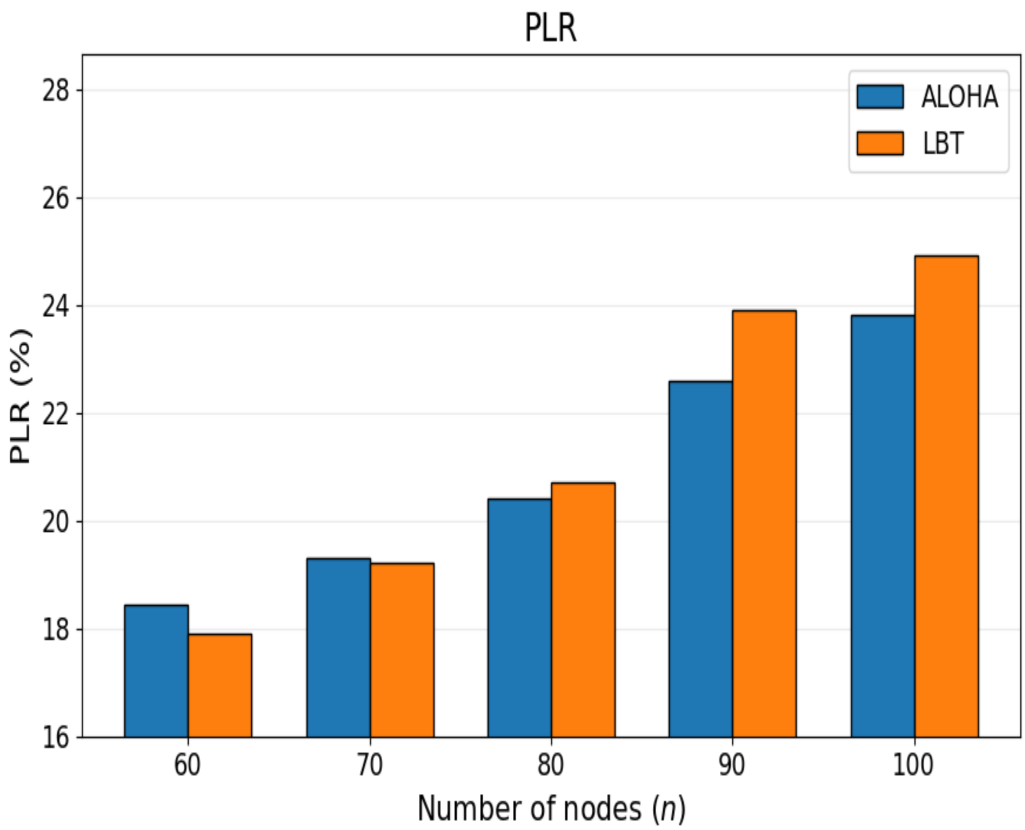

Figure 5: Performance comparison of ALOHA and LBT in terms of PLR (Nodes 51-100)

The performance of ALOHA and LBT is evaluated in terms of End-to-End delay. It can be seen that when there were ten nodes in the network, the wait was 6.5ms for ALOHA and 6.9ms for LBT. When we added ten more nodes in the network, the delay was 12.7ms for LBT; however, the ALOHA shows a slightly higher duration of approximately 12.8ms. Similarly, in a network of 30 nodes, LBT offers an end-to-end delay of 19.5ms, but that delay was noticed as 19.9ms in the case of ALOHA. The sequence goes on and on. The performance is further evaluated in a network of 40 nodes, where LBT seems to provide an end-to-end delay of about 24.3ms. That delay is comparatively low because the ALOHA have shown a delay of 26.7ms. The performance of both candidate technologies is evaluated in a network of 50 nodes, where LBT depicts an end-to-end delay of 34.2ms. The ALOHA seems to beat LBT with the postponement of 38.4ms, as shown in Fig.6:

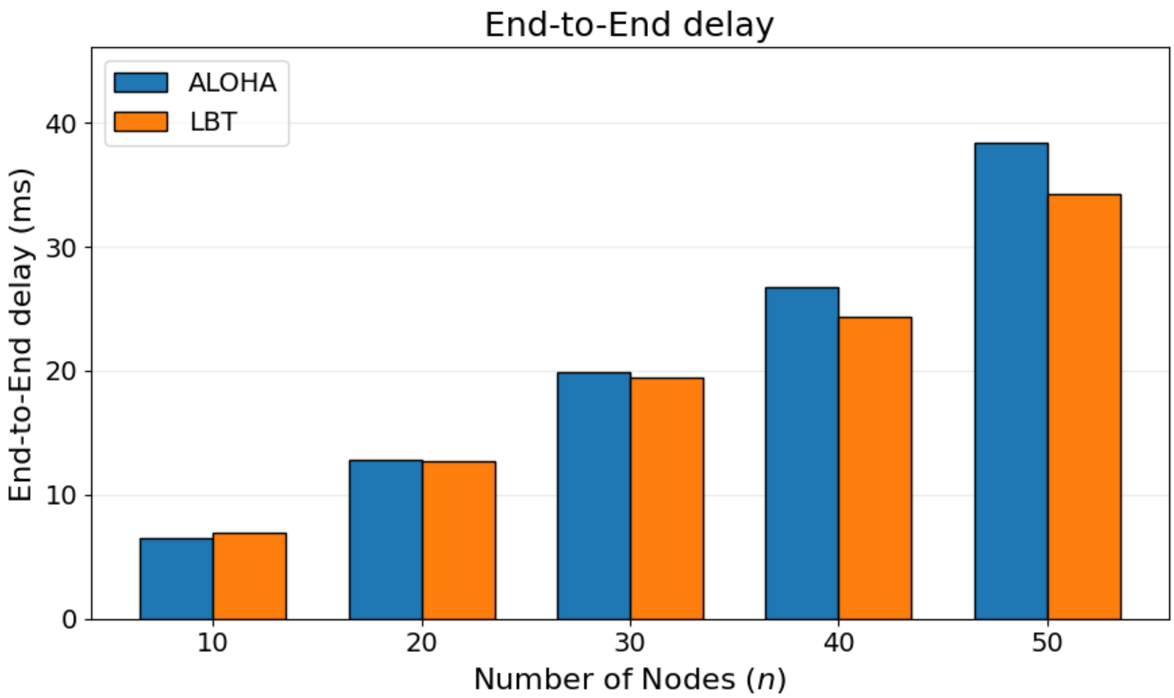

Figure 6: Performance comparison of ALOHA and LBT in terms of End-to-End delay (Nodes 1-50)

To get deep insight into the actual performance of both technologies, the network size is increased to 60 nodes, where LBT have acquired an end-to-end delay of 41.4ms. However, the ALOHA again seems to outclass the previous technology with an end-to-end delay of 40.3ms. In a network of 70 nodes, the end-to-end delay was 47.4ms and 42.2ms in the case of LBT and ALOHA. The same performance pattern can be seen when there were 80 nodes in the network. The delay was 49.3ms for LBT and 45.8ms for ALOHA. The same sort of results seem to have appeared in a network of 90 nodes, in which the delay was 51.6ms and 49.7ms in the case of LBT and ALOHA. Furthermore, finally, in a network comprising 100 nodes, the end-to-end delay was 54.4ms for LBT. However, the proposed ALOHA have shown significantly best result with a delay duration of about 53.4ms. The detailed performance comparison is given in Figure 7.

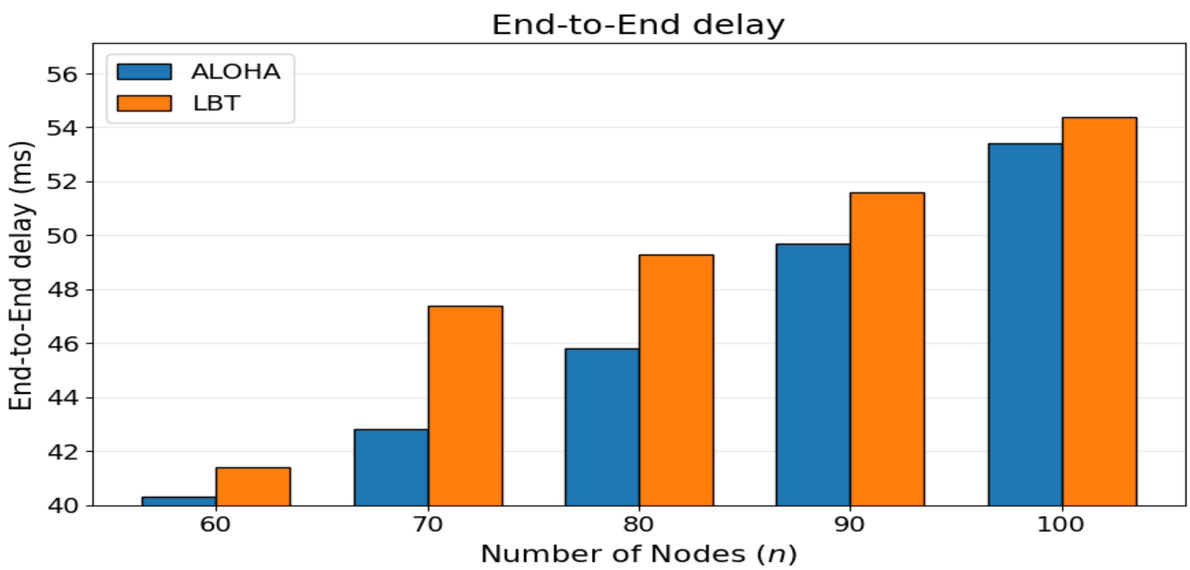

Figure 7: Performance comparison of ALOHA and LBT in terms of End-to-End delay (Nodes 51-100)

The performance of ALOHA and LBT is also evaluated in terms of power consumption. It can be seen that when there were ten nodes in the network, the system consumed 0.29mW for ALOHA and 0.26mW for LBT. When we added ten more nodes in the network, the power consumption was 0.35mW for LBT; however, ALOHA shows a slight increase in power consumption, making it approximately 0.39mW. Similarly, in a network of 30 nodes, LBT consumed power of about 0.44mW, and ALOHA consumed power of 0.48mW. The sequence goes on and on. The performance is further evaluated in a network of 40 nodes, where LBT seems to destroy the power of 0.74mW, which is comparatively high because the ALOHA consumes only 0.67mW of power. The performance of both candidate technologies is evaluated in a network of 50 nodes, where LBT depicts a power consumption of 1.01mW. The comparison is depicted in Figure 8.

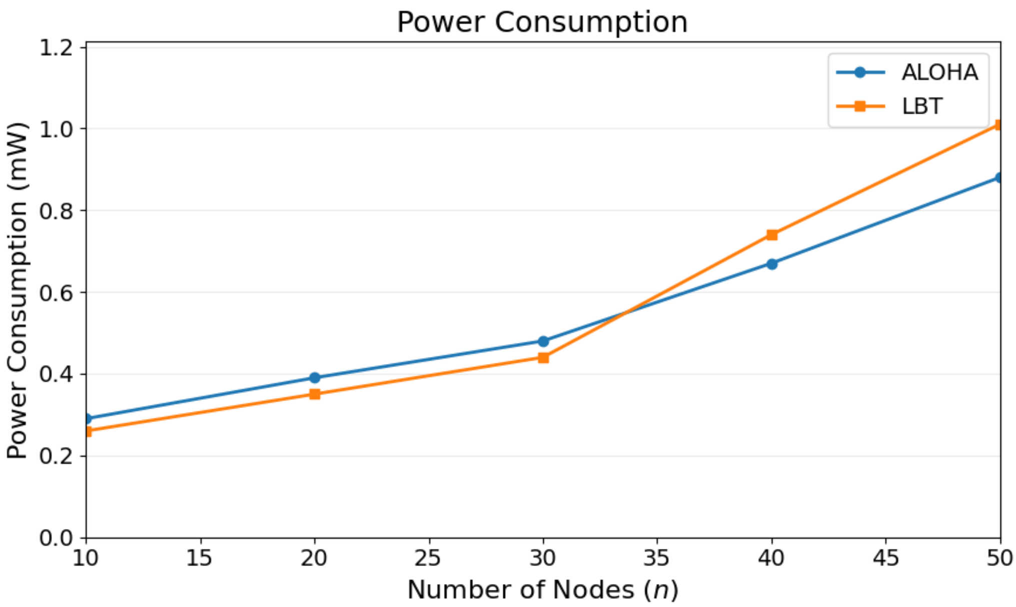

Figure 8: Performance comparison of ALOHA and LBT in terms of Power Consumption (Nodes 1-50)

The ALOHA seems to beat LBT with the reduced power consumption of about 0.88mW. ALOHA and LBT are further evaluated in power consumption when there were 60 nodes in the network; the power utilization was 1.09mW for ALOHA and 1.13mW for LBT. When we added ten more nodes in the network, the power consumption became 1.35mW for LBT, and ALOHA showed a slightly decreased power consumption of approximately 1.29mW. Similarly, in a network of 80 nodes, LBT consumed power of 1.44mW and proposed ALOHA consumed power of 1.33mW. The sequence goes further, and the performance is further evaluated in a network of 90 nodes where LBT seems to destroy the power of about 1.74mW, which is comparatively high as ALOHA consumes power of about 1.63mW. The performance of both candidate technologies is evaluated in a network of 100 nodes, where LBT is utilizing 1.98mW of power, whereas ALOHA seems to outclass LBT with the reduced power consumption of about 1.79mW. The comparison of both techniques in terms of power consumption is given in Figure 9.

ISSN (e) 3007-3138 (p) 3007-312X
Volume 3, Issue 8, 2025

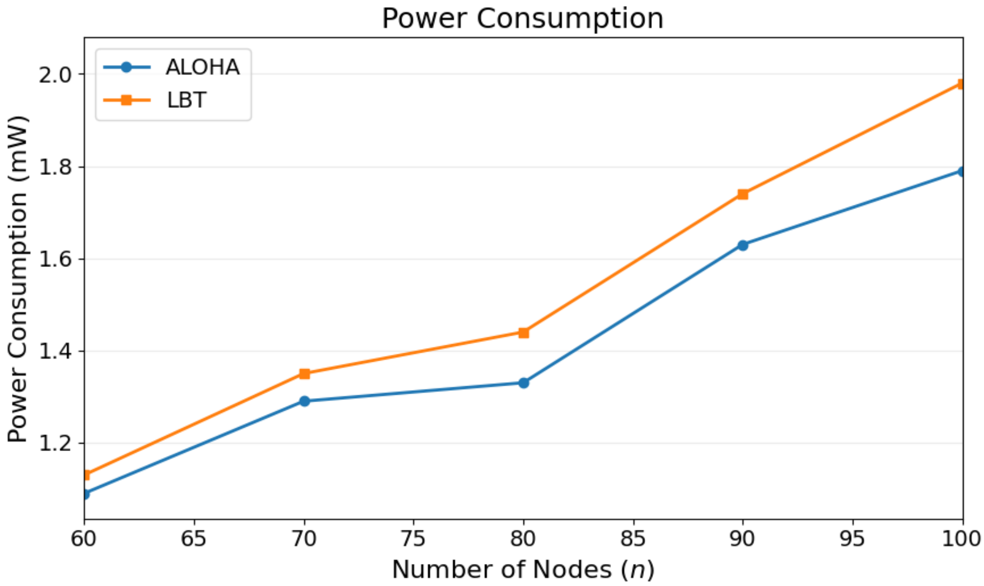

Figure 9: Performance comparison of ALOHA and LBT in terms of Power Consumption (Nodes 51-100)

The performance comparison is also summarised in Table III.

Table III: COMPREHENSIVE PERFORMANCE COMPARISON BETWEEN ALOHA AND LBT

Number of Nodes	PLR		End-to-End delay (ms)		Power Consumption (mW)	
	ALOHA	LBT	ALOHA	LBT	ALOHA	LBT
10	7.65	7.29	6.5	6.9	0.29	0.26
20	10.23	11.4	12.8	12.7	0.39	0.35
30	12.75	12.69	19.9	19.5	0.48	0.44
40	14.58	14.3	26.7	24.3	0.67	0.74
50	16.75	15.4	38.4	34.2	0.88	1.01
60	18.44	17.9	40.3	41.4	1.09	1.13
70	19.31	19.2	42.8	47.4	1.29	1.35
80	20.4	20.7	45.8	49.3	1.33	1.44
90	22.6	23.9	49.7	51.6	1.63	1.74
100	23.8	24.9	53.4	54.4	1.79	1.98

5. Current Applications and Future Prospects

A. Current Applications

LoRaWAN has rapidly become a foundational technology for enabling long-range, low-power wireless communication in the Internet of Things (IoT) ecosystem. Designed to support scalable deployments across thousands of devices, LoRaWAN offers reliable data transmission over several kilometres while consuming minimal energy [21]. Its ability to function in energy-constrained environments makes it an ideal solution for a wide variety of smart and connected applications. In today's interconnected world, LoRaWAN plays a crucial role across multiple domains, such as smart homes, smart cities [22], smart industry, smart transportation, smart agriculture, and smart healthcare [23]. In smart homes, LoRaWAN facilitates energy-efficient home automation systems, including smart thermostats, leak detectors, smoke alarms, and lighting controls — all communicating seamlessly with minimal power usage. In smart cities, it enables intelligent infrastructure such as smart street lighting, waste management, air quality monitoring, and traffic flow optimization, improving overall urban efficiency and sustainability.

Smart industry applications include predictive maintenance, environmental condition monitoring, and asset tracking within manufacturing plants and warehouses. LoRaWAN's low power consumption and extended range make it particularly well-suited for industrial environments where traditional wireless communication may be challenging. Smart transportation systems benefit from LoRaWAN through real-time vehicle tracking, fleet management, and traffic signal coordination, enhancing both safety and mobility. In smart agriculture, LoRaWAN-enabled devices support precision farming through real-time monitoring of soil moisture, crop health, livestock movement, and weather conditions. This data-driven approach helps optimize resource usage, increase yields, and reduce environmental impact. In smart healthcare, LoRaWAN supports wearable devices for remote patient monitoring, emergency alert systems, and medication tracking, especially in rural or underserved areas where cellular connectivity may be limited.

One of the most practical advantages of LoRaWAN lies in its capacity to support large-scale communication across widely dispersed networks, a requirement that traditionally demands high energy consumption. LoRaWAN addresses this challenge through its adaptive data rate feature and energy-efficient communication mechanisms that balance performance and power use. The protocol's two standard Medium Access Control (MAC) classes — Class A (ultra-low power asynchronous communication) and Class C (continuous listening for real-time responsiveness) — provide the flexibility needed to tailor performance for diverse applications. As smart infrastructure becomes an essential part of modern life, LoRaWAN continues to gain momentum as a robust, scalable, and cost-effective communication protocol that bridges the gap between long-range connectivity and energy efficiency across multiple sectors [24].

B. Future Prospects

As the IoT continues to expand globally, the prospects of LoRaWAN are exceptionally promising. With its proven ability to support long-range, low-power, and low-cost communication, LoRaWAN is well-positioned to become a foundational enabler of next-generation smart ecosystems. One of the most significant future trends is the integration of LoRaWAN with other emerging technologies such as 5G, satellite communication, edge computing, and Artificial Intelligence (AI) [9]. Hybrid connectivity models will allow LoRaWAN to complement high-speed 5G networks by providing energy-efficient communication in scenarios where latency is less critical but coverage and battery life are essential—such as rural monitoring, maritime tracking, or remote disaster zones. Another critical development is the expansion of LoRaWAN roaming capabilities. As standardized roaming becomes more widely supported, devices will be able to seamlessly move across networks managed by different operators, making global IoT deployments more scalable and cost-effective. This is particularly relevant for logistics, smart transportation, and supply chain management [25].

LoRaWAN is also expected to play a pivotal role in sustainable development and environmental monitoring. Applications such as carbon footprint tracking, smart energy metering, and water resource management will benefit from its low-power design and wide area coverage, helping governments and industries meet global sustainability goals. Security and trust are also gaining attention in future LoRaWAN deployments. Research into blockchain-enabled LoRaWAN architectures and privacy-preserving communication protocols is advancing, ensuring secure data exchange across open networks. With growing investments, evolving standards, and strong industrial support from organisations like the LoRa Alliance, LoRaWAN is poised to remain a key player in the IoT communication landscape [26].

6. Conclusion

This Research provided an overview of the LoRaWAN protocol that is known as an ideal choice for long-range communication networks. Smart cities, large-scale industrial sectors, and extensive agriculture systems are some key application areas of LoRaWAN. This protocol has to adopt a media access control technology to perform its operation. ALOHA and LBT are two possible MAC technologies that LoRaWAN have to choose from. We have investigated the performance of both MAC techniques in incorporation with LoRaWAN under various performance parameters such as Packet Loss Ratio, End-to-End delay, and power consumption. We have constructed a network of 100 nodes, performing simulations in the OMNET++ simulator. It is observed that ALOHA does not involve any carrier sense mechanism, and it is more energy-efficient. However, it is susceptible to high communication overhead. This may cause higher communication breakdown. On the other hand, LBT involves a proper channel access mechanism, and it is more efficient towards the stable delivery of communication packets. End-to-End delay is another essential performance parameter. The ALOHA does not involve any carrier sense mechanism, so the sender nodes may directly transmit a data packet over a particular transmission channel. It can create higher possibilities over communication overhead that may result in collisions or traffic loss. So here, LBT takes advantage to ensure reliable communication. In terms of power consumption, ALOHA is more energy-efficient due to the absence of carrier sensing, reducing the time spent in receive mode. In contrast, LBT consumes more energy per transmission because of its continuous channel sensing, but this trade-off improves overall reliability in dense network conditions. Moreover, this study provides a detailed examination of LoRaWAN's current applications across diverse domains, including smart cities, industrial automation, environmental monitoring, and precision agriculture. Furthermore, it anticipates the strategic advancement of LoRaWAN as a key enabler of scalable, low-power communication in next-generation IoT architectures and intelligent communications.

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