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A Comprehensive Evaluation of Bluetooth Low Energy Mesh

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***Abstract*—Bluetooth Low Energy (BLE) Mesh is a pivotal multi-hop self-organizing network in the Internet of Things (IoT) domain, offering low power consumption, low cost, and robustness. This paper presents a comprehensive study on the communication performance of BLE-Mesh using commercial off-the-shelf devices, focusing on the impact of key mesh parameters such as transmission power, packet interval, and network structure on performance. Through extensive indoor and outdoor experiments, we quantify the impact of these parameters and conduct a detailed study. Our findings provide insights into the actual communication range of BLE-Mesh, the effect of node design on overall network performance, and the configuration for optimal performance. The research contributes to the establishment of a BLE-Mesh network in real-world environments, answering critical questions for practitioners, and offering a reference for future BLE-Mesh deployments. This work furthers our understanding of the characteristics, challenges, and future directions of BLE-Mesh, setting the stage for advancements in IoT applications such as smart offices and homes.**

***Index Terms*—network measurement, network performance analysis, internet of things, BLE-Mesh.**

I. Introduction

The swift progress in wireless communication technology is linking numerous devices around us, including mobile phones, sensors, and actuators, to the same network, thereby accelerating the expansion of IoT technology. As wireless communication technologies like Bluetooth Low Energy (BLE), Zigbee, and RFID advance, they are overcoming the conventional issues associated with wired communication, such as efficiency, flexibility, and cost, enabling devices to transmit data dynamically over the air [1]. Owing to its simple deployment, affordability, and energy-efficient low data rate, BLE is ideal for IoT applications, including Unmanned Aerial Vehicles (UAVs) [2], which have gained significant attention in recent years. Communication systems in UAVs constitute a major portion of their energy consumption, and BLE offers a compelling solution. Its low power consumption is crucial for extending the operational lifespan of UAVs during missions, making it an attractive choice for enhancing UAV communication systems [3], [4].Excellent features of BLE leading to extensive research endeavors in both industry and academia [5].

Bluetooth Low Energy (BLE) is a wireless communication standard created by the Bluetooth Special Interest Group and first implemented in Bluetooth version 4.0. Subsequent versions like 4.2 and 5.x have seen additional improvements to this technology [6]. In contrast to BR/EDR (commonly known as Classic Bluetooth), BLE can operate for extended periods solely on coin-cell batteries or dry batteries, while also offering new wireless communication methods. Today, Bluetooth beacons are widely deployed due to their compact size and low cost, making them highly promising devices extensively utilized in IoT innovations. For instance, in applications such as secure communications [7]–[9], indoor positioning and tracking [10], [11], UAV communication systems [12], [13], mobile crowdsensing [14], [15], and smart manufacturing [16], BLE has undoubtedly become a crucial solution for various practical applications within the IoT domain.

Although BLE has had great potential for applications since its inception, most Bluetooth devices still utilize a star network topology when transmitting beacons. This significantly restricts the coverage range and flexibility of BLE networks. In 2017, the Bluetooth SIG released the BLE-Mesh protocol, allowing message transmission between any two BLE nodes within a network. The BLE-Mesh protocol stack is designed based on the BLE protocol stack of Bluetooth 4.2. BLE-Mesh has a unique protocol stack structure built on top of the BLE connection layer. Unlike the star topology, BLE-Mesh adopts a mesh topology, and it also replaces the traditional peer-to-peer communication method with a publish-subscribe model for message transmission. These design choices greatly enhance the communication capabilities of BLE networks, enabling BLE-Mesh to achieve a multi-hop, self-organizing, and many-to-many communication network.

Research on BLE-Mesh has been continuous in both academia and industry since its inception. Seyed Mahdi Darroudi, Carles Gomez et al. [17] published a review on the evolution of BLE-Mesh technology just before the Mesh specification was introduced, making it one of the earliest discussions on BLE-Mesh. Muhammad Rizwan Ghori explored the security issues of the BLE-Mesh protocol and compared it with other communication protocols [18]. Furthermore, numerous studies have examined the characteristics and

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challenges of mesh technology [19]–[25]. These studies have provided a general understanding of the various characteristics of BLE-Mesh. However, to our knowledge, no comprehensive measurement study has quantitatively evaluated the promised performance of BLE-Mesh.

In this paper, we designed a series of experiments to investigate the performance of mesh networks, focusing on parameters that affect BLE-Mesh communication performance, such as output power and packet interval, as well as the structure of the mesh network. At the same time, we implemented and completed these experiments using COTS devices. Our aim is to provide a clearer representation of BLE-Mesh's communication capabilities through data measured in real-world environments, offering a reference point for future practitioners. Our objective is to address questions posed by researchers and system adopters, such as: "What is the actual communication range of BLE-Mesh?", "How do the designs of various nodes in a mesh network affect overall network performance?" and "How should parameters be configured to optimize mesh network performance?" Finally, we summarize the characteristics of BLE-Mesh and discuss the challenges and future directions of this technology.

The contributions of this paper mainly include:

- We established a BLE-Mesh network using COTS devices in a real-world environment and conducted extensive measurements on the mesh network.
- We answer several questions of concern for practitioners by designing and deploying such networks and summarize some relevant lessons learned from this evaluation.

The rest of this paper is organized as follows. Section II introduces the background, features, and terminology of BLE and BLE-Mesh, and also reviews related works on the evaluation of BLE-Mesh. Section III describes the experimental equipment, environment, and parameter design. Section IV reported and analyzed the experimental results.In Section V, we summarize the lessons learned from the experiments and outline future work directions. Section VI provides a brief conclusion of the entire paper.

II. Research Background & Related Works

A. Bluetooth Low Energy

After the Bluetooth SIG introduced the Bluetooth 4.0 protocol, Bluetooth was divided into BR/EDR and BLE segments. BR/EDR, also known as Classic Bluetooth, is commonly used today in audio devices such as headphones and speakers. On the other hand, BLE is widely adopted in the IOT field due to its low power consumption and cost-efficiency.

Classic Bluetooth is recognized as a short-range wireless communication technology that emerged as a replacement for wired communications. The reliability of connection-based communication allows classic Bluetooth to effectively meet the stability requirements for information transmission in the audio field. However, the one-to-one communication method of classic Bluetooth limits its scalability and flexibility.

Driven by the development of the IoT, BLE broke free from the constraints of connection-based communication, adopting broadcasting for communication instead. Although this shift sacrificed some reliability, it greatly enhanced flexibility and communication capabilities. Furthermore, the ability to avoid establishing connections and enter "sleep" mode during idle times significantly reduced the power consumption of Bluetooth devices, which is a primary reason for their low power usage. It is important to note that the BLE protocol itself is not backward compatible. However, Bluetooth's dominance in the audio field and its adaptability for IoT applications are both significant characteristics. Hence, the SIG introduced Bluetooth Smart Ready, which explains why many devices today support Bluetooth dual-mode.

BLE opened the door for Bluetooth devices to achieve one-to-many communication. Broadcasting as a means of communication laid the groundwork for mesh networks to achieve many-to-many communication in the future.

B. BLE Mesh

BLE-Mesh is a communication standard proposed by SIG based on BLE. Its birth enables Bluetooth to construct large-scale sensor networks, incorporating smartphones and various IoT devices. A device that only supports Bluetooth 4.0 can still communicate with nodes within a mesh network, which is a reason for the broad application prospects of BLE-Mesh.

In a BLE Mesh network, communication between nodes does not require establishing a connection. Instead, the source node directly broadcasts data packets, and the recipient node is determined by the address contained within each packet. Data transmission between nodes follows a publish/subscribe model. The nodes join the network through a provisioner and are assigned a unique unicast address to receive messages sent specifically to that node. The nodes can also subscribe to one or more group addresses, which can be shared by multiple nodes. Similarly, a source node can send messages to a single target node or publish messages to a group address. This publish/subscribe model allows the mesh network to achieve efficient many-to-many information exchange.

Although many-to-many communication enables Mesh nodes to establish connections, it does not inherently allow them to organize a larger network, as the coverage range remains limited by the transmission capabilities of individual nodes. In a BLE Mesh network, nodes can possess one or more of four features: Relay, Friend, Low Power, and Proxy. During any given transmission process, a node can exhibit only one feature. By strategically allocating and coordinating these nodes, the mesh network enhances overall coverage and throughput. The following sections will introduce each of these features in detail.

1) Relay Node: As indicated by its name, a relay node within a mesh network incessantly monitors and receives broadcast messages from the network, then disseminates them further. The attributes of relay nodes allow source nodes to engage in communication with nodes outside their immediate transmission range, which greatly increases the BLE network's coverage. Furthermore, relay nodes keep a record of a certain quantity of recently received broadcast packets to eliminate duplicate messages that have been transmitted repeatedly, thereby avoiding network congestion.

2) Friend Node: The attributes of a friend node are activated once it forms a connection with low-power nodes. A friend node can establish relationships with one or multiple low-power nodes. Once the connection is established, the friend node logs the subscription addresses of each connected low-power node and allocates memory to store the information these nodes receive. Thereafter, the friend node persistently monitors the mesh network for messages that the low-power nodes have subscribed to and forwards this information to them upon request.

3) Low-Power Node: After being added to the network, a low-power node will announce its intention to find friend nodes by broadcast. It assesses the prospective friend nodes based on the RSSI and Receive Window data provided by them to identify the optimal friend node with which it will then form a friendship. Thereafter, the low-power node will enter a sleep mode to conserve energy and will awaken periodically to request messages from its friend node. As a peripheral node in the mesh network, the low-power node has minimal power consumption, making it perfect for energy-saving devices such as sensors used in IoT applications.

4) Proxy Node: Numerous devices that solely support BLE, including smartphones, tablets, and Bluetooth gateways, do not naturally support BLE-Mesh. The function of the proxy node is to facilitate these devices in communicating with the mesh network. It does this by encapsulating BLE data and transforming it into BLE Mesh protocol data units (PDUs) using the GATT (Generic Attribute) protocol. This integration enables a diverse range of BLE devices to be included in the mesh network. Once a BLE device has joined the network, the proxy node is also responsible for the transmission and reception of messages, akin to the dynamic between a friend node and a low-power node.

The many-to-many communication and message relay features of BLE-Mesh provide the network with significant scalability. However, inevitably, as the number of nodes in the network increases, the volume of relayed messages will increase, leading to a higher likelihood of collisions and network storms. To prevent the indefinite relay of messages within the network, mesh employs two methods to achieve the managed flooding:

- Relay nodes identify duplicate messages by storing recently broadcast packets and prevent the same message from being relayed multiple times.
- The hop count of messages on the network is limited. When the hop count reaches a certain threshold, the message is discarded and is not relayed further.

Managed flooding not only restricts the number of relayed messages but also imposes constraints on the network size.

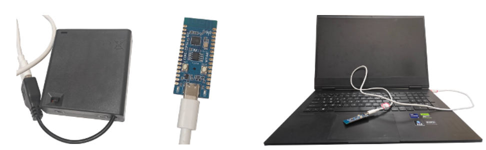
C. Related works on BLE-Mesh

To date, considerable research has been undertaken in both academic and industrial domains regarding the advantages and limitations of BLE-Mesh. For example, Silicon Labs assessed the performance of BLE-Mesh with their hardware and software platforms, as documented in [26]. The experiments were carried out in a commercial office environment with WiFi and Zigbee networks, employing 192 mesh nodes. This particular study concentrated on reliability and latency, without extensively examining the intrinsic properties of BLE-Mesh. Moreover, the core specifications of BLE-Mesh have been reviewed and analyzed in [27]–[30]. The rising popularity of terms like smart office and smart home has ignited a surge in research interest, indicating that BLE-Mesh could be highly significant in these settings [31], [32].

Our research distinguishes itself by focusing extensively on the inherent properties of BLE-Mesh. We have performed a series of experiments aimed at evaluating the performance and potential issues of BLE-Mesh. These experiments are designed to address questions regarding the benefits and challenges.

III. Measurement Setup

In this section, we will present the hardware devices utilized in the networking configuration. Afterward, we will elaborate on the parameters influencing BLE-Mesh communication efficiency and the experimental setting. For our trials, we chose commercially available Bluetooth devices based on the Espressif ESP32C3 SoC. During the experiment, we employed 20 ESP32C3 devices, and the project code was created using the ESP-IDF framework provided by Espressif. To monitor the data on the mesh chips, we accessed non-volatile storage (NVS) or used a Universal Asynchronous Receiver/Transmitter (UART) to read the packet transmission and reception statuses through GPIO on chips linked to a PC. In the experiment, the Bluetooth devices were powered by dry batteries. An 8000 mAh battery can sustain the highest power-consuming continuous scanning device in the network (consuming about 10 mA) for around one month. The hardware used in the experiment is illustrated in Fig. 1.



(a) Dry batteries were used to power the ESP32-C3

(b) The BLE-Mesh project was developed using ESP-IDF

Fig. 1. Hardware utilized for the experimental system.

A. Parameter Impact

1) Transmission Interval: The packet interval refers to the time gap between two consecutive data packets. A longer packet interval indicates a lower transmission rate of the source node. However, as the packet interval decreases, the probability of packet collisions in the channel increases, and the storage pressure on the relay nodes and the friend nodes also intensifies. Relay node failure can have a disastrous impact on surrounding mesh nodes, so selection of the packet interval is crucial for the communication environment of the entire mesh network.

2) Transmission Power: The transmission power affects the "strength" of the signal propagation. As the distance between Bluetooth nodes increases, enhancing the transmission power is an effective method to ensure that the signal can still be accurately received by the receiving node. The ESP32C3 SoC developed by Espressif supports transmission power options ranging from -24dBm to 21dBm. However, in the latest Bluetooth protocol, the transmission power limit for BLE-Mesh devices ranges from -20dBm to 20dBm. Therefore, in the following experiments, we choose the ESP32C3 to compromise with the protocol specifications.

3) Hops: Multi-hop communication provides high flexibility for communication between nodes in a BLE-Mesh network and significantly extends the coverage area of node communication. A single transmission between two adjacent nodes is typically referred to as one hop. If there are 3 hops, it means there are two relay nodes between the receiving and sending nodes. Distant nodes complete the transmission of information through multiple hops via intermediate nodes. As the number of hops increases, the coverage area of the entire mesh network also expands. In practical use, Time to Live (TTL) is commonly used to indicate the maximum number of times data can be relayed during transmission. Additionally, to limit the infinite expansion capability of the mesh network, the TTL value is specified when setting up the data packets.

4) Mesh Structure: A BLE-Mesh network comprises numerous nodes that perform various features. While a single node can have multiple features, it can exhibit only one feature at a time during transmission. Relay nodes within the network retransmit received information, thereby extending the communication range of each individual node. If the relay nodes are uniformly distributed throughout the network, the overall quality of communication will improve significantly. Friend nodes hold the group publication information that their associated LPNs (Low Power Nodes) subscribe to. Having multiple friend nodes can mitigate the risk of data loss due to memory overflow from storing LPN subscription information. LPNs and proxies serve similar roles within the network, functioning as edge nodes that represent the starting or ending points in each communication. Increasing their number can enhance the network's overall throughput, thus boosting communication capabilities across the entire network. However, the publish and subscribe model, akin to multicast, which enhances efficiency also raises concerns about the network's capacity to support a large number of nodes.

B. Outdoor Environment

Fig. 2 illustrates the outdoor experiment environment. The study was primarily conducted on a road in Beijing, measuring approximately 710 meters in length and 20 meters in width. A residential area lies 30 meters to the east of the road, while a park borders it immediately to the west. Due to its relatively secluded location, the area is nearly deserted at night.

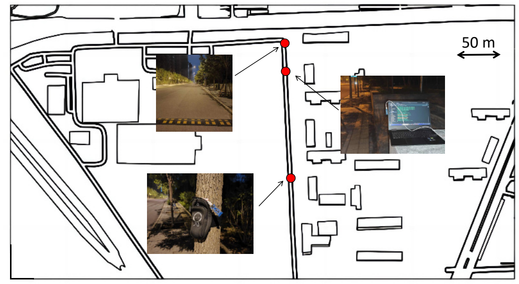


Fig. 2. BLE chip placement in outdoor situations.

As noted previously, BLE-Mesh signals operate in the 2.4GHz public band, making them susceptible to interference from other signals within this spectrum, such as WiFi and Zigbee. Furthermore, signal attenuation caused by reflection or penetration through surrounding objects can significantly impact experimental results. For example, we observed a 30% decrease in the Packet Receive Rate (PRR) when a smartphone connected to WiFi and streaming video was placed within 20 cm of the receiving mesh node. Furthermore, the placement of measurement nodes plays a crucial role in the outcomes. In a prior experiment, positioning the mesh chip on the ground for data transmission resulted in a propagation distance approximately one-tenth of that achieved when the chip was elevated above the ground.

To mitigate these interference factors, we implemented several strategies. First, measurements were conducted between midnight and 4 AM when the road is virtually empty, minimizing potential disruptions. Second, we affixed the mesh chips to trees, ensuring they were not too close to the ground while maintaining a Line-of-Sight (LoS) environment. These precautions helped to optimize mesh signal propagation and reduce external interference, thereby enhancing the reliability of our experimental results.

C. Indoor Environment

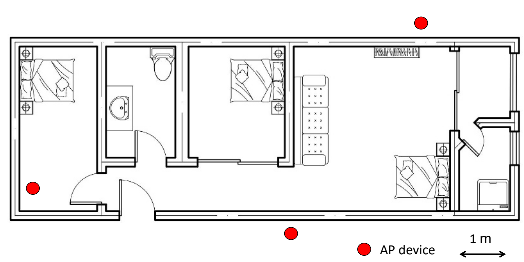


Fig. 3. BLE chip placement in indoor situations.

The indoor environment is depicted in Fig. 3. The indoor experiment was conducted in a room with an approximate floor area of 50 square meters. During the indoor experiment, mesh nodes were placed primarily in the area formed by the bedroom on the far left, the corridor, and the living room, to maximize the communication distance. The figure indicates the presence of three AP points near the room that emit WiFi signals. The measurements show that the RSSI of the WiFi signals covering the entire room is approximately -60 dBm. This indicates that the measurement of indoor experimental data is affected by other signals. These conditions simulate the communication environment of BLE-Mesh smart home devices in a typical residential setting.

IV. Measurement Results and Analysis

A. Transmission Interval

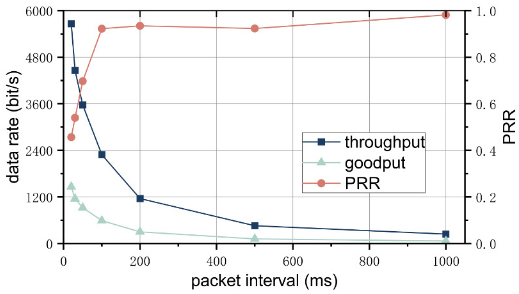


Fig. 4. Effect of transmission interval on PRR and Data rate.

To examine the effect of packet intervals on propagation speed, this study used two ESP32C3 nodes for communication. The nodes were placed 5 meters apart, with the TX Power set to 9 dBm. To mitigate the inevitable random environmental noise that affects the transmission and reception of BLE packets, this study involved exchanging 10,000 packets between the two nodes to determine the PRR. Once the PRR was determined, the corresponding throughput and goodput were calculated. Since adding Friend and LPN features to the mesh network does not affect the experimental results and introduces new variables, no feature attributes were assigned to the two nodes in this study.

Fig. 4 illustrates how different packet intervals affect PRR, throughput, and goodput. When the packet interval exceeds 100 milliseconds, the PRR remains above 90%. In contrast, when the packet interval is shorter than 100 milliseconds, the PRR decreases rapidly as the interval shortens. This phenomenon occurs because it takes time to transmit and unpack a packet. If a new packet arrives before the previous packet is fully unpacked, it is placed in a queue. However, if the incoming packet rate significantly exceeds the depacketization rate, packet loss will occur, causing a sharp drop in PRR.

In the evaluation, the packet size of BLE-Mesh is fixed, with a constant packet composition, leading to a fixed payload size. Therefore, the throughput and goodput of the sending node can be calculated using the PRR. Interestingly, although the PRR decreases rapidly as the packet interval becomes shorter, the goodput increases. This is because the increase in the packet transmission rate outpaces the increase in packet loss rate, resulting in an overall higher goodput despite the higher packet loss ratio at shorter packet intervals.

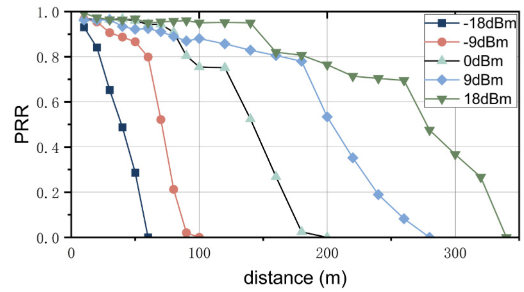


Fig. 5. Effect of TX Power on PRR.

B. Transmission Power

To explore the communication distance of the BLE-Mesh nodes under different power levels in an ideal environment, TX Power experiments were conducted in an open area during the early morning hours. For this part of the experiment, two ESP32C3 chips were used as transceiver nodes without any feature attributes. To comply with both Espressif's chip design and Bluetooth protocol specifications, the output power was selected within the range of -18 dBm to 18 dBm. Furthermore, a packet interval of 100 ms was chosen to minimize the duration of the experiment while ensuring a PRR greater than 90%. In this experiment, 10, 000 data packets were collected for subsequent calculations. Unless otherwise specified, this data quantity was used in all subsequent experiments to minimize interference of incidental environmental noise with the experimental result analysis.

As shown in Fig. 5, TX Power significantly impacts the propagation range of the signal. An increase in power from -18 dBm to 18 dBm resulted in nearly a six-fold increase in propagation distance, from 60 meters to 340 meters. As the signal weakens due to increased distance, the rate of decrease of PRR will accelerate after it drops to 70%. This is because the distance between two BLE-Mesh nodes increases: (1) the likelihood of the signal being affected by incident environmental noise increases, and (2) the resistance of the signal to noise decreases as it continues to weaken.

C. Hops

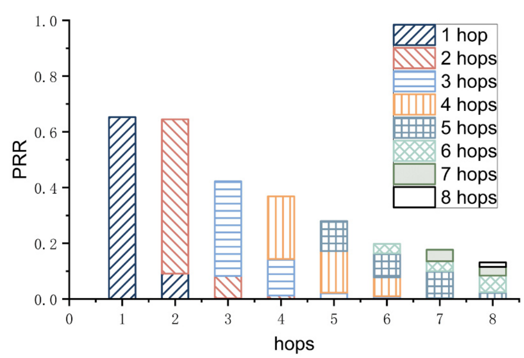


Fig. 6. Effect of hops on PRR.

In investigating multi-hop communication, experiments were conducted in an outdoor environment with a fixed length per hop. Measurements were taken using nine ESP32C3 nodes, ranging from no relay nodes to a final setup with seven relay nodes, i.e., eight hops. To minimize the occupied area, the lowest available transmit power, that is, -18 dBm, was selected. The packet interval was set to 100 ms. An essential parameter in the experiment design was the fixed length for each hop, which presented a dilemma: (1) If the length was too short, data transmission might not require the relay nodes' extension function, rendering the relay nodes redundant. (2) If the length was too long, each hop would suffer significant signal attenuation, causing the PRR to approach zero after a few hops.

Fig. 6 shows the results of the multi-hop measurements. When the number of hops is low, the number of hops equal to the number of relay nodes plus one is the predominant type, indicating that each relay node effectively contributes to transmission over shorter distances. However, as the number of hops increases, the proportion of transmissions with the number of hops equal to the number of relay nodes plus one decreases, while those with the number of hops equal to or less than the number of relay nodes become the main transmission types. The reasons are as follows. (1) During our experiments, we found that although relay nodes should ideally operate with 100% coverage time, this is not the case in practice. Adjustments to scanning frequency and the detection of relay packets consume time, preventing timely packet detection and inevitably leading to packet loss. As distance increases, the packet loss accumulates with each relay node, lowering the PRR for the corresponding number of hops. (2) Although direct transmission over one relay node results in a lower PRR (less than 10% in the case of 2 hops, with a ratio of about 6:1 between 1 hop and 2 hops), it prevents the loss of compounded packets from multiple relay nodes. Together, these factors lead to a higher proportion of transmissions that involve bypassing relay nodes.

D. Mesh Structure

This section presents a series of experiments designed to analyze the entire information propagation process by examining the PRR and TTL of the packets received by the receiving node. These experiments explore different features of mesh nodes—relay, low-power node (LPN), and Friend in an indoor environment (proxy nodes were not tested separately as their operating logic is nearly identical to that of Friend nodes). When investigating nodes with a particular feature, to avoid the influence of other communication nodes in a complex communication environment, other feature components were structurally simplified to the maximum extent. This approach ensures that there are only a few or even a single other type of feature node in the entire communication link.

1) impact of relay nodes: Relay nodes, being the busiest nodes in the entire network, continuously scan the channels for packets and relay them to other nodes. The implementation of relay nodes is a key reason multi-hop communication can be achieved, making the study of relay nodes inherently a study of hops. In exploring hops, we used a method to fix the distance of one hop while continually increasing the number of relay nodes to investigate the characteristics of hops. This part of the experiment fixed the distance between the two Bluetooth transceiver nodes (which is more suitable for the limited indoor environment) and increased the number of relay nodes between them. Relay nodes were added to evenly divide the distance between transceiver nodes. In the experiment, the distance between the two transceiver nodes was 10 meters, with a packet interval of 100 ms and TX Power of -18 dBm.

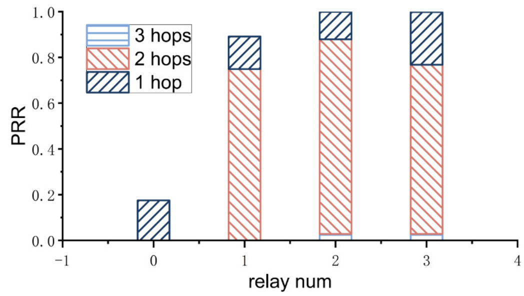


Fig. 7. Effect of relay num on PRR.

The measurement results are shown in Fig. 7. Due to the limited indoor environment, a single relay node achieved a PRR of 89.1% over a relatively short 10-meter transmission path. Adding more relay nodes would lead to significant resource waste. The indoor communication environment is highly complex, and BLE-Mesh broadcasts communication in the public 2.4 GHz band, making mesh node communication highly susceptible to environmental interference. The outdoor measurement of the output power experiments under the same parameters achieved a PRR of 93.06%, while indoors it was only 17.25%. The comparison between relay num = 0 and relay num = 1 highlights the importance of the relay nodes, increasing the PRR by approximately 70%. Interestingly, when relay num = 2, the relay nodes started to be hidden. Throughout the experiment, the proportion of 2-hop communications was the highest, indicating that 5 meters as a single hop distance is very appropriate for indoor environments.

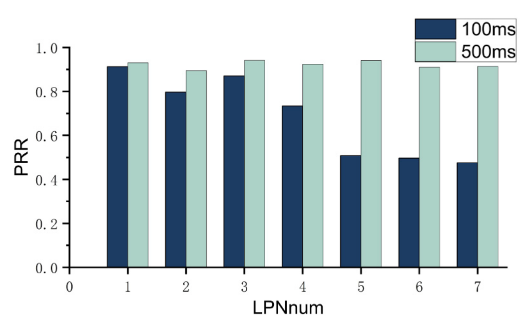


Fig. 8. Effect of LPN num on PRR.

2) impact of low power nodes: Nodes in BLE-Mesh have strong information propagation capabilities not only due to the enhancement of the network's expansion capacity by relay nodes, but also because of the impact of the publish-subscribe mechanism. Multiple LPNs can simultaneously subscribe to a group's messages. In the experiment, a single transmitting node and multiple LPN nodes subscribed to its address were used, with the TX Power set to -18 dBm, to analyze the PRR of LPN nodes under different conditions.

Fig. 8 shows the results for packet intervals of 100 ms and 500 ms. At a 500 ms interval, the PRR did not change significantly with increasing number of LPN nodes, remaining above 90%. However, at a 100 ms interval, there was significant variation, with a noticeable decline when the number of LPN nodes exceeded four. It is important to note that if we only calculate the average PRR of LPN nodes that were active during the experiment, the results for five, six, and seven LPN nodes at a 100 ms interval are 84.7%, 91.56%, and 77.88%, respectively. This situation arises because LPN nodes respond with an acknowledgment when they receive a data packet. This mechanism can lead to an excess of acknowledgment packets received by the source node, causing anomalies.

Espressif's design addresses such network storm scenarios by having the source node emit a signal that instructs some nodes to exit the mesh network, thereby reducing the number of acknowledgment packets. In the experiment, this manifested itself as the number of LPN nodes being reduced to three when more than five LPN's acknowledgment packets were received simultaneously. Thus, it is foreseeable that if more LPN nodes are added at a 500 ms interval, network storms will still occur.

This shows that BLE-Mesh still has design flaws. Although it supports multi-hop and publish-subscribe modes, which can achieve stronger communication capabilities, the mesh network is prone to network storms when there are a large number of subscribing nodes.

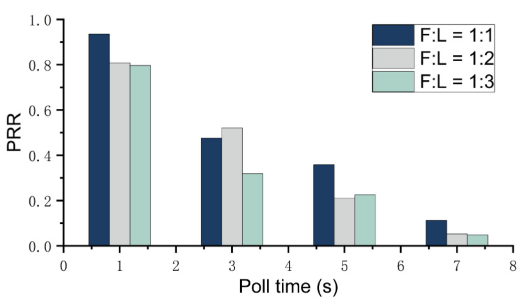


Fig. 9. Effect of friendship on PRR.

3) impact of friend nodes: Friend nodes and LPNs must be connected to form a complete functional unit. Unlike the previous experiments that merely altered the number of corresponding feature nodes, the study of friend nodes essentially explores the characteristics of friendship. A friend node acts as the "open eye" for the LPN while it is sleeping, a temporary buffer. Therefore, the size of the data packet buffer that the friend node sets for the LPN and the time interval the LPN to queries the friend node for packets each time(this duration is called Poll time) are the main factors influencing the communication efficiency between the two nodes. Of course, the rate at which the source node sends data packets that the LPN subscribes to is also a factor, but since its principle is similar to Poll time, no corresponding experiments were conducted.

As shown in Fig. 9, "F:L" represents the number of friend nodes compared to the number of LPNs. The experiment was designed with TX Power = -18 dBm, a packet interval of 500 ms, and each friend node's friend queue size set to 16. Firstly, it is evident that, similar to relay nodes, friend nodes cannot achieve 100% scan coverage under ideal conditions. This implies that as the load on friend nodes increases, the likelihood of packet loss when transmitting through them also increases. A one-to-one ratio of friend nodes to LPNs resulted in the friend queue storing more packets subscribed by that node, thus yielding a higher PRR. However, as Poll time and the number of LPN nodes increase, the friend queue starts to fall short in storing the information subscribed by the LPNs. At poll time = 3 s, even with F:L= 1:1, the PRR drops rapidly while there is still space in the friend queue. This is likely because the friend node, while sending the stored data in the friend queue to the LPN, cannot scan the channel, leading to packet loss. Packet loss becomes catastrophic for PRR as the pressure on the friend node increases. At poll time = 7 s, PRR for F:L = 1:1 drops to only 11.2%.

The exploration of friendship indicates that balancing the storage and transmission rates of packets in the friend queue is crucial for friendship efficiency. A relatively larger friend queue and an appropriately shorter poll time significantly improve PRR. Of course, such choices also need to consider the trade-offs between chip cost and power consumption.

V. Conclusion

The mesh standard, built on the extensive deployment of BLE, exhibits excellent scalability and backward compatibility. It is poised to perform exceptionally well in areas such as industrial IoT, large-scale sensor networks, smart buildings, and smart cities. In this paper, we used COTS devices to discuss the key parameters that affect propagation performance, highlighting how they impact the communication of the mesh network and the issues that arise when these parameters are not properly configured. Although we did not measure a large-scale mesh network, our exploration of various parameters and structural changes has already revealed the limitations of mesh.

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