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Bluetooth Mesh Networks: Evaluation of Managed Flooding in Different Environments

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Abstract

Bluetooth Mesh networks have gained popularity across various industries, showcasing their significant impact on network solutions. This technology is particularly notable for its low power consumption, making it a preferred choice for efficient and sustainable network development.

The objective of this study investigates the behavior of Bluetooth Mesh networks in various environments, aiming to improve network performance and provide guidance for optimal network design. This was achieved by performing experiments in multiple environments.

Data collection and regression analysis along with comparative visualization were employed to understand the relationship between these variables, including distance, number of packets sent, environment, latency, and packet loss ratio.

The results showed a significant relationship between distance and latency in the office and forest environments, as well as between distance and packet loss ratio in all environments. The number of packets sent has impact on latency and packet loss ratio.

The findings contribute to the development of more reliable and efficient communication systems for Internet of Things applications, as well as providing insights into the performance characteristics of the Bluetooth Mesh network in various scenarios.

Key words: *Bluetooth, Bluetooth Low Energy (BLE), mesh networks, managed flooding.*

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1 Introduction

The emergence of the Bluetooth Mesh (BT Mesh) networking protocol has opened up new possibilities for large-scale wireless communication, particularly in the fields of smart homes, building automation, and industrial Internet of Things (IoT) (Kotha & Gupta, 2018). IoT refers to the connection of physical objects and devices to the Internet, allowing them to exchange data and perform actions without or with human intervention. However, the performance and scalability of BT Mesh networks can be impacted by a variety of factors, including network topology, distance between nodes, protocol parameters, and environmental interferences (Rondón et al., 2019).

In this article, cooperating with Husqvarna Group AB we focus on investigating the behavior of BT Mesh networks under various conditions, with the aim of improving network performance, optimizing network design, and providing guidance for the deployment of effective BT Mesh networks. Our findings aim to contribute to the development of more reliable and efficient communication systems for the growing field of IoT.

1.1 Background

Bluetooth is a wireless communication technology that allows devices to connect and communicate with each other over short distances, typically up to 10 meters. It was developed in the 1990s by an association of companies led by Ericsson.

Originally, Bluetooth was designed as a replacement for the cables that were commonly used to connect mobile phones and other devices to computers and other peripherals. The first Bluetooth specification, version 1.0, was released in 1999 and provided a maximum data rate of 1 Mbps. Subsequent versions of the specification, including Bluetooth 2.0, 3.0, 4.0, 4.1, 4.2, and 5.0, have increased the maximum data rate, improved security, and added new features and capabilities.

The significant increase of adopting this technology, where the amount of data transmission has increased, led to the increase of power consumption. Before Bluetooth 4.0, which is the first released version of Bluetooth Low Energy (BLE), batteries were not capable enough to handle this kind of power consumption. Consequently, the BLE was developed and introduced with the main improvement to decrease the power consumption (Gomez et al., 2012).

As a result of this improvement, BLE became a widely used technology in IoT applications where devices connected via BLE exchange data that can be sent over the Internet through a gateway. IoT has numerous applications in various industries, including:

- Smart homes: IoT devices can control various appliances and devices, such as lighting, thermostats, security systems, and home entertainment systems

- Industrial automation: IoT devices can be used in manufacturing and industrial settings to improve efficiency and productivity by monitoring equipment and optimizing workflows
- Healthcare: IoT devices can monitor patient vital signs and transmit the data to healthcare providers, improving patient outcomes and enabling remote patient monitoring
- Smart cities: IoT devices can be used to manage traffic flow, monitor air quality, and provide public safety services

In the context of IoT, there are devices such as sensors that transmit data, devices that receive commands, and a gateway that facilitates data exchange with Internet, as illustrated in figure 1 below.

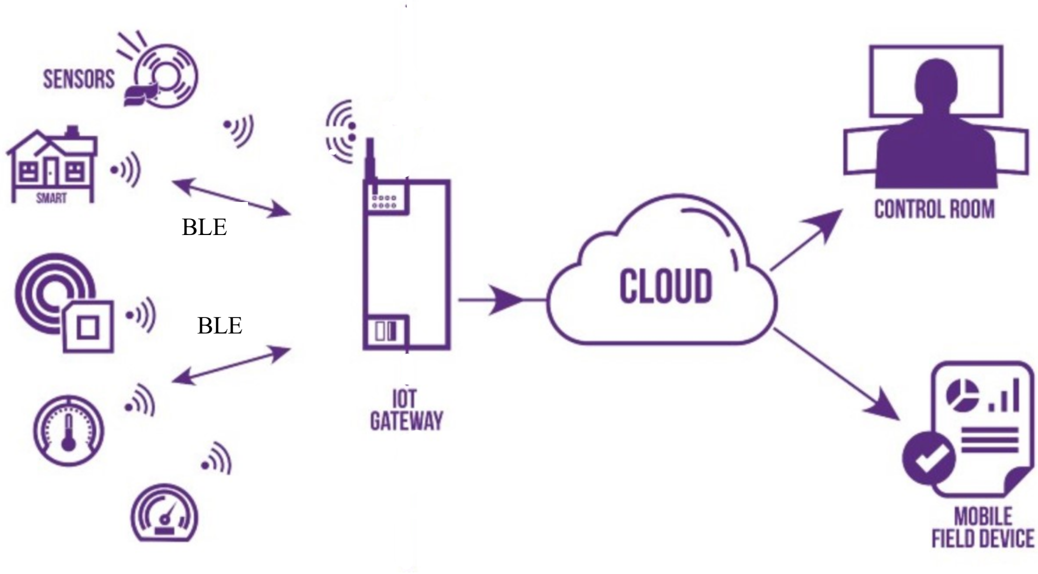

Figure 1. Illustrates data exchange between IoT devices and IoT gateway that can forward the data to the Cloud (Neeson, 2022).

In the case of big projects like industrial monitoring, a network is essential for transferring data to and from the gateway. Such networks have been built using different technologies, such as ZigBee, Z-Wave, 6LoWPAN, and Wi-Fi but these have many limitations (Natgunanathan et al., 2023), as listed below, when it comes to IoT-based systems:

- Wi-Fi cannot be utilized in battery-powered systems due to its relatively high-power consumption
- Zigbee is not well-suited for larger IoT-based systems or networks, and its connectivity is limited to short ranges
- Z-Wave is unsuitable for IoT applications that demand high reliability because of its potential for a single point of failure
- LoRaWAN and Sigfox employ star topology and they are susceptible to single-point failures

According to Natgunanathan et al. (2023), modern industries require reliable, scalable, secure, low-cost, and low-powered wireless technologies to function efficiently, BT Mesh networks fulfill all these requirements, making them the superior choice compared to other options. Natgunanathan et al. (2023) emphasize that BT Mesh communication capabilities make it ideal for creating large device networks.

BT Mesh network is a type of wireless protocol based on the BLE stack of Bluetooth 4.2, introduced in 2017. BT Mesh allows devices to form a mesh network to exchange data and information with each other. Unlike traditional point-to-point Bluetooth connections, where devices connect directly to each other, a BT Mesh network supports many-to-many communications, that allows devices to connect to each other through multiple intermediary devices, forming a "mesh" of nodes.

This creates extended coverage with great robustness while being a cost-effective and power-efficient network where data can be transmitted across long distances, even when some devices are out of range of others. The mesh network can support many devices, making it a popular choice for IoT applications where many devices need to communicate with each other. Bluetooth mesh networks are often used in Smart Buildings, Smart Lighting, Monitoring, Disaster Communication, Smart Factory and Smart Parking (Natgunanathan et al., 2023).

To fulfill the market's requirements for implementing such mesh communications, Bluetooth SIG and the Internet Engineering Task Force (IETF) developed two distinct technologies based on Bluetooth Mesh - BT Mesh and 6BLEMesh (Darroudi et al., 2020) and each of which uses different mechanisms for different use cases as following:

- 6BLEMesh uses a routing mechanism designed to find the most efficient path between the source and the destination node for a given packet, based on various factors such as the distance, signal strength, and network topology. This mechanism approaches ideal packet delivery probability and achieves high reliability as a trade-off for increased latency (Darroudi et al., 2020).
- BT Mesh uses a flooding mechanism which involves broadcasting a packet to all nodes in the network, without any consideration for the network topology or the destination of the packet. This mechanism is better suited for scenarios where low latency is critical, such as real-time data transfer (Darroudi et al., 2020). In addition, this mechanism relies on relaying messages using rely nodes where each node receives a message and broadcasted to other nodes until the message is received on the destination node.

There are different kinds of messages that can be sent in the BT Mesh network. One message can be sent to a specific node, and it is important that that every node receives it. In other cases, a message can be broadcasted, and multiple different nodes are expected to receive it.

However, the effectiveness and reliability of wireless networks may vary depending on the specific conditions in which it is used and there are some factors to consider regarding the impact of the environment on a BT Mesh network. For example, the range of a BT Mesh network can be affected by physical obstacles such as trees, walls, floors, and other objects that can reduce or block the Bluetooth signals. The range of individual devices and the overall coverage of the network can be limited to environments with dense walls or obstacles, reducing the effectiveness of the mesh network. Another fact that can affect the performance of the BT Mesh network is the interference caused by the noise generated by any other radio waves in the environment.

1.2 Problem Statement

The utilization of BT Mesh networks might involve the presence of electric motors in industrial environments, as well as the potential obstacles posed by concrete walls and trees. These factors can introduce interference, potentially causing issues for BT Mesh networks used in such settings. The interference caused by the electric motors, trees and concrete walls can lead to impacts, including decreased range, increased packet loss ratio (PLR), and increased latency.

To achieve optimal performance when designing a BT Mesh network in forests or industrial environment, such as a manufacturing line, or between different manufacturing separated by walls, several parameters must be defined. These parameters include the nodes positioning and distance between nodes. The impact of such environmental interferences on mesh communication has not been fully studied, therefore more experiments are required to study the impact of it with different environments and nodes distribution in the BT Mesh network.

1.3 Purpose and Research Questions

The purpose of this research study is to investigate the impact of varied environmental interferences, including normal office environments, forests, and environments with electric motors, on the PLR and latency changes in BT Mesh networks. The study aims to provide valuable design guidance and considerations for the effective deployment of BT mesh networks.

Based on that, the following research questions were answered to fulfill the purpose of this work:

1. How is the PLR affected depending on varied environmental interferences, namely normal office environment, forest, and environments where electric motors are being used?
2. How is the latency change affected on varied environmental interferences, namely normal office environment, forest, and environments where electric motors are being used?

That will be helpful for network designers to determine in which industries the BT mesh network is applicable.

1.4 Scope and Limitations

The scope of the study is focused on investigating the impact of environmental interferences, such as electric motors, trees, and concrete walls, on the reliability in terms of PLR and latency. The Study also focuses only on sending messages from a source node to one destination, which is the last node in a sequence of nodes. However, the message is relayed by two nodes placed between the source and destination node.

The limitation of the study is that it is limited to three different environments, constant Time to Live (TTL), three connected nodes, nodes positioning variations (nodes are positioned sequentially). Another limitation is that the study does not involve group messaging where a message is sent to multiple destinations.

1.5 Disposition

The remainder of this paper is organized as follows. The methods used to collect and analyse data are introduced in Chapter 2. Chapter 3 contains previous studies and theories that this study is based on. The experiments setup, environment description, data collection presentation, and data analysis are presented in Chapter 4. Results discussion based on the theoretical framework and method discussion are presented in Chapter 5. Finally, Chapter 6 presents the conclusions from the study and suggestions for further research.

2 Method and implementation

This chapter explains the methods used to collect data for evaluating the reliability, in terms of PLR and latency, of a BT Mesh network. Two types of measurements, namely latency and PLR, were performed in different experiments with varying numbers of packets sent, distances between the nodes and the experiment environment. The data collected was analyzed using regression analysis and results comparison depending on the experiment environment.

The aim was to identify the factors that contribute to the network's reliability and provide insights into optimizing its performance.

2.1 Setup and configuration of the BT mesh network

STMicroelectronics provides an evaluation kit with software that is suitable to perform the experiments. In addition, Husqvarna Group AB provided their electric chainsaws which were used in the experiments.

2.1.1 STEVAL-IDB008V2 with BlueNRG-2 Kit

The evaluation board that was used to fulfill the purpose of this study and to obtain experimental results was STEVAL-IDB008V2, shown in figure 2 below, provided by

STMicroelectronics. Three of these boards were used for this study, and in this sense, they are called nodes.

STEVAL-IDB008V2 is built with the BlueNRG-2, a low-power Bluetooth smart system-on-chip. It has 256 KB Flash, 24 KB RAM, and follows the Bluetooth SMART v5.0 specification. This board supports various roles such as master, slave, and simultaneous master-and-slave. It also behaves as a relay node in the BT Mesh network.

Figure 2. Shows the STEVAL-IDB008V2 with BlueNRG-2

Table 1 below, shows the evaluation board details:

Devices	Evaluation boards	Powered by	Programmed by	LEDs	Buttons
BlueNRG-2	STEVAL-IDB008V1 and STEVAL-IDB008V2	Micro-B USB Cable Or AAA x 2 battery	External ST-LINK/V2 or USB port	3x user LEDs +1 power indication	Reset button + 2 x user buttons

Table 1. Evaluation board details.

2.1.2 ST BLE Mesh (the software)

In addition, STMicroelectronics offers an excellent software solution available as an iOS and Android mobile applications that feature plenty of useful functionalities, including advertising packets that is used for data communication using managed flooding and this is the main reason for choosing this development kit with the software for this study since it is focused on managed flooding mechanism. Another reason is the availability of a Software Development Kit (SDK) for the mobile applications. However, the Android mobile application was used.

As mentioned in (STMicroelectronics, n.d.), the mobile application works with STEVAL-IDB008V2 boards that are built with BlueNRG-2. These boards have LCD lights that can be toggled ON or OFF by a command sent from the mobile application and that is all over the BT mesh network.

Using the Android mobile application and the boards, we could set up a BT mesh network that satisfied the needs of evaluating the performance based on our experiments.

But some modifications have been applied to the software to adapt it to the experiments since no software was found to measure the PLR and latency.

2.1.3 Equipment provided by Husqvarna Group AB

- Husqvarna 540i XP which is the type of electric motor that was used under the industrial experiments in the fabric. The battery type is lithium-ion (Li-Ion). Two of these motors were used.
- Hörselskydd X-COM R, Bluetooth. These are hearing protection headsets that were used under the experiments with the electric motors.

2.2 Environment Descriptions

Experiments, in forest environment, were performed deeply in the forest of Hövslet on a sunny day with BT Mesh nodes were hung up to the trees in average height of 1,5 meters from the ground. When performing the experiment with 25 meters distance between nodes, the destination node was about 6 meter higher than the other nodes due to the topography of the Hövslet forest.

Experiments, in industrial environment, were performed outside in rainy weather and all nodes were placed into plastic bags. The destination node, which is the third, was tight to an electric motor using plastic tape as well as the first node while the second node was placed on the ground. One every motor driver was putting on the headset.

Experiments were performed where the nodes are placed above each other where there is a ceiling, that is a concrete wall, between them. The thickness of the concrete walls is 20 cm. The nodes were placed on wooden chairs.

Also, experiments were performed in a normal office environment where the nodes were placed on wooden chairs in a long corridor.

2.3 Data collection

The measurements of Latency and PLR were performed in different experiments, with varying environment and numbers of packets sent. By performing experiments, we can verify the feasibility and effectiveness of BT Mesh technology in practical scenarios. It helps validate the concepts and theories proposed in the research. Experiments also allow us to measure the performance of BT Mesh networks, such as network latency and PLR. Through experimentation, we can analyze the behavior of BT Mesh in different configurations and scenarios.

All experiments were repeated at least at four different distances between nodes.

- Latency Measurement: The latency measurement was performed using Rounded Trip Time (RTT). An ON/OFF message with 2-byte payload was sent from a smartphone to a specific node/destination, and the response from that node was received in the smartphone. The time taken for the message to travel from the smartphone to the node and back to the smartphone was recorded as the RTT.

- PLR Measurement: The PLR measurement was achieved by sending a total of 80 packets, 8 packets each time that is repeated 10 times from the smartphone to a specific node/destination and checking the number of received packets on the destination node's side. The number of lost packets was recorded and used to calculate the PLR percentage.
- The measurements of latency, PLR, were performed at four different distances between the relay nodes, that is 5, 10, 20 and 25 meters. The reason why choosing these distances is because when the distance between one node and another is 5 or 10 meters a message does not need to be relayed since all nodes are in the range of receiving a message from the source node (two nodes can communicate with each other directly). But, when the distance is 20 meters, the message is at least relayed once and for 25 meters the message is relayed twice. Therefore, the experiment is divided in 4 groups where 3 relay nodes are used as following:
    - Group 1: in industrial environment where two electric motors (with output power = 1800W) placed next to each node.
    - Group 2: nodes are placed in the forest environment.
    - Group 3: in a normal office environment.
    - Group 4: the three nodes are placed between concrete walls.

Figure 3 below, shows a scenario of lighting the node 3 light and how the latency is calculated. The scenario is described here:

In the application, each toggle button is related to each node. By toggling these buttons, an ON/OFF message with 2-byte payload is broadcasted to turn a light either on or off. When a message is sent, the sending time is stored in milliseconds in a variable.

Each node that advertises its presence receives the broadcasted message and broadcasts it to other nodes in the BT Mesh network. When the message is broadcasted from each node, the TTL value decreases by one preventing the message from circulating in the BT Mesh network when the TTL value is zero.

When the destination node, node 3 as shown in figure 3 below, receives the message, the light turns ON/OFF and it sends back a response through the BT Mesh network where the response is also a message that is broadcasted back to the source node, which is the mobile application shown in figure 3 below.

When the mobile application receives the response from the destination node, the receiving time is also stored in a variable. To measure the latency and to record it, the sending time is subtracted from the receiving time, and that is printed out on a terminal.

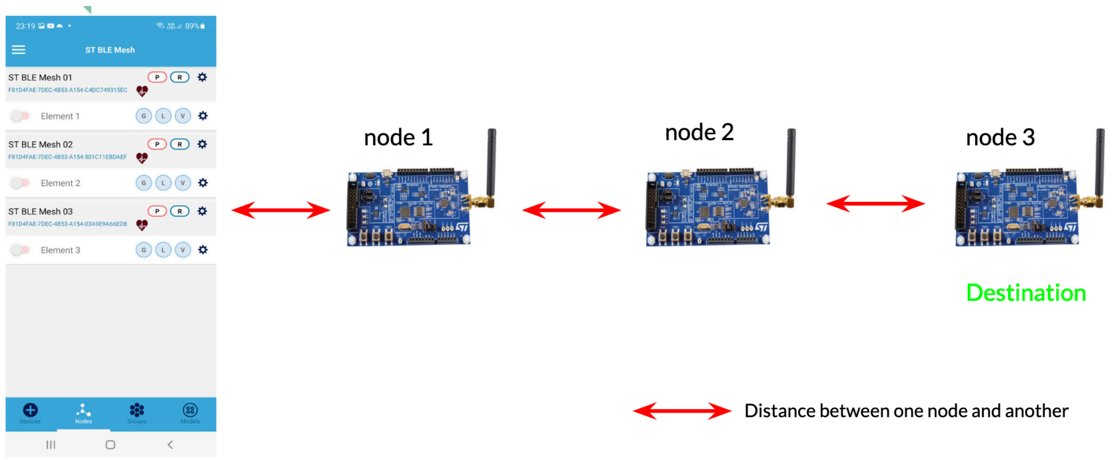

Figure 3. Shows a scenario of sending a message to the BT mesh network to turn on light on node 3.

2.3.1 Number of Packets Sent during the Experiments

When performing the experiments in the normal office environment, the number of packets sent varied to determine the optimal performance depending on the number of packets that were sent in a row using the built-in buffer in the mobile application's software. After trying to send 1, 5, 8, 10 packets, the performance did not change significantly up to 8 packets. Therefore, for the rest of the experiments, 8 packets were sent in all of them.

2.4 Data analysis

Regression analysis, which is a methodology in inferential statistics, was used to model the relationship between the independent variables, namely distance and number of packets sent, and the dependent variables latency and PLR This method helps identify the factors that contribute to the reliability of the BT Mesh network and provides insights into how to optimize its performance. (Alchemer 2021) noted:

> Regression analysis is a powerful statistical method that allows you to examine the relationship between two or more variables of interest. While there are many types of regression analysis, at their core they all examine the influence of one or more independent variables on a dependent variable

The regression analysis depends on a value called P-value. Calculating the P-value of the regression analysis allows us to determine if there is a linear relation between the independent variables and the dependent variables, if the P-value is lower than 0,05 that means there is a relation, if not there is no linear relation.

Along with regression analysis, Comparative Visualization is used to compare BT Mesh network performance because the environment is not representable by numeric values.

The combination of these two methods is useful since the regression analysis works well with datasets containing numeric values and not with categorical values which is in this case the environment.

2.5 Validity and reliability

The methods used in this study, including the measurements of latency and PLR, were well-defined and specific, and the experiments were repeated at four different distances between the relay nodes. This increases the validity of the study.

The experiments groups 1 and 2 were repeated at four different distances between the nodes while group 3 were repeated at six different distances between the nodes and group 4 were performed at only 5 meters distance. In total, 16 experiments were performed, for each experiment the measurements were taken 10 times to increase the reliability of the study. Also, the use of regression analysis as a statistical method helps ensure the reliability of the results.

3 Theoretical framework

Since the BT Mesh is a fresh technology, few studies have been conducted by researchers, which are diverse in nature and aim to discuss and study the performance and functionality of BT mesh network.

3.1 BT Mesh Topology Considerations

In order to evaluate the reliability of BT Mesh protocol in terms of latency, and scalability, (Rondón et al., 2019) used simulations with a grid topology, shown in figure 4 below, where all devices acted as relay nodes, which are nodes that retransmit data when it is received, as shown in figure 4 below.

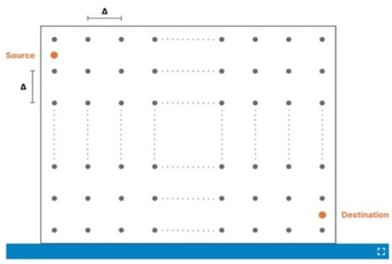

Figure 4. Shows the structure of grid topology (Rondón et al., 2019).

(Rondón et al., 2019) examined how the protocol behaves when considering both self-interference and external interference. Their findings demonstrated that the performance of the protocol is not significantly impacted by interference from other BT Mesh nodes that are part of the same network.

(Natgunanathan et al., 2023) presents the first research work –as far as (Natgunanathan et al., 2023) know– that explores the practical applicability, challenges, and opportunities of using BT Mesh in a diverse set of IoT scenarios. (Natgunanathan et al., 2023) conducted a review of existing experimental investigations related to BT Mesh and also provided insights from their own test-bed in normal office environment, as illustrated in figure 5 below.

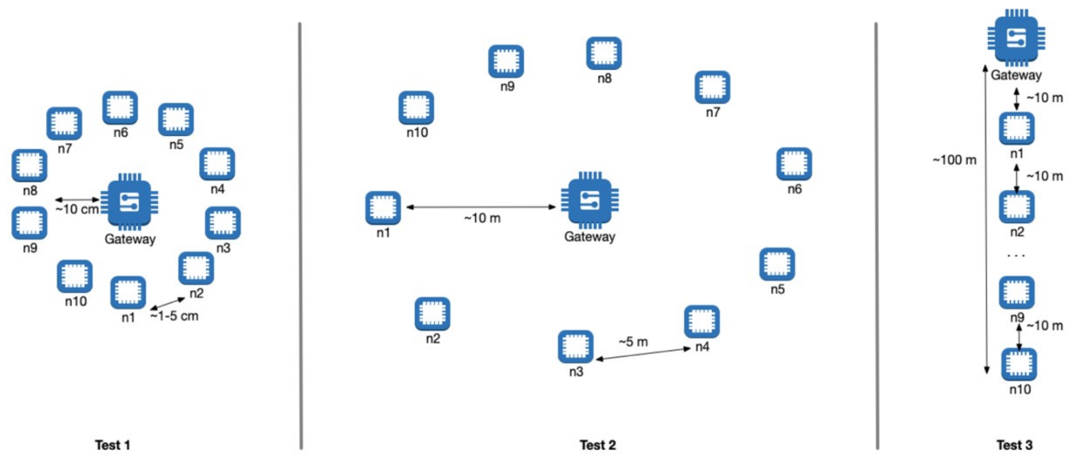

*Figure 5. shows the test-bed used in the experiment (*Natgunanathan et al., 2023)

The findings from (Natgunanathan et al., 2023) on the TTL values indicate that the messages were mostly sent directly to the gateway with a transmission path of 2-4 hops. However, some messages took a longer path, even when the nodes were only 5 cm away from the gateway. This trend was observed in all three tests, ranging from 5% to 11%. Additionally, there was a high amount of dropped, with the gateway receiving only 91% of the messages from group nodes in Test 1, dropping to 78% in Test 2 and 63% in Test 3. This was observed despite visually verifying that the message was received by the nodes.

To study the latency (Baert et al., 2023) has done a physical BT Mesh experimentation measuring the latency in 40 m × 25 m Office lab, using 22 Nordic's nRF52832 SoCs. Measurements were done considering the Round-Trip Time (RTT) for the number of relay nodes and number of hops. Conclusions state that increasing the number of nodes in the same area decreases the latency but also many nodes could also lead to more collisions which causes increasing the latency and PLR.

3.2 Overloaded Managed Flooding

To Evaluate the applicability of BT Mesh for Monitoring Applications (Lion & Nabi, 2020) has conducted experiments using a network of 33 micro:bit nodes. These nodes are placed randomly throughout a 500 m^2 space in an office environment. To generate traffic, the nodes periodically broadcast 8-byte data payload messages with a total packet size of 47 bytes. (Lion & Nabi, 2020) mentioned that relay nodes have a maximum capacity of handling 8 messages per second. If the network becomes overloaded by relay nodes, the managed flooding technique will not be effective. The study shows that BT Mesh is more suitable for very low-rate applications. However, for high data rate monitoring applications, this technology fails to deliver acceptable packet delivery performance.

3.3 Environmental Factors and Interference Considerations

There is a study that investigated the environmental interference in a BT Mesh network in Toyota Material Handling Europe which is a is a company that develops, builds, and sells different kinds of trucks used in an industrial environment (Berglund, 2018). In this environment there are many metal walls and floors that were considered in the evaluation of the BT Mesh network. According to (Berglund, 2018), In a mesh network, most nodes received at least 60% of the messages in all measurements, with some nodes in every case achieving this result across several measurements.

According to (Harvanova & Krajcovic, 2011), the obstruction caused by wood and foliage can lead to signal degradation, resulting in increased attenuation and potential signal loss. It is important to consider these environmental factors when planning and designing communication systems to ensure optimal signal quality and reliable transmission.

In industrial settings, as shown by (Kand & Meena, 2017), factors other than standard Radio Frequency (RF) devices can cause interference. These interfering sources encompass electromagnetic noise resulting from arcs generated by large equipment or processes, such as welding, turbines, and motors. These sources can hinder the desired performance of network connectivity.

For manufacturers where production lines are employed, requirements such as all-over reliable communication are different according to use-cases. Hence, further experiments should be done in order to determine if BT Mesh can be adopted for such applications to measure its performance to transfer messages. By deploying BT Mesh in a real-world scenario, we can encounter similar conditions to those of actual applications. This approach enables us to establish a solid foundation for defining the technology's limitations, which ultimately determines its suitability for specific manufacturers employing production lines.

4 Results

Throughout this chapter, the results are presented in a clear manner, supported by relevant figures and tables to enhance the understanding of the findings. The implications and significance of each set of results are analyzed, contributing to a comprehensive evaluation of the BT Mesh network's latency and PLR.

4.1 Data Collection Presentation

The data was collected in three different environments, namely normal office environment, industrial environment (three small electric motors), and forest. This was performed by sending messages with a 2 bytes payload to the last node (destination node) in the BT Mesh network.

Many experiments were done in the office to compare it to the industrial and forest environments since these two are assumed to have significant effects on the network.

However, the experiments were taken with a specified range between one node and another where each of which was repeated 10 times as follows:

NOTE: Single Packet Latency (SPL) represents the average time of 10 times repeated experiment when one single packet is sent to the destination node and a response was received from it. Latency represents the average time of 10 times repeated experiments when multiple packets are sent to the destination node and a response was received from it. Distance represents the range between one node and another where the total distance from the first one to the destination is 3 * Distance (Total = 3*Distance).

4.1.1 Office

1 packet was sent to the destination node. Table 2 below shows how the PLR, SPL are affected when varying the distance.

Distance (m)	**5**	**10**	**15**	**20**	**25**	**30**
Total (m)	**15**	**30**	**45**	**60**	**75**	**90**
SPL (ms)	274	266	303	403	449	463
PLR	0%	0%	0%	1%	2%	2%

Table 2. Shows SPL and PLR when sending 1 packet in normal office

5 packets were sent to the destination node. Table 3 below shows how the PLR and latency are affected when varying the distance.

Distance (m)	**5**	**10**	**15**	**20**	**25**	**30**
Total (m)	**15**	**30**	**45**	**60**	**75**	**90**
Latency (ms)	555	569	608	712	873	891
PLR	3%	6%	2%	9%	14%	14%

Table 3. Shows PLR and latency when sending 5 packets in normal office

8 packets were sent to the destination node. Table 4 below shows how the PLR, and latency are affected when varying the distance.

Distance (m)	**5**	**10**	**15**	**20**	**25**	**30**
Total (m)	**15**	**30**	**45**	**60**	**75**	**90**
Latency (ms)	724	736	746	998	1382	1423
PLR	10%	13%	14%	14%	17%	14%

Table 4. Shows PLR and latency when sending 8 packets in normal office

10 packets were sent to the destination node. Table 5 below shows how the PLR and latency are affected when varying the distance.

Distance (m)	**5**	**10**	**15**	**20**	**25**	**30**
Total (m)	**15**	**30**	**45**	**60**	**75**	**90**
Latency (ms)	837	827	947	1232	2177	2214
PLR	19%	24%	25%	29%	36%	40%

Table 5. Shows PLR and latency when sending 10 packets in normal office

4.1.2 Forest

1 packet was sent to the destination node. Table 6 below shows how the SPL is affected when varying the distance.

Distance (m)	5	10	20	25
Total (m)	15	30	60	75
SPL (ms)	373	394	599	510

Table 6. Shows SPL when sending 1 packet in forest

8 packets were sent to the destination node. Table 7 below shows how the PLR and latency are affected when varying the distance.

Distance (m)	5	10	20	25
Total (m)	15	30	60	75
Latency (ms)	633	715	1049	1062
PLR	19%	13%	14%	14%

Table 7. Shows PLR and latency when sending 8 packets in forest

4.1.3 Electric Motors

1 packet was sent to the destination node. Table 8 below shows how the SPL is affected when varying the distance.

Distance (m)	5	10	15	25
Total (m)	15	30	45	75
SPL (ms)	270	304	374	573

Table 8. Shows the SPL when sending 1 packet where electric motors are used

8 packets were sent to the destination node. Table 9 below shows how the PLR, and latency are affected when varying the distance.

Distance (m)	5	10	15	25
Total (m)	15	30m	45	75
Latency (ms)	696	778	942	1029
PLR	9%	11%	14%	16%

Table 9. Shows the PLR and latency when sending 8 packets where electric motors are used

4.1.4 Concrete Walls

Table 10 shows the SPL, PLR, and latency.

Distance (m)	5
Total (m)	15
SPL (ms)	371
Latency (ms)	848
PLR	26%

Table 10. Shows SPL, PLR, and latency through concrete walls

4.2 Data analysis

Based on the regression analysis of the collected data, the results indicate a significant relationship between distance and latency within a normal office environment. Specifically, the obtained P-value from analyzing the relation between distance and latency, and distance and SPL, is shown in tables 11 below.

PACKETS SENT	INDEPENDENT VARIABLE	DEPENDENT VARIABLE	P-VALUE
1	Distance	SPL	0,002
5	Distance	Latency	0,002
8	Distance	Latency	0,007
10	Distance	Latency	0,01

Table 11. Shows the regression P-value in office

That suggests a statistically significant association, that is as the distance between nodes increases, the latency also increases, implying a direct correlation between these two variables as illustrated in figure 6 below.

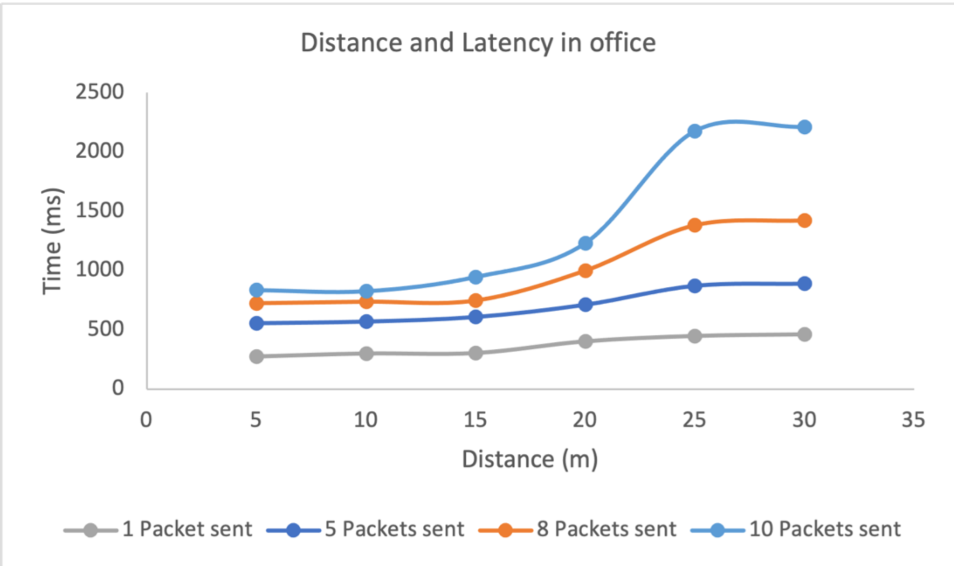

Figure 6. Shows the relation between SPL and distance with 1 packet sent in office

The results also reveal a relation between the PLR and the distance, where the regression P-value is significant as shown in table 12 below.

PACKETS SENT	INDEPENDENT VARIABLE	DEPENDENT VARIABLE	P-VALUE
1	Distance	PLR	0,008
5	Distance	PLR	0,02
8	Distance	PLR	0,047
10	Distance	PLR	0,0004

Table 12. Shows the regression P-value for relation of distance and PLR in office

As illustrated in figure 7 below, as the distance increases the PLR increases and this indicates a strong relation between these two variables, see the p-values in table 12 above.

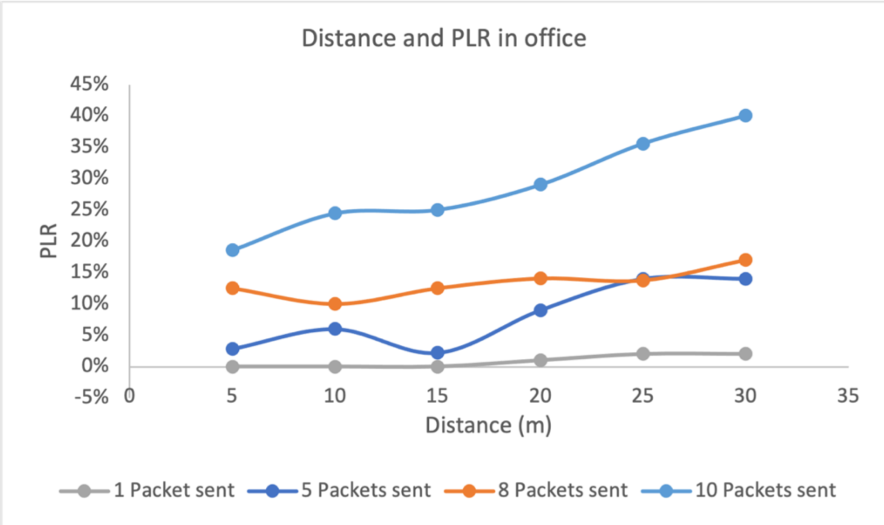

Figure 7. Illustrates the relation between the distance and PLR in office

Within the forest, the results suggest a strong relation between the distance and latency. According to the regression P-value, as shown in table 13 below, as the distance increases the latency increases. Figure 8 below illustrates the relation and shows how the variables are correlated.

The decision to conduct this experiment with 8 packets was influenced by our observations from previous experiments conducted in the office environment. During these experiments, we found that the network's performance remained acceptable when handling a maximum of 8 packets at the same time. This fact was also proven by (Lion & Nabi, 2020) where they claimed that the maximum of a relay node’s capacity is to handle 8 packets per second.

PACKETS SENT	INDEPENDENT VARIABLE	DEPENDENT VARIABLE	P-VALUE
1	Distance	SPL	0,03
8	Distance	Latency	0,01

Table 13. Show the P-value for relations of distance with latency and SPL in forest

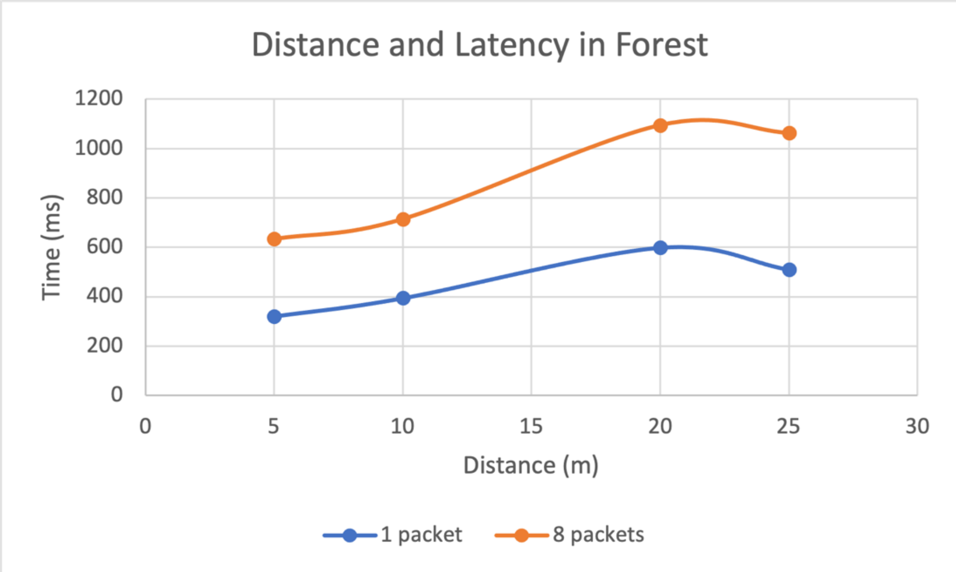

Table 8. Illustrate the relation between distance and SPL in forest

When it comes to the PLR, the regression shows a strong relation between the distance and PLR in this forest environment, as illustrated in figure 9 below, since the P-value was 0,046.

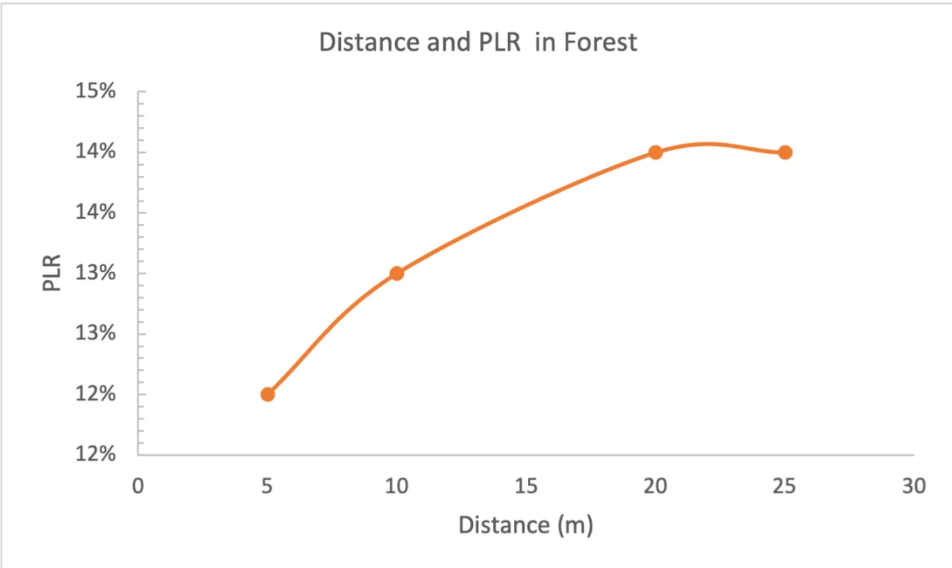

Figure 9. Illustrates the relation between distance and PLR in forest

Within the specified industrial environment, the results show a strong relation between the distance and latency and that is also based on the regression P-value as shown in table 14, as well as illustrated in figure 10 below.

PACKETS SENT	INDEPENDENT VARIABLE	DEPENDENT VARIABLE	P-VALUE
1	Distance	SPL	0,04
8	Distance	Latency	0,001

Table 14. Shows the P-value for relations of distance with latency and SPL in industrial environmen

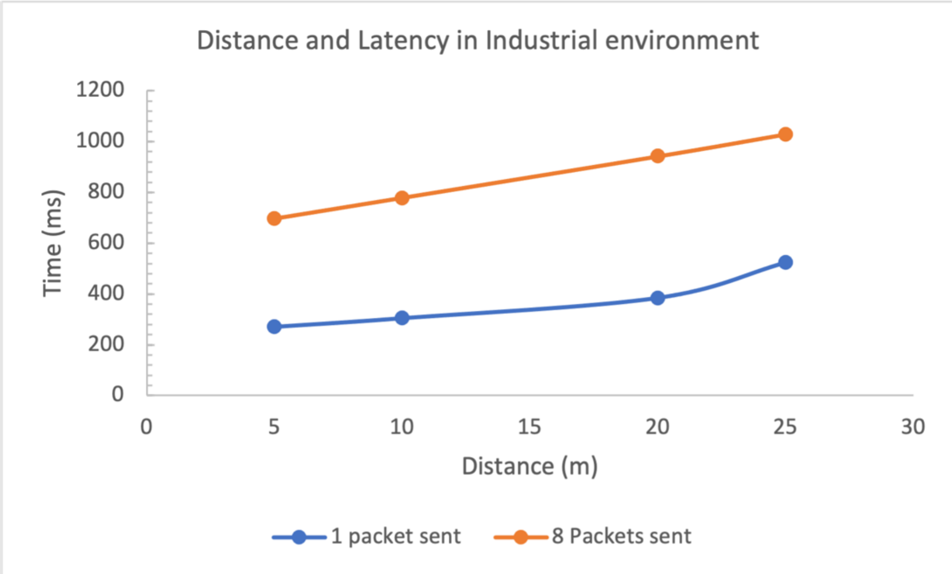

Figure 10. Illustrate the relation between distance and latency in industrial environment

The P-value for the regression between distance and PLR is 0,002 which indicates a strong relation between the variables as it also illustrated in figure 11 below.

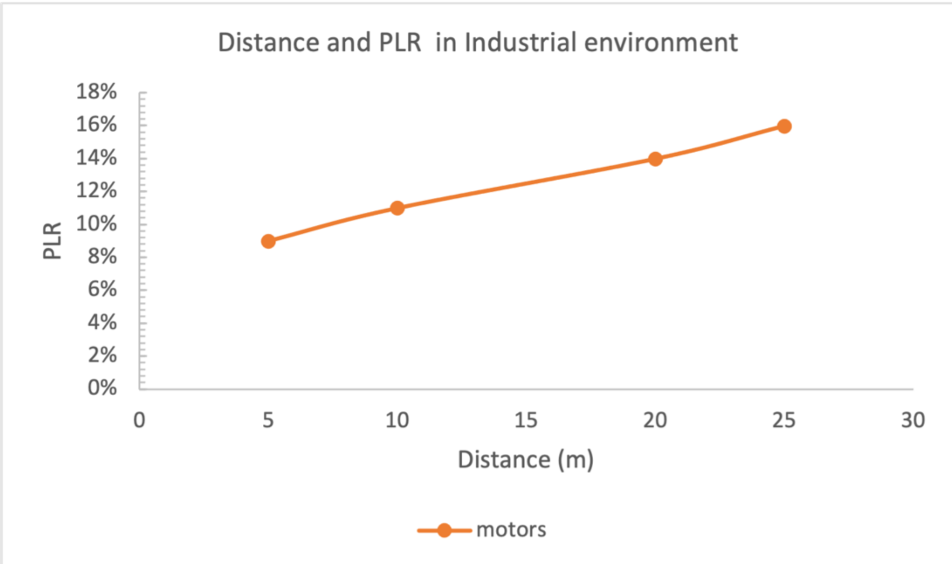

Figure 11. Illustrate the relation between distance and PLR in industrial environment

Experimenting BT Mesh network performance through concrete walls with only four-to-five-meter distance between a node and other shows that the concrete walls increase the SPL by about 35%, Latency 50% and PLR 800%.

Analysing the impact of number of packets sent on Latency in office shows, that as the number of packets sent increases, the latency also increases, implying a direct correlation between these two variables as illustrated in figure 12 below and according to P- values in table 15 below.

DISTANCE	INDEPENDENT VARIABLE	DEPENDENT VARIABLE	P-VALUE
5	Packets sent	Latency	0,002
10	Packets sent	Latency	0,005
15	Packets sent	Latency	0,007
20	Packets sent	Latency	0,004
25	Packets sent	Latency	0,043
30	Packets sent	Latency	0,041

Table 15. Shows the regression P-value for relation of number packets sent and latency in office

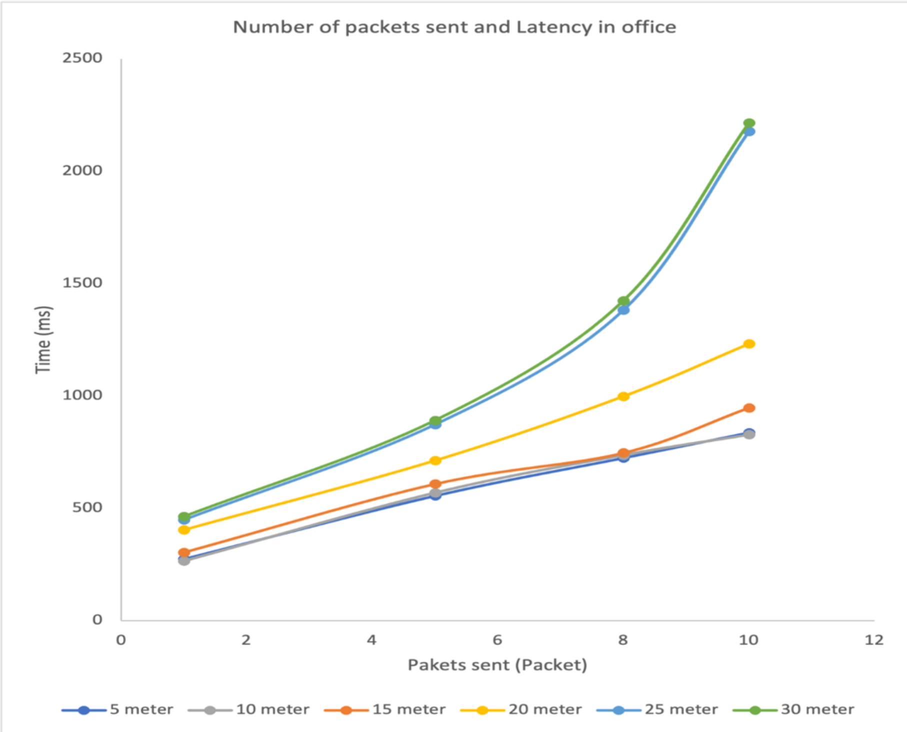

Figure 12. Illustrate the relation between number of packets sent and latency in office

The experiment in the office shows also impact of number of packets sent on PLR even though the P- value, in table 16 below, proves that this relation is not linear see figure 13 below that illustrates the relation between these two variables.

DISTANCE	INDEPENDENT VARIABLE	DEPENDENT VARIABLE	P-VALUE
5	Packets sent	PLR	0,045
10	Packets sent	PLR	0,81
15	Packets sent	PLR	0,085
20	Packets sent	PLR	0,061
25	Packets sent	PLR	0,11
30	Packets sent	PLR	0,088

Table 16. Shows the regression P-value for relation of number packets sent and PLR in office

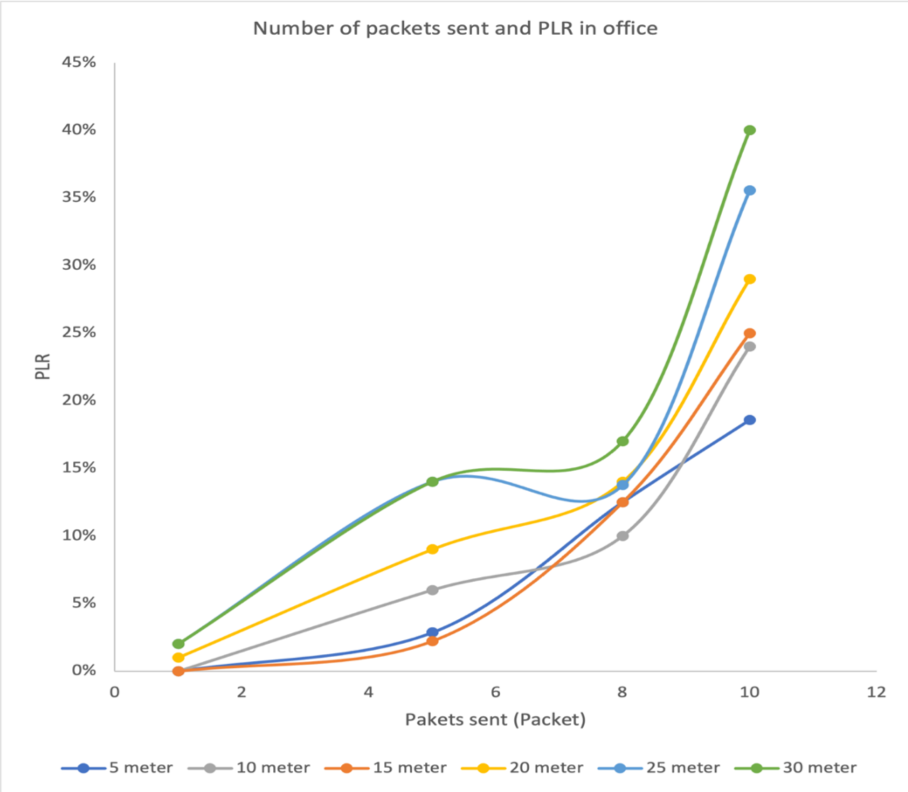

Figure 13. Illustrate the relation between number of packets sent and PLR in office

4.2.1 Results Comparison

In this sub-chapter, a comprehensive comparison of the results is viewed. Specifically, we analyze and compare the outcomes obtained from the normal office, forest, and the industrial environment in relation to varying distances between nodes.

Our results show that the PLR in the forest is higher than the PLR in the office up to 20 meters distance between one node and another. Based on figure 14 shown below, it can be observed that the office environment shows a higher PLR than in industrial environment in the range of 0-7 meters when compared to the higher ranges.

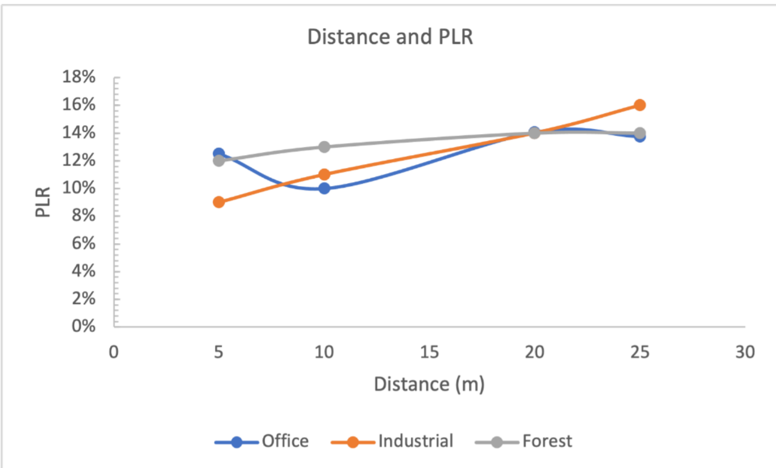

Figure 14. Illustrates how PLR varies depending on the environment.

Moreover, our analysis demonstrates, as illustrated in figure 15 below, that the BT Mesh network experiences varied effects in different environments. The forest environment exhibited higher impact on SPL as distance increased, while the industrial environment maintained lower SPL values compared to the others.

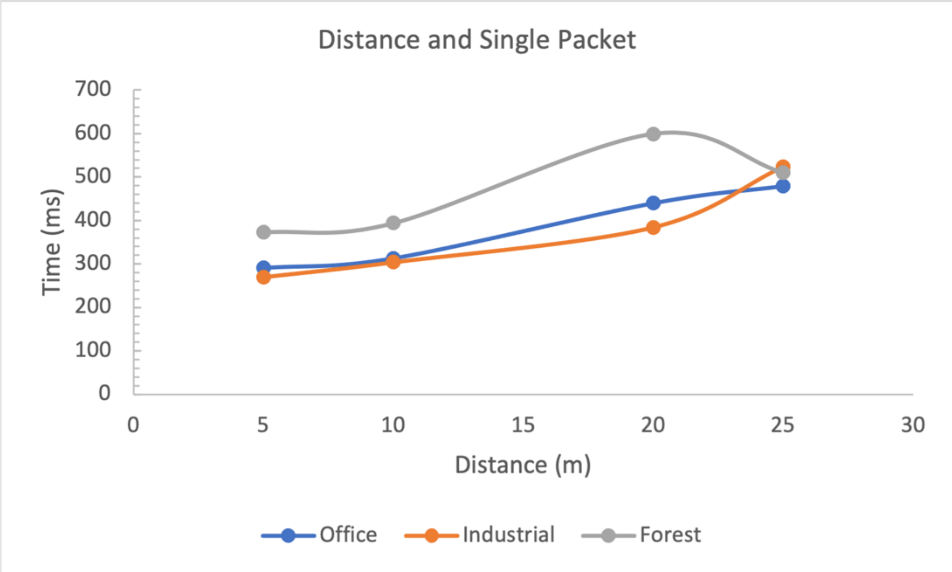

Figure 15. Compares the SPL in three different environments

Upon analyzing the collected data, as illustrated in figure 16 below, we found that there was no significant difference observed in latency across the different environments of office, forest, and industrial settings. Despite our efforts to compare and examine latency in these environments, no considerable variations or patterns emerged that would indicate a notable impact of the environment on latency.

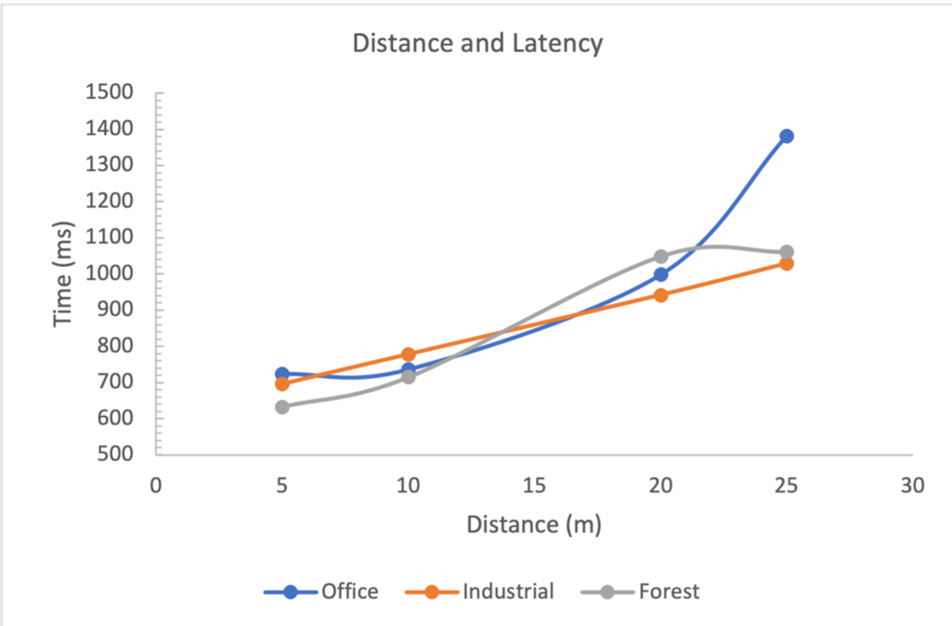

Figure 16. *Compares the latency in three different environments*

5 Discussion

This chapter aims to provide a discussion of the study results in relation to previous research conducted in the field. Additionally, it intends to explore the implications of the study findings and acknowledge any limitations encountered during the research process.

5.1 Result discussion

The utilization of BT Mesh networks might involve the presence of electric motors in industrial environments, as well as the potential obstacles posed by concrete walls and trees.
The purpose for this study is to determine if BT Mesh networks are applicable to the presence of electric motors in industrial environments, as well as the potential obstacles posed by concrete walls and trees. Therefore, it is crucial to compare the behavior of BT Mesh network between multiple environments to be able to evaluate the performance when it comes to PLR and latency.

In the experiments performed by (Natgunanathan et al., 2023), there was a PLR of 37% in Test 3, where each message had 2 bytes of payload which was the same amount of payload as in our experiments. Compared to the PLR which is 14% of our results when sending 5 packets to the destination, their tests show worser PLR even though the distance between the source node and the destination node is the same in both experiments. Based on this, an improved reliability can be achieved with decreased number of nodes in a BT Mesh network in the same total distance.

The findings of (Lion & Nabi, 2020) about relay nodes maximum capacity of handling 8 messages per second can be clearly seen in our experiments when recognizing the extreme increase of PLR when sending 10 packets comparing to sending 8 packets and 5 packets.

In the context of the specified industrial environment, when the electromagnetic waves from the electric motors, which are mentioned by (Kand & Meena, 2017), were interfering with the BT Mesh network PLR and Latency was not significantly impacted compared with office. This means that, in terms of PLR and Latency the interference, caused by electric motors and headsets in our experiment, is not significantly higher than the interference caused in normal office environment where BT Mesh is widely deployed and studied. In term of SPL the impact of the electromagnetic waves interference from the electric motors comparing to the interference in normal office was even lower in most experimented distances.

In the context of forest environment, when signal loss is potential according to (Harvanova & Krajcovic, 2011), the BT Mesh network PLR and Latency was not significantly impacted compared with office. This means that, in term of PLR and Latency the interference, caused by wood and foliage, is not significantly higher than the interference caused in normal office environment. In term of SPL the impact of signal loss comparing to the interference in normal office is clearly shown and in average SPL is about 30% higher.

5.2 Method discussion

Regression analysis can help us to identify and quantify the relationships between PLR, SPL and Latency as dependent variables and distance and number of packets sent as independent variables. With using regression analysis, we could determine the strength, direction, and significance of the relationships of the dependent variable based on the independent variables.

Regression analysis assumes a linear relationship between the dependent and independent variables which did not help us to study the relation between PLR and distance even though the figures illustrate a strong relation which is more exponential.

High correlation between the dependent variables PLR and Latency made it challenging to interpret the individual effects on each variable accurately especially when sending 10 packets with distance between nodes less than 15 meters.

To avoid outliers, which has a significant impact on the model's results, we had to control all external factors that might appear and lead to outliers or invalid records. Controlling the external factors in the office, such as people passing through, was easy but controlling the external factors in the forest or in the industrial environment was almost impossible especially when it comes to rainy weather or an animal in the forest preventing the BLE signal when the nodes were not seen at all.

6 Conclusions and further research

This chapter presents the conclusions from our study and suggestions for further research.

6.1 Conclusions

After conducting extensive research, we can confidently conclude that environments, such forest, and manufacturing using small motors, have no significant impact on the reliability, in terms of PLR, SPL, latency, on BT Mesh networks. That means that each experiment, that was done in a normal office environment, is valid to consider and rely on when designing a BT Mesh network in such environments.

However, it is important to note that a notable impact on BT Mesh networks is observed when implementing BT mesh network in environments characterized by nodes separated by concrete walls, particularly with regards to PLR. The presence of concrete barriers significantly affects the network's performance and must be carefully considered during the design.

In addition, the BT Mesh network achieves optimal and identical performance and reliability, in terms of PLR, SPL, and latency, when the distance between one node and another is between 5-20 meters. Therefore, for designing cheaper BT Mesh networks, it is recommended to position the nodes 15-20 meters far from each other.

6.2 Practical implications

The industry can benefit from the knowledge that BT Mesh networks are highly reliable, in terms of PLR, SPL, and latency in environments such as forests and manufacturing facilities. This information can guide designers in developing and implementing IoT devices and systems that rely on BT Mesh networks, ensuring robust connectivity and minimizing concerns about network performance.

The public sector can leverage the research findings to enhance the implementation of BT Mesh networks in public spaces, such as parks, gardens, and other natural environments. This can facilitate the deployment of smart city applications, including environmental monitoring, smart lighting, and public safety systems, enabling efficient and reliable communication between devices in these outdoor settings.

6.3 Scientific implication

The research supports the validity of conducting experiments in controlled office environments as a representative model for evaluating BT Mesh networks' performance in various settings. This validation provides confidence in the reliability of experimental results obtained in such environments, establishing a benchmark for future studies in the field of wireless mesh networking.

The research sheds light on the impact of specific environmental factors, such as the presence of small motors in manufacturing facilities and the use of concrete walls as barriers. This knowledge deepens our understanding of how different elements in the environment can affect wireless connectivity and network performance. It paves the way for further investigation into the mechanisms and characteristics of wireless communication in challenging environments.

6.4 Further research

Future research can investigate the impact of varying the number of nodes in a BT Mesh network. This can involve studying how network performance, such as PLR, latency, and throughput, is affected as the number of nodes increases or decreases.

Investigating the impact of TTL settings on BT Mesh network performance can be a valuable area of research. TTL determines the lifespan of messages and affects their propagation throughout the network. Research can explore how adjusting TTL values affects factors such as PLR, latency, and energy consumption.

Research can explore techniques for maximizing throughput while ensuring low latency and reliable data transmission. Investigating the impact of different environments on the throughput can also provide insights for designing BT Mesh networks tailored to specific use cases.

Finally, it can be valuable to investigate the impact of other high-power electrical devices, e.g., with higher power than the one used for our experiments, on BT Mesh networks.

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