Bachelorarbeit

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Performance evaluation of Bluetooth Low Energy mesh network

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Kurzzusammenfassung

n den letzten Jahren ist die Nachfrage nach Konnektivität [21] stark gestiegen. Entwicklungen in Bereichen wie Internet of Things (IOT) erfordern die Vernetzung einer Vielzahl unterschiedlicher Geräte. Viele dieser Geräte kommen auch in Bereichen wie Industrie 4.0, Gesundheitswesen oder Heimautomatisierung zum Einsatz.

Für diese Bereiche wurde von der Bluetooth Special Interest Group (SIG) eine Technologie namens Bluetooth Low Energy (BLE) entwickelt. Diese Technologie hat sich aufgrund ihrer Eigenschaften wie geringer Stromverbrauch, Kosteneffizienz und integrierte Sicherheitselemente durchgesetzt.

Um die Leistungsfähigkeit der Bluetooth Technologie zu bestimmen, untersucht die folgende Arbeit ein Bluetooth Low Energy mesh (BLEM) Netwerk anahnd von zwei Experimenten. Dazu werden zunächst die Grundlagen von IOT, BLE und Mesh-Netzwerken ausführlich diskutiert.

Um die Leistungsgrenzen von BLE-Knoten zu verstehen, untersucht das erste Experiment die Übertragungsleistung einer einzelnen BLEM-Quelle mit einer einzelnen BLEM-Senke. In diesem Experiment wird die Leistung des Ein-Hop BLEM-Netzwerks durch Messung der packet delivery ratio (PDR) bei verschiedenen Entfernungen zwischen den BLEM-Knoten bewertet.

Das zweite Experiment zielt darauf ab, ein BLEM-Netzwerk unter verschiedenen Szenarien zu evaluieren. Es untersucht ein Zwei-Hop BLEM-Netzwerk mit einer variablen Anzahl von gesendeten Nachrichten, einer steigenden Anzahl von sendenden Quell-Senke-Paaren und einer steigenden Anzahl von Weiterleitungsknoten. Alle Messungen werden sowohl für unidirektionale als auch für bidirektionale Kommunikation wiederholt. Die abschließende Diskussion der Ergebnisse zeigt, dass unterschiedliche Faktoren die Netzwerkleistung beeinflussen, je nachdem, ob es sich um unidirektionale oder bidirektionale Kommunikation handelt. Zusätzlich wird eine Aussage über die Eignung von BLEM Netzwerken, für die beschriebenen Anwendungsfällen getroffen.

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Abstract

In recent years, the demand for connectivity has increased significantly [21]. Due to developments in areas such as the IOT paradigm, the interconnection of many heterogeneous devices is crucial. These devices are found in areas like Industry 4.0, healthcare or home automation.

For these areas, a wireless technology called BLE has been established by the Bluetooth SIG [19].Due to its characteristics including low power consumption, cost effectiveness, and built-in security elements, it has established itself.

To investigate the performance of BLE technology, the following work examines a BLE mesh network using two consecutive experiments. For this purpose, a detailed examination of the basics of IOT and BLE mesh networks is given.

To understand the performance limitations of BLE nodes, the first experiment examines the transmission performance of a single BLE mesh source (SRC) with a single BLE mesh sink (SK). In this experiment, the performance of a single-hop BLEM network is evaluated by measuring the PDR at different distances between the BLEM nodes.

The second experiment is designed to evaluate a mesh network under different scenarios. It examines a two-hop mesh network with a varying number of sent messages, an increasing number of sending SRC-SK pairs, and a gradually increasing number of relay nodes. All measurements are also repeated for unidirectional and bidirectional communication.

Finally, the results are presented and discussed. These results show that different limiting factors affect network performance depending on whether the chosen communication is unidirectional or bidirectional. Additionally, a statement is made regarding the suitability of BLEM in the described use case.

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Abbreviations

ADV advertising bearer.

BLE Bluetooth Low Energy.
BLEM Bluetooth Low Energy mesh.
BLR Bluetooth Long Range.

CSR Cambridge Silicon Radio.
CSV comma-separated values.

ESP-BLE-MESH Espressif Bluetooth Low Energy mesh.

GATT generic attribute profile bearer.
GUI graphical user interface.

IDE integrated development environment.
IOT Internet of Things.

OOB out of band.
opcode operation code.

PDR packet delivery ratio.
PDU protocol data unit.
PHY physical layer.

RTT round trip time.

SAR segmentation and reassembly.

SEG Segmentation indication bit.

SEQ sequence number.

SIG Special Interest Group.

SK sink.

SRC source.

TID transaction identifier.

TTL time to live.

UUID universally unique identifier.

Wi-Fi wireless fidelity.

Symbols

cm - *Centimeter* - Unit of measuring distance in the International System of Unit, equal to one thousandth of a meter.

m - *Meter* - Unit of measuring distance in the International System of Unit.

bit/s - *Bit per second* - Unit of data transmitted per second over a communication link in a data transmission system.

bit - *Binary digit* - Unit of a logical state information in computing and digital communications.

byte - *Byte* - Unit of a logical state information in computing and digital communications, equal to eight bits.

dBm - *Decibel milliwatts* - Unit of power measurement in telecom and signal processing.

kilobit - *Kilobit* - Unit of a logical state information in computing and digital communications, equal to 1000 of bits.

megabit - *Megabit* - Unit of a logical state information in computing and digital communications, equal to 1000 of kilobits.

MHz - *Megahertz* - Unit of frequency in the International System of Unit.

msg/s - *Message/second* - Unit of messages per second.

ms - *Millisecond* - Unit of measuring time in the International System of Unit, equal to one thousandth of a second.

s - *Second* - Unit of measuring time in the International System of Unit, equal to one sixtieth of a minute.

1 Introduction

The motivation for this work is given in this chapter. It also discusses the role of a wireless connection in the context of IOT. Finally, two use cases with example applications are described to enhance the understanding of IOT.

1.1 Motivation

As described in section 1.3, IOT devices are used in many ways. In addition, IOT devices should be low cost because they are embedded in a large number of electrical devices. Due to its characteristics such as low power consumption, cost-effectiveness, and built-in security elements, BLE has established itself. BLE is a wireless technology with a wide range of use cases [21].

One use case is the establishment of a mesh network communication. Mesh networking enables communication between a large number of nodes, where any node on the network can exchange data with any other node. This can be done either directly or via multi-hop communication. Such a network is self-organizing, self-healing, and enables path diversity.

The purpose of this thesis is the evaluation of the performance and behavior of the BLEM protocol. This protocol is designed by the Bluetooth SIG and implemented on ESP32-C3 development boards. The ESP32 boards are developed by Espressif in China and the code used to implement the logic is written in C. Under different load and spatial scenarios, the network behavior of the ESP32 boards is evaluated. The aim is to determine whether the measured results of the ESP32 boards are similar to the results investigated in the section 3.2 and 3.1.

This work is further divided into four chapters. Technical basics are given by the second chapter. Here, the Bluetooth communication is introduced. Additionally, an architectural overview of the implementation on the ESP32 boards is given. The state of the art of related work is presented by the third chapter. While in the fourth chapter the experiment and the measured data will be described. A discussion of the results and an outlook for further work is given in the last chapter.

1.2 Internet of Things

In the following section the term IOT is defined. Since this thesis is in the context of IOT and its usage, a detailed view of the IOT topic is given.
The term *IOT* refers to a network of heterogeneous physical devices. These devices can be vehicles, home appliances, and other items embedded with sensors, software, and connectivity. Most of the devices used for IOT are under constraints such as battery usage or low computing power. Through the use of a wired or a wireless communication, devices are enabled to exchange data directly with each other or with other systems over the Internet [14]. Direct wireless communication is discussed in more detail in the following thesis.
A higher level of optimization, automation and maintenance is achieved through the use of IOT devices [21]. Driven by the given reasons and low prices, the use of IOT has been increased over the past years in home automation and in the industrial context. Furthermore, a doubling of the number of IOT devices used worldwide, up to 30 billion, is expected in the next 7 years [16]. The upward trend also goes hand in hand with increased connectivity. Derived from the previously mentioned constraints of the IOT devices, a low-power communication technology is needed to exchange the data.

1.3 Use cases

The 1.3 section is provided to give a better understanding of how IOT devices might be used. Therefore, a brief description of two possible use cases for an IOT application is presented.

1.3.1 Smart Home

There are many applications for IOT. In this case, a closer look at on smart homes in the context of buildings is taken. Therefore, a sample building is shown in Figure 1.1, equipped with fire alarms in every room. The focus here is, to enable a general fire alarm in this building. Suppose there is a room in our building that is threatened by fire. In this case, every fire alarm in every room in our building should sound. This requires nodes that can communicate with each other independently of a wired power supply or wired communication backbone. Otherwise, communication could be interrupted in the event of a fire. To ensure that each device is included in the alarm sounding in the event of a fire, reliable communication is also required on the network. In addition to the fire alarm scenario, a missing node should be detected by other nodes to output the missing state to the user.

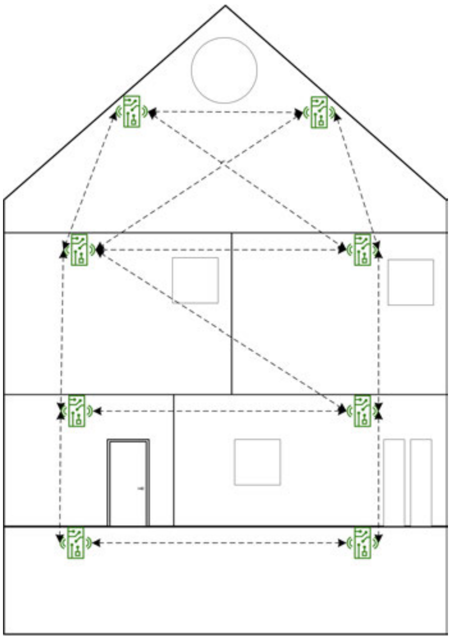


Figure 1.1: Example for connected fire alarm in a smart home use case

As mentioned above, a wireless communication technology that meets the reliability requirements is needed. Messages are also required to periodically inform other nodes of their own node status. Furthermore, a long battery life has to be supported by low energy consumption during operation. On the other hand, the need to transfer large amounts of data at the same time in terms of network load is not present. Heartbeat messages, status messages and control messages to add other nodes to the network are the only data transmitted.

1.3.2 Health care

The second example scenario considered in this thesis is a hospital scenario. Here the SRC nodes represent battery-powered sensor nodes, mounted on each bed. These nodes monitor the patient's vial values, such as temperature or whether the patient is in bed [13]. The collected data is then sent to a central server within the hospital. Due to the mobile nature of hospital beds, long battery life and reliable message delivery from anywhere in the hospital building are required. Examples of such needs include elevator rides or hours of surgery. The requirements for the message interval and the amount of data transmitted per message are relatively low.

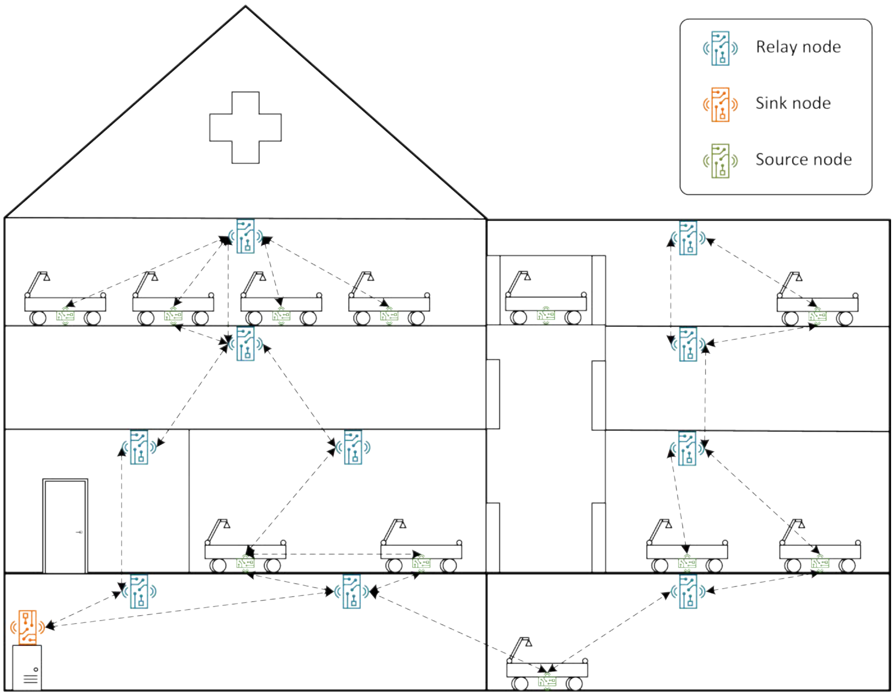


Figure 1.2: Example for connected patient beds in a hospital scenario

As shown in Figure 1.2, there are multiple mobile SRC (beds) that send their data to a SK, the central server. Thus, the topology the topology of such networks is not static. The technology must be able to handle regular connection and disconnection of different nodes. Finally, the technology must be able to handle a more or less dense network with a longer or shorter transmission distance. To accomplish this, relay nodes are required whose primary responsibility is to transmit the received traffic back into the network.

2 Basics

To improve the understanding of the BLE technology and its usability, this chapter is given. For this reason, a detailed description of the BLE technology is presented. Finally, the implementation of the BLEM architecture on the ESP32 boards is shown.

2.1 Bluetooth

The way devices are connected and communicate with each other has been transformed by Bluetooth [7]. Bluetooth is a wireless communication technology characterized by characteristics such as low power consumption and cost effectiveness. It is a widely adopted standard for short-range wireless communication between various devices, including smartphones, laptops, tablets, and wearable devices [21]. The first iteration of Bluetooth technology was known as Bluetooth Classic. As an evolution, BLE was introduced in 2010 [22]. This technology is based on a low-power, short-range radio communication protocol that enables fast and secure data transfer between devices. This section provides an overview of the technical specifications of Bluetooth. In particular, a closer look at BLEM and its structure is taken.

2.1.1 Communication

Transmission power similar to Bluetooth Classic is provided by BLE technology. The maximum transmission power is about 10 dBm in the Bluetooth 4 standard [19] (p. 2181) and 20 dBm in the Bluetooth 5 standard [20] (p. 2536). In general, reduced power consumption in BLE is achieved by minimizing the time the radio and transmitting small amounts of data. The 2.4 GHz band with 2 MHz spacing is used by BLE and has 40 channels. For the BLE mesh purpose, three channels are utilized to advertise the data through the network. More specifically, channels 37, 38, and 39 are reserved for the exchange of data through the advertising bearer (ADV). The remaining 37 channels are used to exchange data through the connection-oriented approach, called generic attribute profile bearer (GATT). To minimize interference from wireless fidelity (Wi-Fi) systems operating in the same 2.4 GHz band, the BLE advertising channels are located at 2402, 2426, and 2480 MHz, as shown in 2.1.

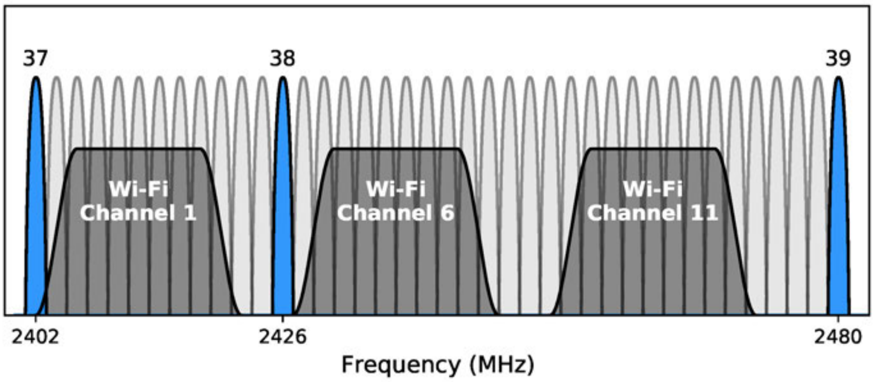


Figure 2.1: BLE channel division [4]

The advertising channels are used by BLE to broadcast short messages for device discovery, connection establishment, and beacon services. Advertising messages are sent periodically, beginning with a broadcast on all three or a subset of the advertising channels. This enables fast discovery and connection, unlike Bluetooth Classic, which requires 32 channels to be scanned for the discovery service [22]. The advertising interval ($t_{interval}$) can be set between 10 ms and 10.24 s, with a step size of 0.625 ms. A small random time (t_{rand}) between 0 ms and 10 ms is added between every advertising event. This random time prevents multiple devices from overlapping transmissions. Otherwise, there would be an increased risk of message collision if all devices in range were to scan and retransmit a message at the same time. Additionally, the number of repetitions (n) for each message can be configured. This results in a maximum advertising event duration of

$$t_{adv_{event}} = \sum_{i=1}^{n} (t_{interval} + t_{rand})$$

All data exchanged in the BLE mesh network is accomplished by sending messages. Messages are defined as having an operation code and associated parameters. Used to establish a bidirectional or unidirectional communication, messages can be separated into acknowledged or unacknowledged messages. The former message type require a response, the latter do not. In order to receive related data, messages sent through the advertising channels must be scanned by a node. Therefore, nodes are always in scan mode when there is no data to be advertised. If there is no response to a sent acknowledge message, a timeout event is passed to the application layer to handle the missing acknowledgement. As long as the acknowledgement is missing and no timeout event has occurred, no further messages can be sent to the associated node via its unicast address [10].

Finally, there is a segmentation and reassembly (SAR) mechanism which allows to split messages into up to 32 segments. Thus, the maximum message size is 384 bytes for a segmented message and eleven bytes for an unsegmented message, excluding up to 3 bytes for the operation code [10] (p. 22).

To avoid SAR overhead, only unsegmented messages are utilized in the following experiment. While acknowledged messages are used to determine the RTT, unacknowledged messages are used to examine the PDR. A size of 144 bits will be assigned to each message. This size is based on a 16 bits payload, described in more detail in 4.1, and a overhead of 104 bits, described in more detail in 2.1.3.

2.1.2 Profile specification

Connectionless communication through mesh networking technology is enabled through the use of BLEM. A more detailed look at the communication stack and the topology of the network is provided in this section. An overview of the architecture of the BLEM specification on ESP32 chips is also discussed.

2.1.3 Stack layers

To gain a better understanding of how the Bluetooth mesh protocol works, the layered architecture of the current Bluetooth profile specification is shown in Table 2.1.

Protocol Stack	**Function**
Model layer	Defines application models and thus functionality
Foundation model layer	Defines models to configure and manage a mesh network
Access layer	Defines format of application data, controls data encryption/decryption and maintains network context
Upper transport layer	Handles encryption, decryption and authenticates application data. Handles transport control msg like heardbeats
Lower transport layer	Handles SAR of transport PDUs
Network layer	Defines addressing of transport messages, rules to relay/accept/reject messages
Bearer layer	Defines how to exchange message among nodes using ADV or GATT
BLE core specification	BLE stack

Table 2.1: Bluetooth mesh protocol stack [15]

There are two specific layers that need to get explained to better understand BLEM. First, the model layer. Functionality based on the device product type is implemented using models. There are several models available, identified by the SIG [5]. Starting with simple generic models to represent a IOT device like a switch to turn on/off a light. Further to special models used to represent a light bulb with all its functionality like brightness and light color. Finally, there are vendor models that can be used by vendors to meet their own requirements. The vendor model is also utilized in this thesis to enable data exchange in subsequent experiments.

The second layer to be explained is the bearer layer. Based on the connectionless approach of BLEM networking, there is a need for messages to be flooded throughout the network. For this purpose, the ADV is used to transmit the data over the BLE advertising channels. This bearer carries most of the traffic on the network.

To support non-mesh devices, a second bearer is part of the bearer layer. GATT is used to establish connection-oriented, point-to-point communication between two devices. Coupled with the proxy node feature, GATT clients are allowed to be part of a BLEM network. Therefore, Bluetooth proxy protocol PDUs are converted by proxy nodes into mesh PDUs and vice versa. This feature can be used to connect devices such as smartphones, providing a graphical user interface (GUI) for network control.

To illustrate the model organization within a BLE mesh node, the following Figure 2.2 is shown.

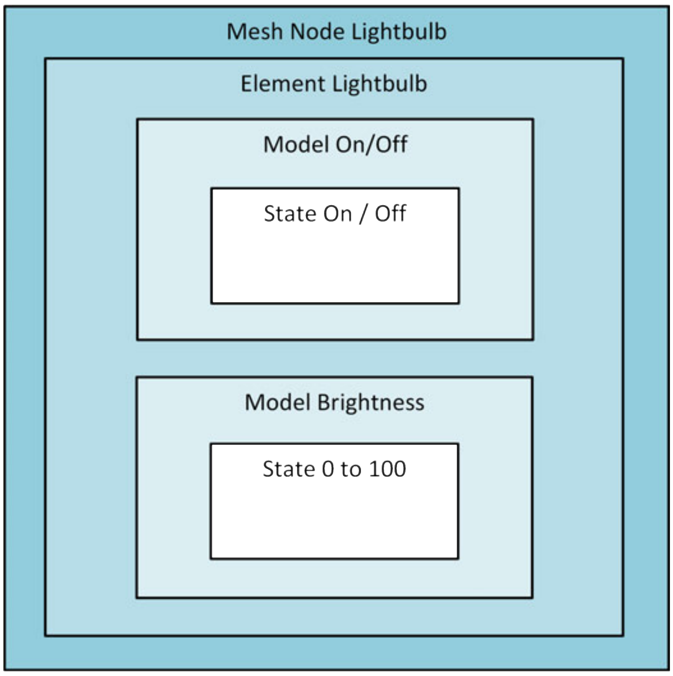


Figure 2.2: Example lightbulb node with element and two models

One or more elements within a model are held by a node. State is the term used by a data element that represents the status of a particular model. Values such as *on* or *off* can be used to represent a generic on/off model state. Each model can be either a client, which does not contain state, or a sever, which does. Client models can send access messages, which are used to get or set values in server models. In addition to access messages, control messages sent by both model types are used to handle mesh network operations in the upper transport layer [8]. Control messages are used to satisfy the heartbeat approach. To send a mesh network message by the BLE technology, the message needs to be encapsulated in the underlining PHY advertising message. An example of an undirected advertising event used in this thesis is shown in Figure 2.3.

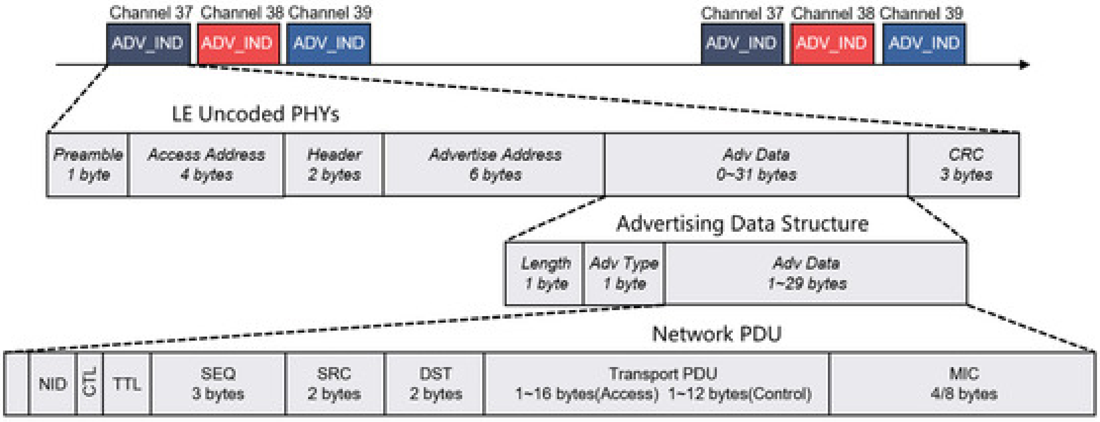


Figure 2.3: Bluetooth mesh network encapsulation. Network PDU based on PHY [12]

The first ADV PDU is related to the PHY called LE uncoded PHY. The PDU has a total length of 41 bytes, including a maximum payload length of 31 bytes. Within this payload, a specific advertising structure is included. Each ADV structure consists of a field of 1 byte length and another field of 1 byte type. The remaining bytes are used to hold the network PDU. The PDU shown in the figure above contains the following fields:

IVI Least significant bit of the initialization vector index.

NID Network identification.

CTL Indicates the type of message (Access/Control)

TTL Time-To-Live

SEQ Sequence number.

SRC Source element address

DST Destination element address

Transport PDU Next layer data

NetMIC Network message integrity check (MIC)

The up to 16 bytes of the transport PDU are used by the lower transport layer to provide a reliable transmission mechanism for the upper transport PDU, including segmentation and reassembly of up to 380 bytes messages.
Using the upper transport layer PDUs, the access and control messages are generated by the upper transport. When transmitting an access message (CTL = 0) the NetMIC is reduced by 4 bytes because an additional MIC is added at the transport layer. This is called TransMIC, meaning Message Integrity Check for Transport and allows encryption using application keys, which are described in the following section. In this thesis, the unsegmented control messages are used to exchange data between the different nodes and so the corresponding transport PDU is about 12 bytes. The unsegmented control message PDU is illustrated in the Figure 2.4 below.

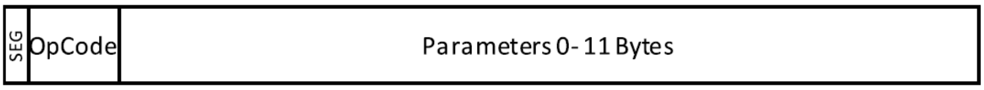


Figure 2.4: Upper transport layer PDU, unsegmented control message [12]

As shown in the Figure above, the unsegmented control message PDU is carried by a 1 bit named Segmentation indication bit (SEG). It is represented by the field whether the message is unsegmented or not. The remaining 11 bytes are divided into an operation code (opcode) field and a parameter field. The former field has a length between two and three bytes, whether it is a vendor opcode or standard opcode. The parameters are held by the latter fields, which in our case is the application generated payload. So the maximum amount of application payload that can be transmitted with an unsegmented control message is about eight bytes.

2.1.4 Provisioning

Since this thesis is about BLE nodes, understanding how a node is defined in the BLEM context is necessary. A node is a device that has been provisioned and is a member of the mesh network [10]. Provisioning is the process of adding a new device to a Bluetooth mesh network.
Up to 32,000 nodes can be provisioned to a network on the fly [6]. To complete the provisioning process, unicast address, network key, and application key are received by a node. Access to a particular network is granted by the network key. In addition, access

to a specific BLEM network application is granted by the application key, which is bound to a specific network key. The provisioning process is managed by a provisioner. This can be done either automatically by a node responsible for a provisioner role, or manually by a user using scanner applications.

Initially, a node that is requesting access to a BLE mesh network sends advertising messages to be discovered by a provisioner. To support non-mesh devices as provisioners, the messages are sent on both BLE communication bearers [10]. These messages, also known as beacons, also include the node's BLE address, its universally unique identifier (UUID), and whether out of band (OOB) authentication is enabled [10]. The UUID is used to distinguish between unknown and known nodes, the latter being added to the mesh network. Next, the new node is prompted by the Provisioner to share its capabilities. The data exchanged includes information such as the number of elements supported or the ability to return a value to the user. For the purpose of encrypting/decrypting messages, public keys are exchanged in the next step.

To increase the security level, the OOB authentication can be utilized. To achieve this, a randomly generated number from the output of a node is entered by the user into the input of the provisioner, or vice versa. Also, the above mentioned UUID can be used to prevent foreign nodes from connecting to the network. This feature is utilized in this thesis to ensure an undisturbed experimental process. The described provisioning process is visualized in the following diagram 2.5. The process corresponds to the provisioning process used in this work to add new nodes such as vendor clients and vendor servers to the network.

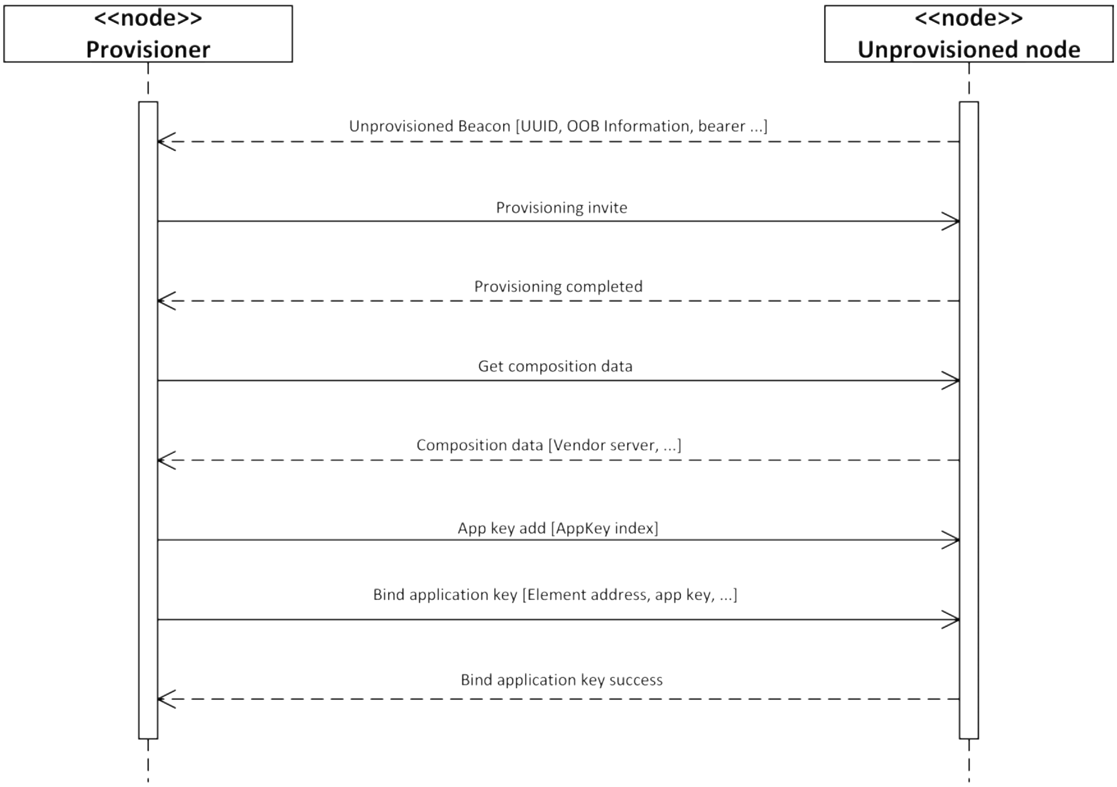


Figure 2.5: Sequence diagram of BLE mesh provisioning in ESP-IDF framework

In case of broken or faulty nodes, these nodes need to be removed from network. To ensure that nodes containing security keys, are not used to compromise a network, a replacement of the entire set of keys is needed. To do this, the provisioner adds the faulty nodes to a reject list. A key refresh process is then initiated. Therefore, new network and application keys will be issued to all nodes except those on the reject list [9].

2.1.5 Node features

The functionality of the Bluetooth mesh node is generally based on the type of product the device represents. However, additional functionality may be present in nodes related to network operations or supporting other nodes within the network. As specified by the Bluetooth SIG, there are several node features available. These features can be configured as needed within the programming code.

Relay feature

The capability to receive and forward network PDUs over the advertising bearer to enable larger networks.

Proxy feature

The capability to receive and forward network PDUs between the protocols given with the bearer layer

Low-Power feature

The capability to operate within a mesh network at significantly reduced receiver duty cycles. This leads to a lower power consumption through establishing a friendship with a friend node.

Friend feature

The capability to store network PDUs destined for low-power nodes. PDUs will be forwarded only at the request of the low-power node.

2.1.6 Network topology

Managed flooding technology is used to achieve a targeted communication in the Bluetooth mesh network. Using the ADV, messages are continuously scanned and retransmitted by the nodes in the network. Each message has its own time to live (TTL), which is decremented before it is retransmitted. To satisfy the managed part of the flooding network slice, the message is only rebroadcast if its TTL is greater than zero and the message has never been rebroadcast by the node before. To avoid multiple message forwarding, a message cache is used to store the SRC address and sequence number (SEQ) for each network message Group [10] (p. 48). The size of the cache can be configured as needed.

In addition, whether a message is addressed to itself can be determined by a node based on its destination (mesh) address. There are three types of addresses used in messaging. First, a message can be sent to the smallest addressable unit held by a node, called an element. This is done using the unicast address. Second, the group address, which is used to send a message to multiple elements from one or more nodes. This type of address can also be utilized to communicate with all nodes of a model type, such as proxy nodes or friend nodes. The final type of address is called a virtual group. This group address is used to implement a publish/subscribe functionality, that will not be discussed further in the following thesis. All of these addresses are different from a regular public or private BLE address.

An example network topology with the different node features described in 2.1.5 is shown in the following Figure. To represent possible mesh communication within the network each node is labeled with letters and connected to a varying number of neighboring nodes using different communication bearers provided by the Bluetooth mesh profile specification [10].

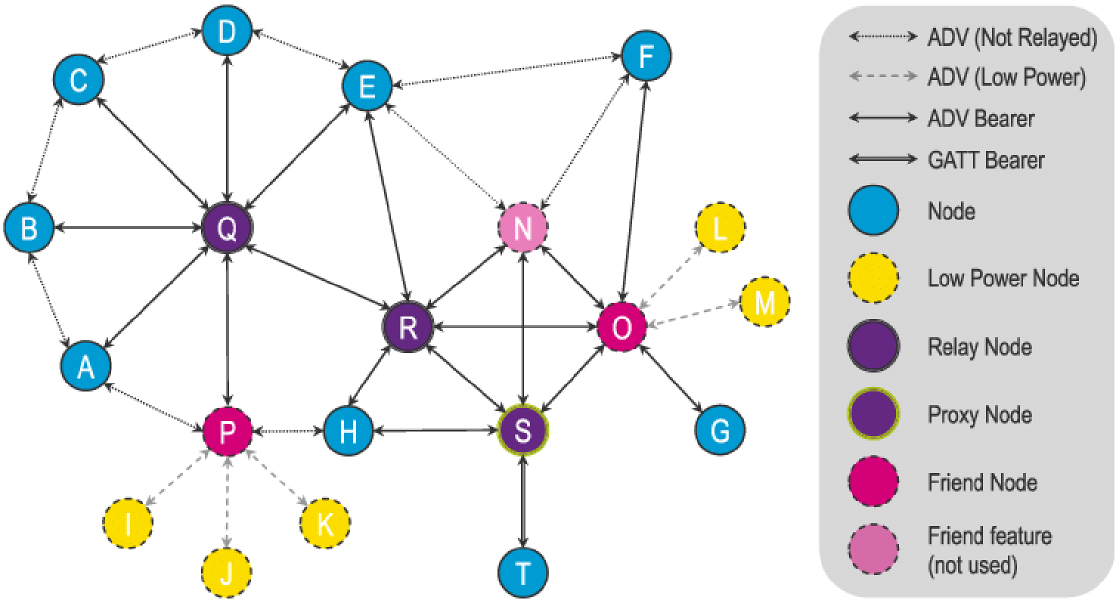


Figure 2.6: Example BLEM topology [2]

2.2 ESP-BLE-MESH architecture overview

Since ESP32 chips are used in this thesis, an overview of the current implementation of the ESP-BLE-MESH protocol stack is given. ESP-BLE-MESH is implemented and certified based on the latest Mesh Profile v1.0.1 [10].

To configure and use the ESP32 chips, a framework called ESP-IDF is provided by the manufacturing company named Espressif. For the following thesis, the experiments are written in C programming language using the ESP-IDF Release v5.0.1 in the CLion IDE. To illustrate the implementation, the layers that make up the architecture of ESP-BLE-MESH are illustrated in the following Figure.

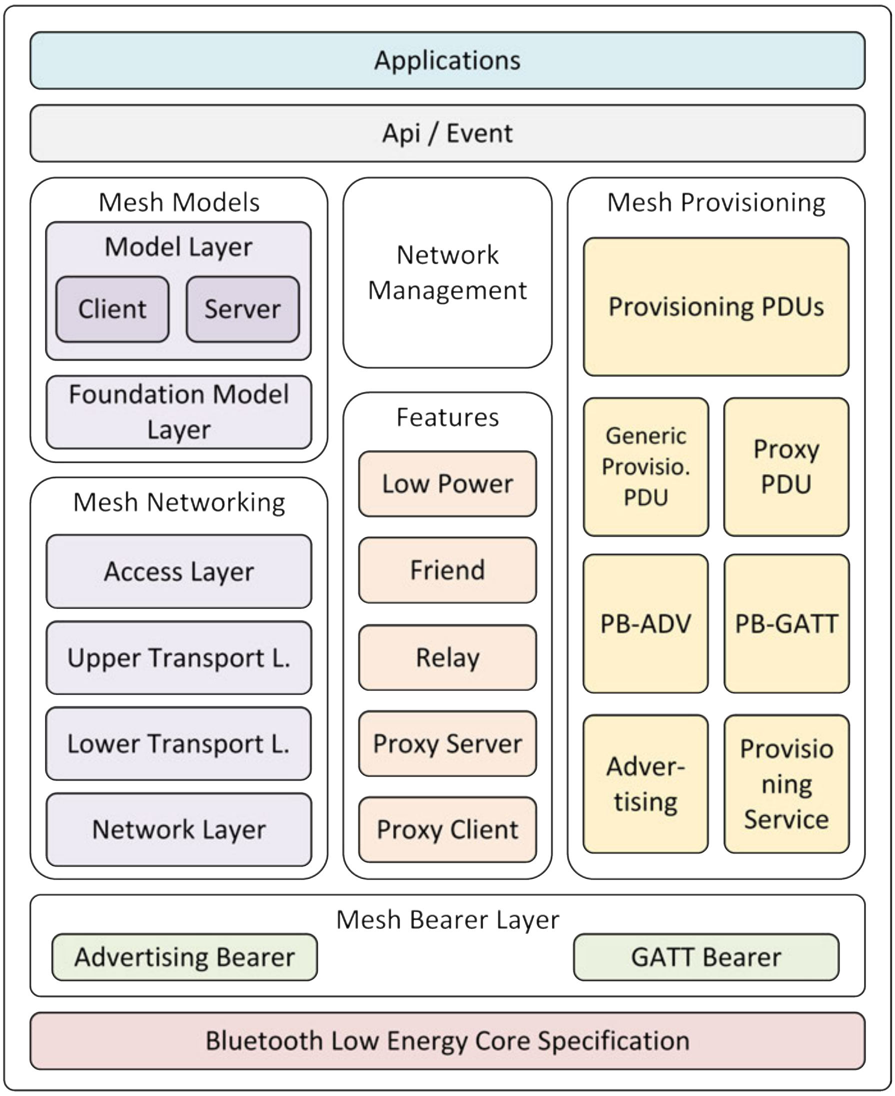


Figure 2.7: ESP-BLE-MESH architecture diagram [17]

In general, the ESP-BLE-MESH architecture can be divided into five key parts. The first part, which constitutes the core of the ESP-BLE-MESH architecture, includes mesh models, mesh networking, and mesh provisioning within the mesh protocol stack. The two model layers prescribed by SIG models are encompassed by the mesh models part.

Messages sent from ESP-BLE-MESH nodes are processed by mesh networking, as described in 2.1.3. Mesh provisioning is used to add new ESP-BLE-MESH nodes to the network. More details about the provisioning process are given in 2.1.4.
Several node types based on SIG-defined features are given by the features part. The data transmission between the BLEM protocol stack and the BLE is handled by the mesh bearer layer, which is the crucial layer. For this purpose, it is built on top of the BLE core and is described in more detail in section 2.1.3.
The underline PHY is used by the BLE core to transmit the data. To archive this Espressif has chosen the Low Energy Uncoded PHY with a datarate of 2 megabits, as well as the newly coded PHY with a datarate of 125 kilobit and 500 kilobit, to approximately quadruple the transmission range of Bluetooth 4 without increasing the required transmission power [3] [18].

3 Related Work

An description of the current state of the art in BLE mesh networking is given in the following section. To the best of the author's knowledge, BLEM technology has not yet been evaluated with real-world experiments on ESP32 microcontrollers.

3.1 Cambridge Silicon Radio BLE mesh evaluation

As a proprietary solution, the Cambridge Silicon Radio (CSR)mesh protocol has been developed by the CSR company. The suitability of CSR BLE mesh networks in the context of IOT is examined in the paper [23].
After a detailed overview of common wireless communication standards, several experiments are described. The experiments are implemented on CSRmesh development boards and Flairmicro BTM101 modules. A CSR1010 Bluetooth chip with the Bluetooth 4.2 standard is used by both devices.
The first experiment is started with a baseline measurement to determine the maximum transmission range within a two-node mesh network. At a transmission power of eight dBm, the result given by the experiment is an even PDR up to a distance of 18 m.
Next, a mesh network with up to 12 relay nodes is examined. As shown by the results, there is a higher PDR for the lower message send rate of 10 msg/s sent through the network than for the higher message send rate of 20 msg/s. Additionally, the number of sending SRC-SK pairs is increased. Here, the results indicate a greatly reduced PDR for multi-path communication compared to a single-path message flow through the network.
As a second experiment, a simulative approach is used to study the mesh protocol in a large network with different types of topologies.
The experimental setup of the first experiment of the paper is used by this thesis to perform the baseline measurement. This is done to study the PDR under increasing distance. In contrast to the hardware used in the paper, this work is implemented on

an ESP32-C3 development board using the Espressif ESP-IDF framework environment with the BLEM protocol.

3.2 Nordic semiconductor BLE mesh evaluation

In paper [1], the BLE has been described, and several points of the BLEM technology are examined in more detail. First, the architecture of the Bluetooth mesh standard, including the underlying Bluetooth node communication, is analyzed. Second, a statistical estimation of the RTT is given. This is followed by an experimental evaluation. The baseline measurement examines the commutation flow between two nodes by determining the RTT. Subsequently, the number of relaying nodes is gradually increased. This is done by analyzing the effect of more nodes within a two-hop mesh network on the RTT. A second set of measurements is then performed using 22 nodes, each with a corresponding single-board computer accessible over a wired Ethernet backbone. So the BLE communication flows are allowed to be evaluated by the researchers.

Finally, the authors used the knowledge gained from the statistical and experimental parts to build a theoretical model. Within this model, a large and dense BLEM network is simulated to analyze the limitations of the Bluetooth mesh standard.

As a main conclusion, it is shown that the backoff time has a large impact on the RTT. This time is used to avoid message collisions for messages sent via the BLEM network. Furthermore, a higher number of relay nodes leads to a lower RTT, as indicated by the results of the two-hop communication measurements. This is due to the higher probability of having lower backoff times and receiving a message on the first channel 37 than with fewer neighbors.

The experimental setup for the two-hop measurement is used by this work to perform the second and third experiments. As described in 4.1.3, the experiments are realized with a mesh network of maximum ten nodes to study the RTT. In addition, the PDR is measured during all experiments in this thesis. Also the hardware used in this work is different from the Nordic nRF52832 modules used by the authors.

4 Experiment

The experimental design is described in this chapter. Therefore, two experiments are described in detail. First, a conceptual overview is given. Second, the data obtained from the experimental measurements are presented and interpreted.

4.1 Conception

In order to understand how the experiments are conducted and how they support the achieving goals of this thesis, a detailed view of the experimental design is given in this section. Therefore, the ESP-IDF framework release v5.0 and the Jetbrains CLion integrated development environment (IDE) are used to configure the boards with the given parameter.

4.1.1 Measurement

A metric is needed for the comparison of network behavior under different experimental conditions. Therefore, two key metrics are identified.

RTT

- The time required to send a message from the SRC node to the SK node and vice versa

PDR

- The ratio between the number of sent messages (n_{rx}) and the number of received messages (n_{tx})

$$r_{pdr} = \frac{n_{rx}}{n_{tx}}$$

Each metric is determined by the log files generated from SRC nodes and SK nodes. During the experiment, the log data is transmitted by connecting these nodes with a computer via UART.

PDR and RTT, are measured by two different types of advertising messages. The former is measured using the unacknowledged control messages. For this type of message, a response by the sender node is not needed. As a result, the PDR is not affected by the higher network load caused by reliability and timeout functionality.

On the other hand, the RTT must be measured by an acknowledge control message, which forces the SK node to send an acknowledge message to the SRC node. The time elapsed between successfully sending a message and receiving a response by the SRC node can be determined by this acknowledgment. In addition, reliable application-based message delivery can be achieved using acknowledged messages. Therefore, a timeout is generated if no acknowledgment is received in a given time. For the purpose of this work, the reliable message transfer is not used. To avoid SAR overhead, only unsegmented messages are used in the following experiment. A 16 bits transaction identifier (TID) is sent within the message payload, to distinguish the messages from each other. This TID is increased for each unrepeated message. For each of the two measurements, 300 messages are sent. Every measurement is repeated six times.

The BLE PDU, described in more detail in section 2.1.3, results in an advertisement message with a length of up to 47 bytes. With the inclusion of the three bytes opcode, an unsegmented control message allows the transmission of eleven bytes of payload. The control message used for the following experiment is 41 bytes long, including the 2 bytes payload. Each message is transmitted once per advertising channel, and thus, a single message is retransmitted three times by each node during one advertising event.

The ESP32-C3 boards are build by Espressif with two antennas to allow simultaneous scanning and advertising. To make the RTT results comparable to the work described in 3.2, only one antenna is used in this work. All experiments are conducted during normal working hours on the second floor of the building Berliner Tor 7 at the Hamburg University of Applied Sciences. The rooms on this floor are equipped like a normal office with computers and peripherals.

The results are printed to a comma-separated values (CSV) file and the following graphs are generated using matplotlib and python programming.

4.1.2 Single-hop - baseline measurement

As described in sections 2.1.1 and 2.1.6, a managed flooding approach is used by the BLEM technology to transmit data through the network. Like mentioned in section 1.1, the purpose of this thesis is to evaluate the overall performance of the BLEM network technology. Therefore, the first scenario presented in this section is used to determine the maximum transmission distance between two nodes forming a BLEM network. To do so, the distance between two nodes is gradually increased while measuring the RTT and PDR.

The expectation about the measured PDR is that as the distance increases, the PDR will be decreased until no messages are delivered beyond a certain distance. To examine this single-hop network, a two-node testbed is used, as shown in Figure 4.1.

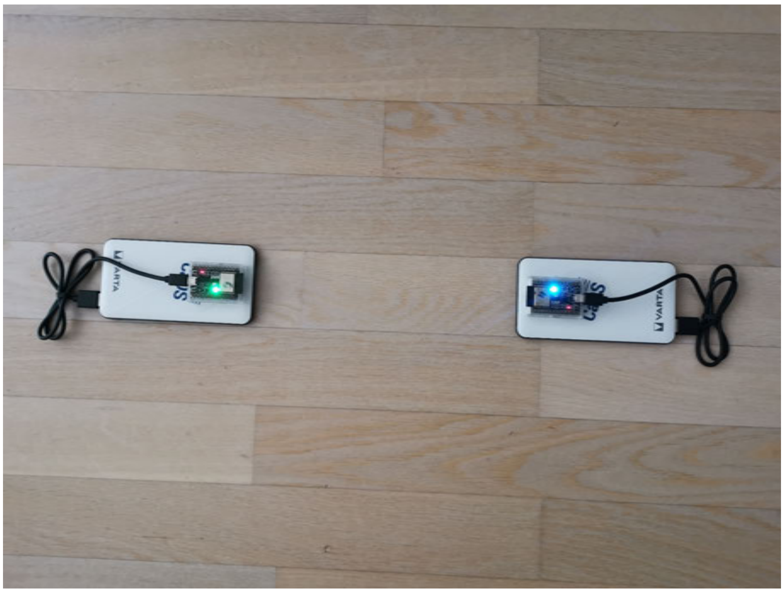


Figure 4.1: Two-node testbed to perform the first experiment

For the realization of the first experiment, the SRC node is a vendor client model that establishes a unidirectional communication with the SK node. To do so, unacknowledged messages are sent over the network by the SRC node through the ADV bearer. The SK node is a vendor server model that is added by the provisioner node via its unicast address. During the experiment, the two nodes were gradually separated from each other, starting from a distance of one meter up to 30 meters. This is the only parameter that was changed during the first experiment. To have a clear view of the other parameters set during the first experiment, the Table 4.1 is shown below.

Parameter	**Value**
Node distance	1-30 m
Maximum node count	2
PDU size	2 bytes
Messages send	10 msg/s
SRC-SK pairs	1
PDU retransmission count	3
Advertising interval / ms	10 + rand(0-10)

Table 4.1: First experiment parameter table

4.1.3 Two-hop - mesh performance measurements

To achieve the performance evaluation approach, another experiment with a two-hop mesh network is required. With the maximum range determined in 4.2.1, it can be ensured that there is no direct communication between SRC and SK nodes.

It is important to understand that there is a TTL of 127 for each message, but it is filtered out for retransmission if the node has seen it before. This results in a maximum number of repetitions per message based on the maximum number of relaying nodes available in the network.

An overview of other parameters used during the experiment is given in Table 4.2.

Parameter	**Value**
Maximum node count	10
PDU size	2 bytes
Message Timeout	2000 ms
Messages send	10 msg/s, 20 msg/s
SRC-SK pairs	1-3
Relaying neighbor nodes	1-4
PDU retransmission count	3
Advertising interval / ms	10 + rand(0-10)
Send buffer size	60 PDU

Table 4.2: Second experiment parameter table

Table 4.2 contains four scenarios that were conducted during the experiment.

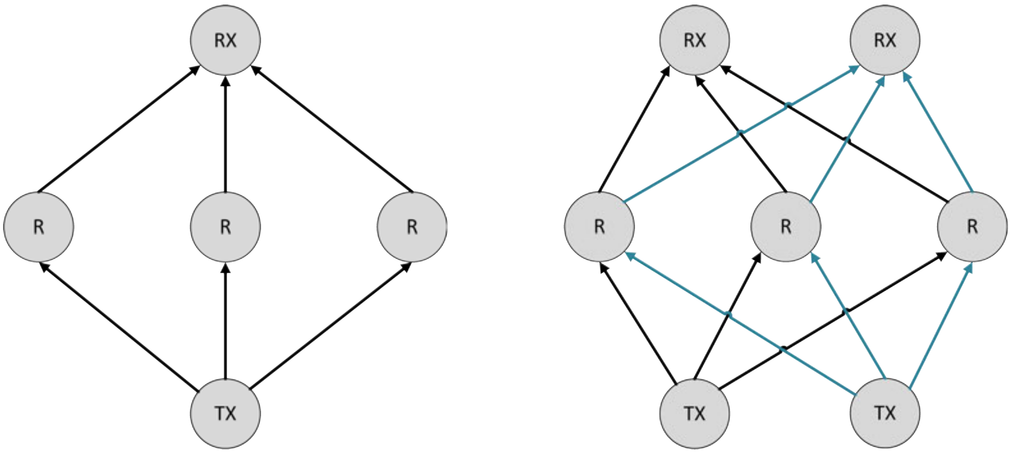
Message send interval

To study the network behavior under a normal load and an overload scenario, two message transmission intervals are defined. For this purpose, the messages are sent within an equidistant time interval. In terms of messages sent per second, the time interval between two consecutive messages is about 100 ms for the higher send interval and 50 ms for the lower send interval, to send 10 msg/s and 20 msg/s respectively. So, in our case, the maximum duration of an advertising event for a single message is about 60 ms (3 retransmissions, each with a maximum of 20 ms advertising interval), which conflicts with the lower send interval. For this reason, lower PDR results are generally expected for the lower send interval.

This configuration also applies to relaying and acknowledging nodes. In particular, this is to determine how the behavior of the BLE mesh stack is affected if more messages are attempted to be sent by a node than allowed by the advertisement duration configuration.

Single-path, multi-path communication

This scenario is designed to examine the effect of having only one SRC node sending messages into the flooding oriented network, versus having two SRCs sending messages in parallel. Each message sent by an SRC node is directed to a specific SK node, which is assigned by the provisioner node. When communicating with multiple SRC nodes, it is expected that the PDR results per node will be worse than for a single node. This expectation is based on the fact that the entire communication must be retransmitted through the relay nodes, which are subject to the same transmission constraints as any other node. To gain a better understanding of network communication, an example message flow is shown in Figure 4.2.



(a) Single-path (b) Multi-path

Figure 4.2: Example communication path in a BLEM network, using relay nodes (R) to enable a two-hop message flow

As shown in Figure 4.2 the nodes are arranged in groups. One group containing the SRC nodes, another group containing the relay nodes whose sole duty is to relay the received message, and the last group with the SK nodes. Based on the result shown in Figure 4.3, a distance of 15 m is chosen between the SRC node and the SK node to avoid single-hop communication between those nodes. To allow two-hop communication, a distance of about seven and a half m is chosen to center the relay nodes. Relay nodes transmit at the maximum possible power of +24 dBm, in addition to the other node groups, which transmit at -9 dBm. The node spacing within groups is about one cm.

Relay nodes

After conducting a first two-hop experiment, the question arose as to whether varying the number of nodes relaying the received messages might affect the measured metrics. To determine how the increased network traffic caused by the relay nodes affects the RTT, the two-hop measurements are repeated with a gradually increasing number of relay nodes from one to four. Grounded in the findings described in paper [1], which indicate that more relaying neighbors result in a shorter scanning time and thus a shorter RTT, it is expected that a lower RTT will also be caused by an increased number of relay nodes in this study.

Unidirectional / Bidirectional communication

Depending on the chosen type of communication between the SRC and SK nodes, the number of messages required to establish unidirectional or bidirectional communication is different. This is due to the acknowledged message mechanism described in 2.1.1. How the resulting network load affects the PDR is also investigated in the second experiment. Therefore, the same messages are sent for the unidirectional measurement without acknowledgment and then in the bidirectional measurement with acknowledgment. Due to the fact that messages have to be transmitted twice through the network, bidirectional communication is expected to have much higher RTT results. In addition, packet loss affects twice the PDR for bidirectional communication, so a reduced PDR result is also expected.

4.2 Results

The results of the two experiments that have been conducted are presented and interpreted in this section. Visual aids are used to enhance the presentation. The discussion of the results is covered in the following chapter.

4.2.1 Single-hop - baseline measurements

As described in 4.1.2, this experiment should provide a range for the optimal distance between two nodes to ensure the best possible data exchange. The measured metric in this experimental evaluation is the PDR. During the experiment, the ESP32 boards were pointed at each other. The Bluetooth standard used was Bluetooth 5.0. A detailed view of the PDR results at the distances is shown in Table 4.3. These results were collected from the log files generated by the SK node.

Distance / m	**PDR 10 msg/s**	**Distance / m**	**PDR 10 msg/s**	**Distance / m**	**PDR 10 msg/s**
1	0.995	11	0.993	21	0.996
2	0.994	12	0.996	22	0.995
3	0.997	13	0.994	23	0.997
4	0.995	14	0.995	24	0.997
5	0.997	15	0.994	25	0.995
6	0.997	16	0.994	26	0.996
7	0.997	17	0.994	27	0.995
8	0.996	18	0.996	28	0.996
9	0.996	19	0.996	29	0.995
10	0.995	20	0.996	30	0.993

Table 4.3: PDR baseline results, for a single-hop unidirectional communication with a transmission power of +9 dBm

It can be seen from the results in Table 4.3 that there is no significant variation in the measured PDR. This does not correspond to the expected decreasing PDR with increasing distance. Measurements at a greater distance were not possible to be taken due to the limited space available. For this reason, the experiment was repeated with a reduced transmission power of -24 dBm. This is the minimum value that Espressif allows to be configured by the ESP-IDF framework. In Figure 4.3 the results of the second run are shown. A more detailed look at the experimental findings is given in table 4.4.

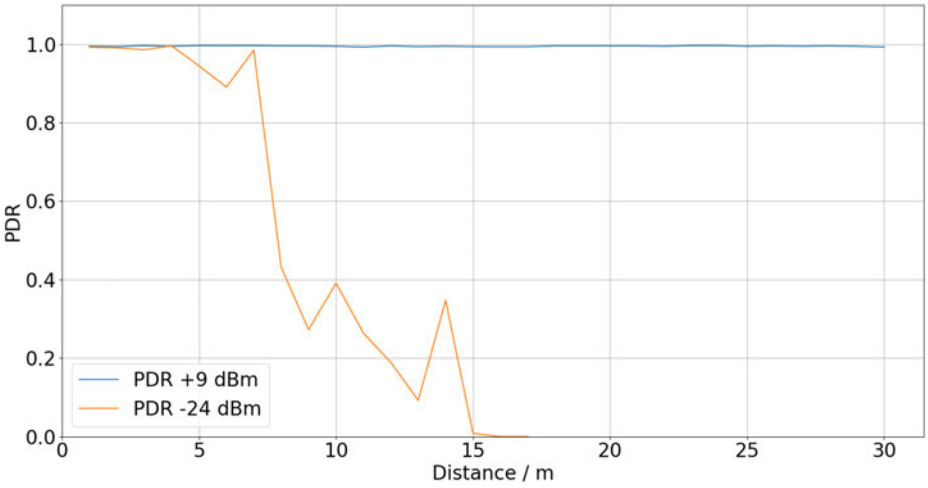


Figure 4.3: PDR baseline results, for a single-hop unidirectional communication with a transmission power of +9 dBm / -24 dBm

Distance / m	PDR 10 msg/s	Distance / m	PDR 10 msg/s
1	0.993	11	0.264
2	0.991	12	0.189
3	0.986	13	0.092
4	0.996	14	0.347
5	0.945	15	0.008
6	0.891	16	0.000
7	0.985	17	0.000
8	0.432	18	-
9	0.272	19	-
10	0.391	20	-

Table 4.4: PDR baseline results, for a single-hop unidirectional communication with a transmission power of -24 dBm

In contrast to the +9 dBm graph presented in Figure 4.3, a significantly lower PDR is shown by the graph for -24 dBm. In general, the data measurements in the plot can be separated into three parts. Up to a distance of seven m a rather high PDR result is observed. Within this first part, the PDR is between 99 % and 89 %. At longer distances, packet loss is sharply increased. Between eight m and 14 m, the PDR drops below 43 %

for the second part of the graph. The last part is characterized by a PDR value close to zero. So, up to a distance of 15 m no data is transmitted between the SK node and the SRC node. The increasing PDR value at a distance of 14 m cannot be explained exactly. Some uneven ground was an observation that could be made. Further research is needed to disprove or prove this observation.

To better understand the RTT data measured in the second experiment, Figure 4.4 is given. The RTT result within the testbed of the first experiment is shown. For bidirectional communication within a single-hop mesh network, a median of 38 ms is observed for the RTT measurement.

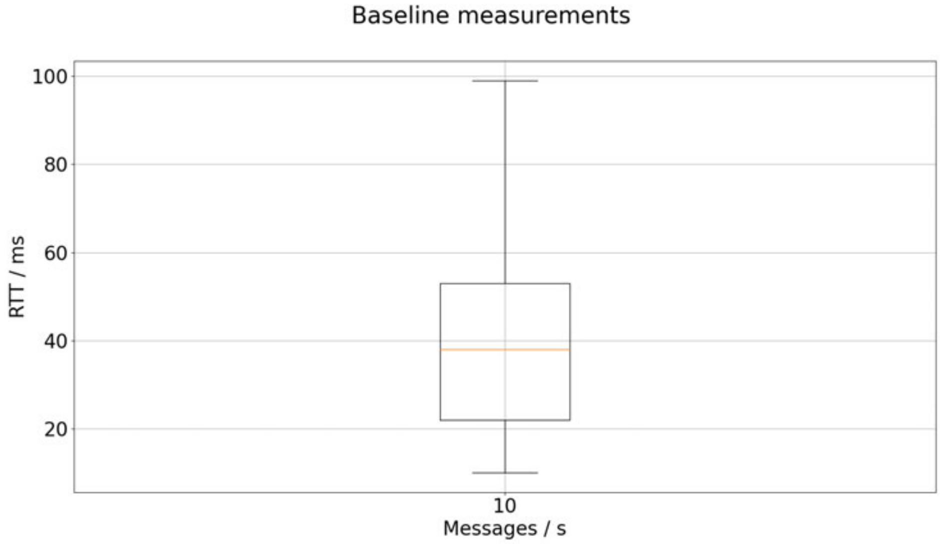


Figure 4.4: RTT results, for single-hop bidirectional communication with a transmission power of -24 dBm

4.2.2 Two-hop - mesh performance measurements

As discussed in 4.1.3, the second experiment was conducted to examine the performance of the BLE mesh network. Therefore, two different measurements are performed for a gradually increasing number of up to three SRC nodes sending messages to a specific SK node. The first measurement is to determine the PDR for a unidirectional, two-hop communication between the SRC and SK nodes. Additionally, the second measurement is done to determine the RTT within a bidirectional communication, including the communication path back from the SK to the SRC node.

Unidirectional communication

Within this section the results of the PDR measurements is presented. The data was collected from the log files generated by the three SK nodes. The measurements were repeated six times with a gradually increasing number of relay nodes. For each measurement, 1800 messages (300 messages with 6 repetitions) are sent from each SRC node to a specific SK node.
The PDR results for unidirectional and bidirectional communication with a single SRC-SK pair and varying numbers of relay nodes are shown in the following two figures.

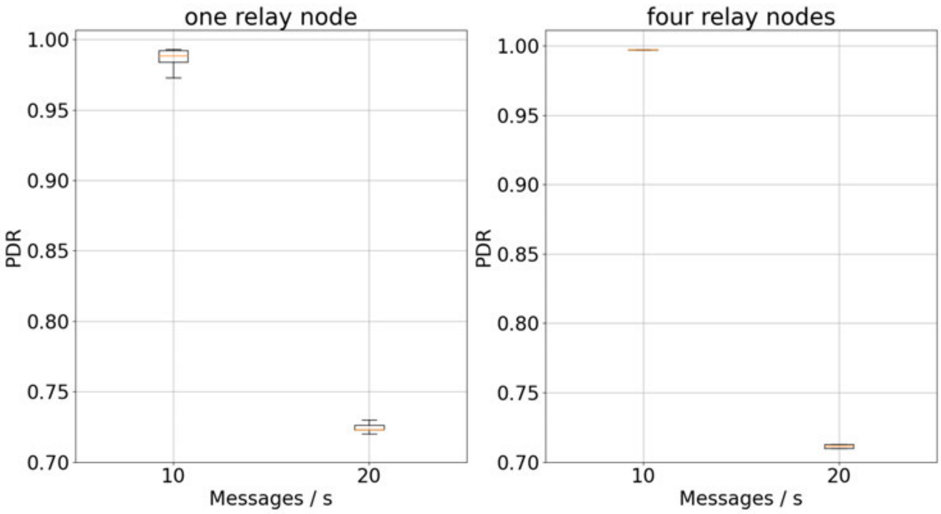


Figure 4.5: PDR results, for unidirectional single-path communication with an increasing number of relay nodes

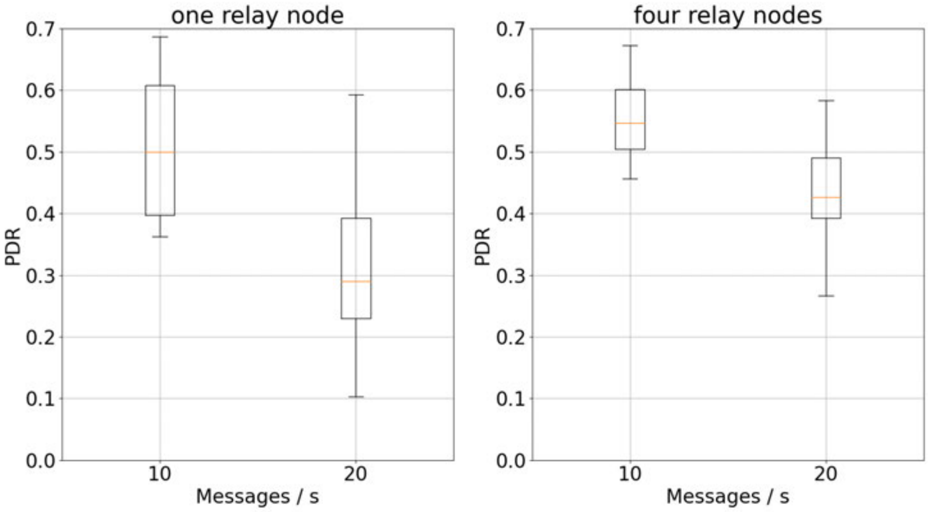


Figure 4.6: PDR results, for unidirectional multi-path communication with an increasing number of relaynodes

There is no observed effect on the PDR results for a unidirectional, single-path communication when the number of relaying nodes is increased. This is shown in Figure 4.5. On the other hand, an increase in the PDR result is observed for unidirectional multi-path communication. This is illustrated in Figure 4.6.

All PDR results measured for the bidirectional communication between the SRC and SK nodes are contained in Table 4.5. The relay node count and the number of communication paths within the mesh network are described by the first two columns. The PDR results measured under different send intervals are shown in the following two columns. It should be noted that the multi-path communication results are an average of all participating SK nodes.

Relay node count	**Sending pairs**	**PDR 10 msg/s**	**PDR 20 msg/s**
1	1	0.987	0.724
1	2	0.625	0.383
1	3	0.423	0.254
2	1	0.997	0.726
2	2	0.574	0.363
2	3	0.425	0.338
3	1	0.996	0.719
3	2	0.558	0.431
3	3	0.540	0.386
4	1	0.997	0.713
4	2	0.577	0.488
4	3	0.542	0.395

Table 4.5: PDR results at SK nodes, for single/multi-path unidirectional communication with a varying number of neighbors.

As shown in the Table 4.5, there are two major differences in the results.

The first difference shown is between the columns containing the PDR results for the different transmission intervals. Here, the PDR of the lower send interval will always be found below the PDR results of the higher send interval. The difference is between 15 % and up to 39 % less PDR result.

The second major difference is between the single-path communication in the first row and the multi-path communication in the following two rows. For the PDR measurements, the multi-path ratios are at least 37 % lower than the single-path ratios. In general, the PDR result is reduced by including more sending SRC nodes in the network communication. This effect on the PDR decreases as more relay nodes are presented.

With respect to the 1800 messages sent during the single-path communication measurements, the maximum number of messages received by a SK node is approximately 1795. This was achieved during single-path communication within the higher send interval and with one or four relay nodes. On the other hand, the minimum number of received messages was measured during the high send interval within three SRC - SK pairs and only one relay node.

Bidirectional communication

This section presents the results collected on the three SRC nodes during the RTT measurements. The measurements are repeated for a gradually increasing number of relay nodes within a multi-path communication. 1800 messages are sent from each SRC node to a specific SK node and back, the PDR and RTT results are measured by the SRC node from the time taken to receive the acknowledgement from the SK node.
The comparison of PDR results for single-path and multi-path bidirectional communication with different numbers of relay nodes is shown in the following two Figures.

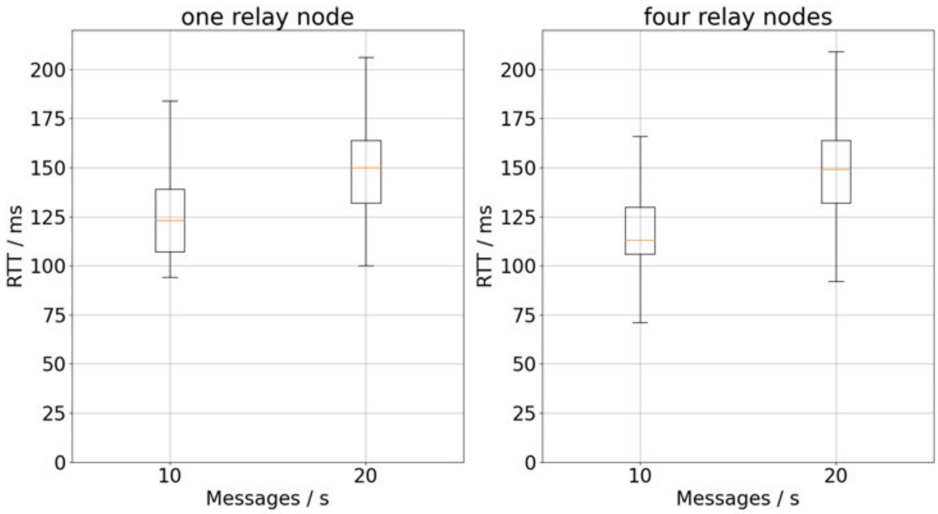


Figure 4.7: RTT results, for bidirectional single-path communication with increasing number of relay nodes

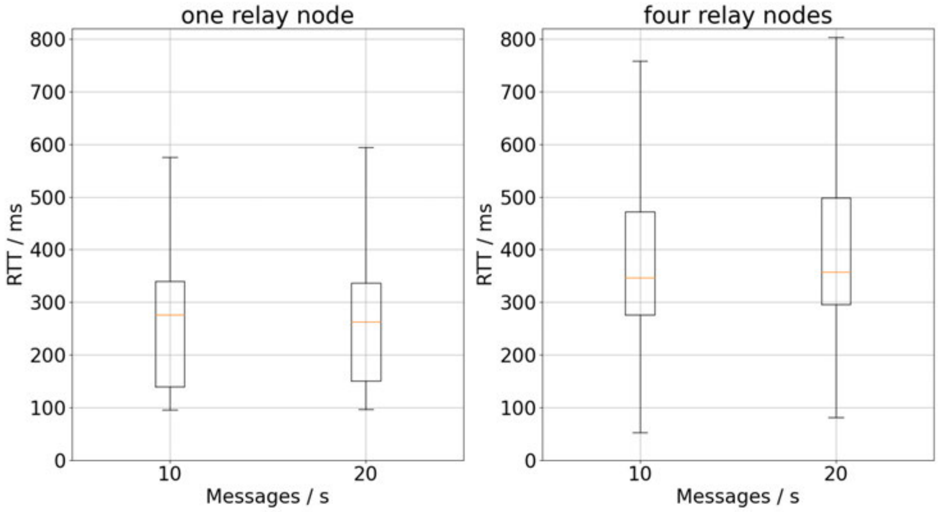


Figure 4.8: RTT results, for bidirectional multi-path communication with increasing number of relay nodes

As shown in Figure 4.7, there is only a minimal difference in the RTT results between the different numbers of relay nodes. However, a different picture is given by the RTT result of the multi-path communication. Here, the RTT result is increased by the number of relay nodes. This increase is particularly strong for the first increment of relay nodes. For a more detailed look at the experimental results, the following two tables are shown. The PDR result for the first part of the bidirectional communication from the SRC nodes to the SK nodes is given in Table 4.6. In the following table 4.7 the PDR and RTT results of the entire bidirectional communication are given. To simplify the presentation, the multi-path communication results shown in the last two columns, are an average of all the participating SK nodes and all the participating SRC nodes, respectively.

Relay node count	**Sending pairs**	**PDR 10 msg/s**	**PDR 20 msg/s**
1	1	0.382	0.202
1	2	0.231	0.116
1	3	0.174	0.083
2	1	0.443	0.227
2	2	0.259	0.133
2	3	0.185	0.093
3	1	0.461	0.238
3	2	0.274	0.139
3	3	0.186	0.093
4	1	0.483	0.257
4	2	0.273	0.139
4	3	0.185	0.093

Table 4.6: PDR results for single/multi-path bidirectional communication with a varying amount of neighbors

Relay node count	**Sending pairs**	**PDR 10 msg/s**	**PDR 20 msg/s**	**RTT 10 msg/s**	**RTT 20 msg/s**
1	1	0.373	0.197	126	149
1	2	0.223	0.112	225	222
1	3	0.164	0.077	315	323
2	1	0.437	0.223	122	148
2	2	0.256	0.132	248	258
2	3	0.184	0.092	452	463
3	1	0.467	0.237	124	151
3	2	0.271	0.139	273	293
3	3	0.183	0.092	453	473
4	1	0.481	0.256	120	148
4	2	0.272	0.138	282	302
4	3	0.183	0.092	462	481

Table 4.7: RTT results for single/multi-path bidirectional communication with a varying amount of neighbors

The PDR results given in both tables can be described as a strongly reduced overall PDR result with a maximum value of 0.382. Furthermore, there are hardly any differences to be seen between the related PDR results that represent a single experiment within the two tables.

There are also two other differences between the two tables. The first difference concerns the PDR results. The results of the lower send interval will always be found below the PDR results of the higher send interval. The second point concerns single-path communication, represented by the first two lines, and multi-path communication, represented by the next two lines. The PDR results of the multi-path communication will be found least 40 % lower than the single-path PDR. In addition, the PDR within a column is decreased by the number of sending SRC-SK pairs added to the communication. This effect is reduced by increasing the number of relay nodes.

The third significant difference concerns the RTT results, shown for the entire communication in Table 4.7. Here, the RTT results are affected by both, the number of relay nodes and the number of sending pairs. In almost all cases, it can be seen that the RTT tends to increase as more relay nodes are involved in the BLEM communication. This is especially true for multi-path communication, which shows an increased RTT of at least 53 %. On the other hand, there is not such a large effect on the RTT with respect to the chosen send interval. In general, the RTT is only slightly increased for the higher message flow.
Finally, the minimum RTT result which can be found, is for single-path communication with four relay nodes. On the other hand, the maximum RTT is measured during multi-path communication with four relay nodes and three sending SRC-SK pairs.

5 Evaluation

The results of the collected data are discussed in this chapter. Therefore, the main findings are presented, and a conclusion summarizing the work is provided. Furthermore, a presentation of the realization of the use cases described in 1.3 with the current network configuration is included. Finally, an outlook is given as a basis for future work.

5.1 Discussion

Within this section, the results interpreted in 4.2 are discussed and justified. In addition, the relations between the results given by the experiments in related work and the practical evaluation done as part of this thesis are shown. In particular, the differences and similarities are pointed out.

5.1.1 Single-hop - baseline measurements

Choosing the most similar transmission power, a much higher transmission range is indicated by the +9 dBm baseline measurement in section 4.2.1, than by the results in paper 3.1. This can be attributed to the fact that the ESP32 boards implement the more recent Bluetooth 5.0 standard and support an extension called Bluetooth Long Range (BLR) [20] (p. 291). BLR allows data transmission over a distance of several hundred meters, depending on factors such as transmission power, interference, and the given PHY [11]. As shown by the results of the -24 dBm measurement, a similar baseline can be achieved by reducing the transmit power.
Regarding the different BLEM protocols used (Bluetooth SIG mesh specification vs. CSRmesh protocol), no concrete statement can be made. Based on the fact, that there is only one node sending messages to a single SK node, without relaying or acknowledging messages, the assumption is that there is no such influence on the results.
Regarding the RTT, a higher result was measured than presented in the authors' paper

in section 3.2. The RTT required by the ESP32-C3 chips was 61 % higher than the 23 ms required by the Nordic nRF52832 chips. There is no proven explanation for the longer RTT. One assumption is about the different scan intervals used by the different hardware. Both chips are configured to scan continuously, but only Nordic allows changing the scan interval for each advertising channel. Due to the 30 ms scan interval for the ESP32-C3 chips, the time needed to scan all three advertising channels is about 90 ms. This contrasts with the 10 ms scan interval configured for the Nordic chips presented in section 3.2. The lower scan interval may be responsible for messages being scanned faster on different advertising channels, possibly resulting in a shorter RTT.

5.1.2 Two-hop - mesh performance measurements

The results given in segment 4.2 are discussed in the following section. First, the unidirectional and bidirectional communication results are discussed separately. Second, a comparison between the different communication methods is made, where the differences are worked out in detail.

Message send interval

The first major scenario described in 4.1.3 is about the different send intervals. While the normal load scenario is characterized by a send interval of 100 ms and an advertising event duration of 60 ms per message, it is important to take into account the overload scenario, which arises from a send interval of 50 ms. For 300 messages send within 15 s, this leads to a calculated loss of 50 message or 16.67 %.
As shown by the results for both communication flows, there is a decreased PDR for the lower send interval. Based on the fact that the excessive messages generated need to be buffered within a limited send buffer of 60 messages, which may lead to a buffer overflow. This is proven by the log files, which show an average of 77 error messages per measurement. These errors occurred in the context of a send buffer overflow generated by the transport layer. Therefore a packet loss of 26% is resulted. Here a difference of 10 % is noticeable. In the case of relay nodes or bidirectional communication, each node has to scan for incoming messages. Based on the overload scenario given by the advertising duration, there should be no more time available to scan for incoming messages. This could be an explanation for the extra 10% loss, but also raises the question of why messages are received at all.

Within the ESP32C3 documentation, no indication could be found of how to receive messages when the transmit buffer is permanently full and the transmit duty cycle is close to 100 % [18].

In addition, the question is to what extent other buffer sizes would affect the result. Would a buffer size greater than the current size for maximum 60 outgoing messages lead in a higher PDR or not. Further examination is needed to solve this questions.

Singel-path, multi-path communication

For both communication methods, it can be seen that there is a reduced PDR per SRC-SK pair when more pairs are sending and receiving messages within the network. Therefore, the same reasoning as in the paragraph above can be applied. Due to the two-hop nature of the examined network, messages must be relayed through a relay node. This node has the same limitations in terms of advertising interval and outbound message buffer size as mentioned above.

Given a fixed number of relay nodes, with an increasing number of sending nodes and thus an increasing number of incoming messages, the communication bottleneck will be found at the relaying nodes. For example, if messages send with an interval of 100 ms by two SRC nodes, this leads to the same congestion for the relay node as for one SRC node sending with the lower send interval of 50 ms.

It should also be noted that the PDR metric masks the overall performance of the network. Thus, it makes comparison difficult for a varying number of sending SRC-SK pairs with a fixed number of relaying nodes. To provide a fair comparison between increasing numbers of SRC-SK pairs, the total network throughput is shown in the following Figure 5.1. The throughput was calculated from the messages received per second, derived from the sum of the PDR results for each pair and multiplied by the message size of 41 bytes, presented in section 2.1.3.

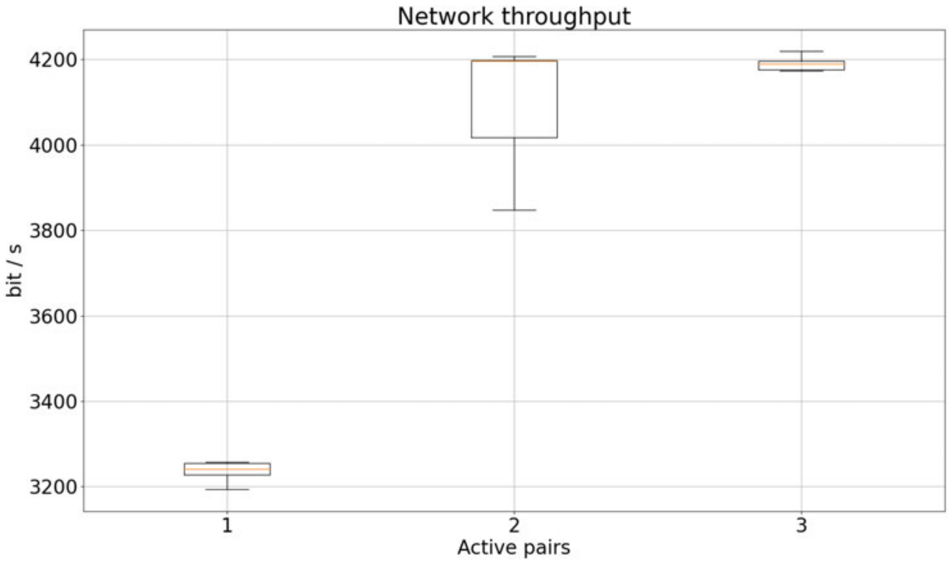


Figure 5.1: Data throughput for 10 msg/s for unidirectional communication with 1 relay node and increasing number of SRC-SK pairs

As shown in Figure 5.1, the overall network throughput increases with the number of sending SRC-SK pairs. This is in contrast to the PDR given in Table 4.5, which decreases per sending pair. However, it can be seen that the change from two to three sending SRC-SK pairs does not lead to a significant increase in network throughput. Therefore, it can be concluded that the performance limit for a relay node is reached with 4200 bit/s or two sending SRC-SK pairs. This is equivalent to 13 msg/s that can be processed by the relay node under the given network configurations. To confirm this conclusion, further work is needed to track the log files of the relay nodes and examine them for buffer overflow error messages.

Relay nodes

The PDR results for unidirectional communication show that an increasing PDR is led by an increasing number of relaying nodes. This improvement is especially true for the multi-path communication with three sending SRC nodes. The higher number of relaying neighbors leads to a higher number of relayed messages during one scan interval and so in a higher probability of scanning a message during a single scan interval.

In the case of single-path communication, no such PDR improvement is measurable. For the higher send interval, it is based on a result close to the maximum of 1.0 from the beginning. The reason for the lower send interval is that the communication bottleneck is not the relay node itself. As mentioned above, it is the advertising duration configuration of the SRC node that causes messages to be discarded. So in the case of the examined mesh network, the PDR results will not be improved by increasing the number of relay nodes.

For bidirectional communication, the PDR results are also improved for one sending SRC-SK pair, but to a lesser extent.

To demonstrate the improvement for the unidirectional communication, a comparison of the pooled network throughput for each relay node and over all SRC-SK pairs is illustrated in Figure 5.2.

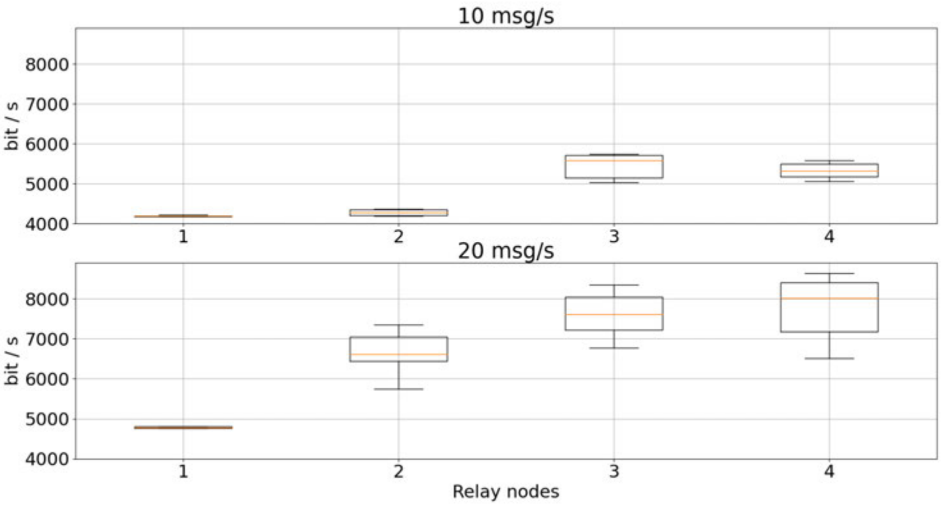


Figure 5.2: Network throughput for unidirectional communication with increasing number of relay nodes.

Regarding the results for the single-path communication with lower transmission interval, there is a slight decrease in RTT with each relay node added to the network. This is shown in Figure 4.7. As described by the authors in [1], the higher probability of overhearing a message on the first advertising channel during a scan interval is led by the higher number of relaying neighbors. This is based on the fact that each relay node has a $\frac{1}{3}$ chance of being listened to by a SK node on one of the three advertising channels while the relay node is transmitting. The slight difference measured of only two ms as

opposed to five ms in the paper [1] can be attributed to the fact that the aforementioned effect is mitigated due to this experiment involving only one message repetition per relay node. To prove this explanation, further research with a higher TTL is needed.
For multi-path communication, the RTT results increase for an increasing number of relay nodes. This effect decreases as more relay nodes are involved in the network communication. It should be mentioned again that messages are scanned by destination address and advertising data, to avoid multiple repetitions by one relay node. In our case, the cache size is configured for a maximum value of 100 PDUs. So the maximum number of repetitions per message is equal to the number of relay nodes in the network. Because with this filtering mechanism, it is not possible for the higher RTT to be caused by more nodes and thus a higher buffering delay in the network. Due to time constraints and without more information, such as log files generated by each relay node, no further assumptions can be made about the increasing RTT.

Unidirectional, Bidirectional communication

Within the scope of this experiment the two-hop performance was evaluated by measuring the PDR and RTT. As described as the first key point in text 4.2.2 there is a significant lower PDR result for the unidirectional communication in comparison to the bidirectional communication during the RTT experiment. This can be justified with two significant reasons:

> **Advertising-scanning ratio**
>
> Based on the given node type, either scanning or sending is the only task to be performed by nodes. This is true for the PDR experiment with unidirectional communication. During the RTT experiment, both tasks must be performed by SRC nodes and SK nodes. In the case of the lower send interval, a send duty cycle close to 100 % is reached for the lower send interval. Therefore a higher probability to overhear messages is given while sending new messages through the network.
>
> **Consecutive sending**
>
> As mentioned in section 2.1.1, sending two messages in succession to a single unicast address is not allowed by the definition of an acknowledged message in ESP-BLE-MESH. This attempt is rejected until the appropriate response is received or the timer for generating a timeout event has expired. With respect to this constraint,

multiple messages generated within the transmission pause are first buffered in the send buffer and then discarded if a buffer overflow occurs. Due to the limited buffer size the point of overflow is reached faster with lower send intervals. Thus, the PDR results for measurements with lower send intervals are impacted more negatively than for measurements with higher send intervals.

With regards to the RTT results shown in Table 4.7, there is an average increase value of 10 % between the RTT results for the lower message flow and the higher message flow is evident. Assuming that each node within the mesh communication is affected by the higher message flow, message buffering must to be performed first. Due to multiple buffering delays, the RTT result for the lower send interval should be increased many times over. However, no such results can be found for a certain number of SRC-SK pairs. In addition, it was shown in Table 4.5, that for the first part of the bidirectional communication, the PDR values are very close to the final result. This supports the above assessment of the consecutive sending problem.
As shown in Figure 5.3, the throughput is almost the same for both send intervals.

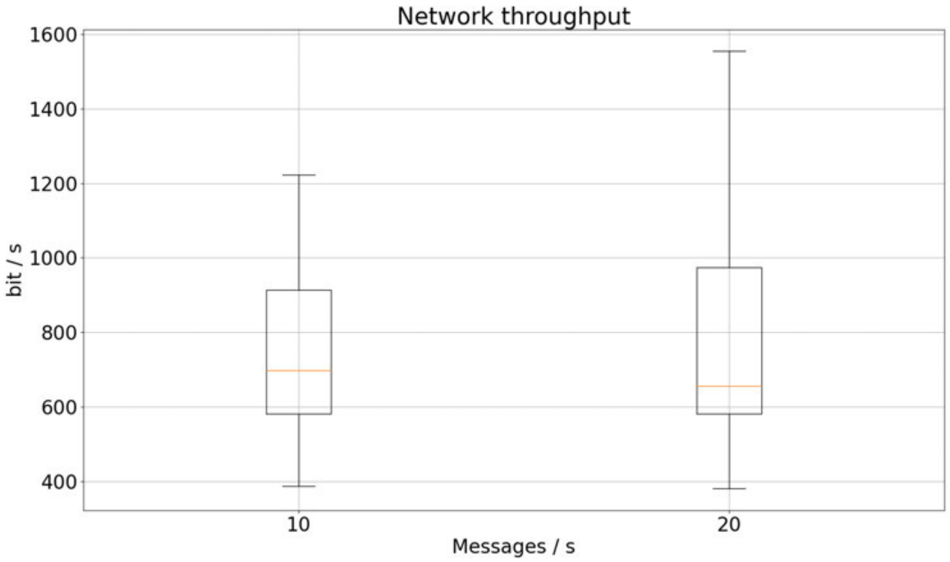


Figure 5.3: Data throughput per node for bidirectional communication .

It can be seen, that the maximum network throughput for bidirectional communication has already been reached with the higher send interval. This congestion is also evidenced by the minimum RTT required within this network. As shown in the results in Table 4.7, the minimum RTT needed is about 120 ms, which is always longer than the higher send interval of 100 ms. Thus, within the given message send intervals, there is no scenario that wouldn't result in network congestion for bidirectional communication.

Including the low values for the PDR results of the higher send interval, it can be seen that the maximum network performance has already been exceeded. To better understand, the network throughput for all measurements during the higher send interval experiment is illustrated in the Figure 5.4 below. Here, the maximum amount of data sent by the SRC node during the higher send interval is about 3280 bit/s. In order to have a fair comparison of the different communications, the results of the unidirectional communication results are compared with the results of the first part of the bidirectional communication and finally with the entire bidirectional communication.

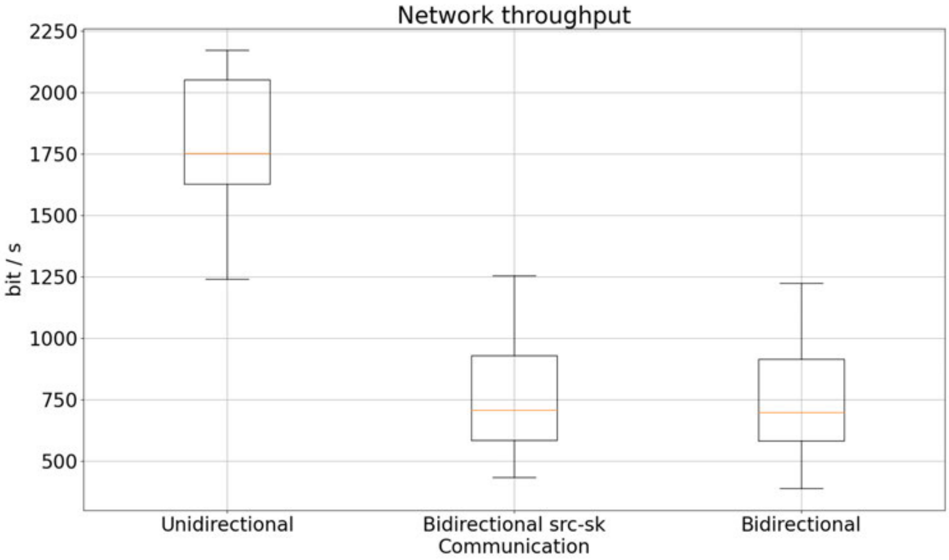


Figure 5.4: Data throughput comparison between unidirectional, one-way bidirectional and entire bidirectional communication with 10 msg/s.

In Figure 5.4, it can be seen that there is no difference in network throughput between the two bidirectional parts. However, the results of the unidirectional communication show that a higher network throughput is possible. Grounded in this comparison and the fact that the rest of the bidirectional communication after the SRC node is based on the same unacknowledged message type as the unidirectional communication, it can be seen that the bottleneck of the network throughput is caused by the first part of the

communication.
At this point the argumentation regarding the consecutive sending problem can be continued. If there is no way for further messages to be sent by a single SRC node, unless it receives an acknowledgment or a timeout, then the RTT and ultimately the chosen timeout is the limiting factor for network performance. Finally, the conclusion can be made, that the limiting factor can be reduced by reducing the RTT. A positive effect on the performance of the network will be achieved.

5.2 Conclusion

Along with this thesis, many parameters and configurations have been discussed to evaluate the performance of BLEM networks. First of all, there was a continuous evolution of the newer standards of BLE. Especially with the implementation of the new coded PHY that comes with the new Bluetooth 5.0 standard, a vastly improved transmission range has been found.
In a further investigation, a two-hop mesh network was analyzed using different configurations. A distinction was made between unidirectional and bidirectional communication. It was found that the most limiting factor in the network depends on the type of communication. With bidirectional communication, nodes spent most of their time waiting for an acknowledgement. Even the use of multiple relay nodes did not improve this communication type.
This was in contrast to unidirectional communication, where network throughput could be increased many times over by adding more relay nodes. For a network with multiple SRC-SK pairs, this effect is particularly noticeable.
It has also been shown that the overall network throughput is affected by the advertising duration configuration. At worst, messages may be discarded if the selected advertising duration is longer than the shortest time between two consecutive messages. In the best case, the messages are buffered and sent with a time delay.
As discussed in the section 5.1.2, there were several differences measured regarding the RTT compared to the results presented in paper [1]. First, a higher RTT was found for the BLEM network established with the ESP32 chips. This can also be seen when examining the RTT in a two-hop mesh network. Second, the effect of reducing the RTT by adding more relay nodes to the network could not be measured as assumed.
Finally, it could not be clarified why the RTT increased while the number of vertical added relaying nodes increases.

Related to the use cases defined in 1.3, it can be assumed that it is possible to implement such a fire alarm system with Bluetooth mesh. The minimum time interval between two successive messages generated by the fire alarms must be taken into account. Mechanisms such as message acknowledgement can also be used to establish reliable message transmission between these fire alarm nodes. Even functions such as checking that the fire alarm is working are provided by the Bluetooth standard using heartbeats.

In the case of patient data sent through the hospital, it is conceivable to choose unidirectional communication. To meet all requirements, patient data can be sent several times at shorter intervals and relayed to the central server to be stored as a continuous record.

5.3 Outlook

In the course of this thesis, several network parameters were examined. For further optimization, it could be investigated how the RTT is affected by disabling the message filtering mechanism. This would cause multiple messages to be retransmitted using TTL and the impact on network performance can be studied.

Advanced logging could be implemented to better understand the bottleneck caused by relay nodes. This would allow the sending behavior of the nodes to be studied in more depth. For example, different configurations such as advertising duration or different send buffer sizes could be examined in more detail.

A study is missing where a reliable communication is examined for its overall network performance. This would allow a comparison between the performance of reliable and unreliable communications.

To enhance the results of this thesis, performance evaluation could be done with larger BLEM networks. This could help to find more data configuration parameters for larger use cases, such as industrial IOT. Finally, the issue of energy consumption has not yet been addressed. This may be the subject of entirely new work.

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Glossary

C programming language A programming language developed by Brian W. Kernighan and Dennis M. Ritchie in 1972.

Industry 4.0 Smart manufacturing with the help of Iot and AI.

UART A universal asynchronous receiver-transmitter is a computer hardware device for asynchronous serial communication to transmit data.

Erklärung zur selbstständigen Bearbeitung

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