Automation for BLE 5.2 TECHNOLOGY

Submitted By

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21MECE03

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

INSTITUTE OF TECHNOLOGY

NIRMA UNIVERSITY

AHMEDABAD-382481

May 2023

Automation for BLE 5.2 TECHNOLOGY

Major Project

Submitted in partial fulfillment of the requirements

for the degree of

MASTER OF TECHNOLOGY in DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

Submitted By

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Certificate

This is to certify that the major project entitled **"Automation for BLE 5.2 TECHNOLOGY"** submitted by **Devarsh Jani (Roll No: 21MECE03)**, towards the partial fulfillment of the requirements for the award of degree of Master of Technology in ELECTRONICS AND COMMUNICATION ENGINEERING (EMBEDDED SYSTEMS) of Nirma University, Ahmedabad, is the record of work carried out by him under my supervision and guidance. In my opinion, the submitted work has reached a level required for being accepted for examination. The results embodied in this major project part-I, to the best of my knowledge, haven't been submitted to any other university or institution for award of any degree or diploma.

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Statement of Originality

I, **Devarsh Jani**, Roll. No. **21MECE03**, give undertaking that the Major Project entitled "**Automation for BLE 5.2 TECHNOLOGY**" submitted by me, towards the partial fulfillment of the requirements for the degree of Master of Technology in **ELECTRONICS AND COMMUNICATION ENGINEERING (EMBEDDED SYSTEM)** of Institute of Technology, Nirma University, Ahmedabad, contains no material that has been awarded for any degree or diploma in any university or school in any territory to the best of my knowledge. It is the original work carried out by me and I give assurance that no attempt of plagiarism has been made.It contains no material that is previously published or written, except where reference has been made. I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere; it will result in severe disciplinary action.

_____

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Date:

Place:

Endorsed by

Guide Name

(Signature of Guide)

Acknowledgements

It gives me immense pleasure in expressing thanks and profound gratitude to my internal guid **DR. Nagendra Gajjar**, Professor, Electronics and Communication Department, Institute of Technology, Nirma University, Ahmedabad for his valuable guidance and continual encouragement throughout this work. The appreciation and continual support he has imparted has been a great motivation to me in reaching a higher goal. His guidance has triggered and nourished my intellectual maturity that I will benefit from, for a long time to come.

It gives me an immense pleasure to thank **Dr. Usha Metha**, Hon'ble Head of Electronics and Communication Department, Institute of Technology, Nirma University, Ahmedabad for his kind support and providing basic infrastructure and healthy research environment.

A special thank you is expressed wholeheartedly to **Dr. Rajesh Patel**, Hon'ble Director, Institute of Technology, Nirma University, Ahmedabad for the unmentionable motivation he has extended throughout course of this work.

I would also thank the Institution, all faculty members of Electronics and Communication Department, Nirma University, Ahmedabad for their special attention and suggestions towards the project work.

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Abstract

A class of wirelessly connected digital accessories is starting to develop as customer demand for consumer electronics continues to soar daily. In this situation, energy efficiency is seen as a fundamental requirement for a wireless device. To be well-suited for internet of things (IoT) applications, the communication system. In order to reduce power consumption, the protocol's settings must be tailored to the application in question. In order to anticipate the energy consumption of a wireless device based on Bluetooth low energy (BLE), for example, for different parameter values, an energy model is needed. The BLE 5 method can be a very good solution in this situation. The Bluetooth 5 standards were recently released in order to provide notable advancements over the protocol's earlier iterations. In order to provide stronger long-distance connections, but at a reduced data rate, Bluetooth 5 coded is a new special sort of connection that comes with trustworthy communication capabilities that vary in speed, range, and battery consumption. In compared to Bluetooth 4, Bluetooth 5 aims to increase speed by two times, range by four times, and advertising by eight times. The evaluation of the coded mode of the recently specified BLE 5 technology is discussed in this thesis. This study examines the energy efficiency of the BLE 5 (S = 8) coded mode solution both analytically and experimentally. It combines Matlab programming, analytical modelling, and practical measurement utilising Nordic Semiconductor's nRF52840 development kit. The recently disclosed BLE 5 coded approach's performance is contrasted with that of the BLE 4 coded technique, which is currently seen as being the most commonly employed in cases of commercial wireless devices.

BLE 5 coded mode employs a forward error correction (FEC) mechanism to extend the communication range of this low-power approach for IoT applications. The packet length grows and the performance falls as a result of coding overhead. The 2.4 GHz frequency is taken into account in this thesis. Two more phases are added to packet transmissions and reception by the LE Coded PHY. In order for the receiver to repair bit mistakes when the packet is received and be able to reduce packet error rates, the FEC method is first applied to the packet (PER). Second, the packet is subjected to

a pattern mapper technique. Better sensitivity is obtained as a result of the FEC and pattern mapping. The experimental findings from this thesis demonstrate that BLE 5 technique outperforms BLE 4 in terms of packet error rate (PER), communication range, and received signal strength indicator (RSSI). Additionally, BLE 5 technique uses less energy than BLE 4 technique, which was determined through analytical modeling.

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Chapter 1

Introduction

This master's thesis project work was completed as a research component of the Wireless Communications Engineering master's degree programme at the Centre for Wireless Communications (CWC) at the University of Oulu in Finland. A large demand for applications in the internet of things (IoT) space gave rise to the concept of analysing the energy efficiency of Bluetooth low energy (BLE) 5 coded technology. BLE 5 appears to be a more trustworthy candidate than other technologies in the industrial, scientific, and medical (ISM) band. By 2021, 48 billion devices will be connected to the internet, with 30 percent of those devices predicted to be Bluetooth devices, according to Allied Business Intelligence (ABI) research. In order to serve as the primary enabler of the IoT, BLE has been actively developed. With substantial technological improvements, Bluetooth 5 is now more suitable than ever for a variety of IoT applications. It has been observed that in many cases, data transfer using wired medium is not regarded as being more efficient than wireless data transport. As a result, research and development into energy-efficient short-range wireless communication technology has become crucial in recent years. Researchers and engineers have improved the energy efficiency of and decreased the financial costs for wireless data transmission through consistent efforts.

1.1 Background and Motivation

Due to the rising need for numerous new technologies utilised in wireless communication, energy-efficient communication has grown to be a significant problem. In this instance, BLE 5 coded technology aims to provide much lower power consumption and prices compared to BLE 4.2 technology, while maintaining the same communication range. The

Bluetooth special interest group (SIG) claims that the two key shortcomings of BLE 4 are its speed and range. The BLE 5 technology, which addresses the issue of extending the communications range and the maximum throughput by adding three new physical layer (PHY) possibilities, is in this case an advancement of the BLE technology. However, BLE 5 provides the ability to remedy errors. Information can be properly decoded at a lower signal-to-noise ratio (SNR) and, therefore, at a greater distance from the transmitter when errors are corrected utilising known error correction methods. BLE 5 offers impressive gains for energy economy and wireless coexistence with shorter radio communication times in addition to better speeds. BLE 5 offers data transfers up to 2 Mbps, which is twice as fast as Bluetooth 4.2, without increasing power consumption. Faster transmit speeds allowed BLE 5 to interact with radioactive material less frequently, potentially reducing battery consumption.

NXP Semiconductor is a leading semiconductor manufacturer that provides high-performance mixed-signal and standard product solutions for a wide range of industries, including automotive, industrial, and communication sectors. Bluetooth technology is one of the key areas where NXP Semiconductor has made significant contributions, with its advanced system-on-chip (SoC) products and software solutions for Bluetooth low energy (BLE) and classic Bluetooth applications. As an automation engineer at NXP Semiconductor, my work has focused on developing and implementing automated testing solutions for Bluetooth products.

Bluetooth technology is widely used in the industry for wireless communication between devices. Bluetooth Core the latest version of the Bluetooth standard, which introduced several new features and enhancements to the previous version. However, with the increasing complexity of Bluetooth devices and the need for testing multiple profiles and use cases, manual testing becomes time-consuming and error-prone. Therefore, there is a need for automation to streamline the testing process and ensure product quality.

In this thesis, I will describe my work at NXP Semiconductor as an automation engineer, specifically focusing on Bluetooth testing. The thesis will cover my experiences as an SQA for Bluetooth, the transition to automation, and the development of automa-

tion scripts to test different Bluetooth profiles on SoCs. I will also discuss my work in DevOps, which includes using tools like Jenkins, MongoDB, and InfluxDB for managing continuous integration and continuous delivery (CI/CD) pipelines.

The primary goal of this thesis is to assess the energy efficiency of the BLE 5 coding approach by analysing the performance of the PER and SER metrics. This investigation aimed to assess PER performance at various distances as well as communication range performance. Additionally, an analytical model was utilised to investigate how well PER and SER performed for BLE 4 and BLE 5 at various distances, and the energy efficiency for both scenarios was assessed. This master's thesis used a combination of methods for its research, including a review of the literature, analytical modelling, simulations with Matlab, and field testing with a Nordic Semiconductor nRF52840 9 development kit.

1.2 Reserch Objective

The primary objective of this thesis is to describe my work at NXP Semiconductor as an automation engineer, specifically focusing on Bluetooth Core 5.3 testing. The thesis aims to achieve the following objectives:

- To provide an overview of Bluetooth technology and the significance of Bluetooth Core 5.3 in the industry.
- To review the existing literature on Bluetooth testing and automation and discuss the advantages and disadvantages of manual and automated testing.
- To describe the manual testing process for Bluetooth Core 5.3 and the different Bluetooth profiles and use cases tested.
- To explain the need for automation and describe the advantages of automated testing over manual testing.
- To present the development of automation scripts for testing different Bluetooth profiles on SoCs.
- To discuss my work in DevOps and explain how it integrates with automation to manage CI/CD pipelines.

- To present the results of the automated tests and compare them with the manual tests.
- To provide recommendations for future work and improvements in the automation and testing process.

1.3 Thesis outline

The thesis paper presents an overview of BLE technology and discusses how BLE 5 will affect Internet of Things (IoT). The thesis is set up in the manner shown below:

- Chapter 1 provides an introduction to the thesis, including background information on NXP Semiconductor, Bluetooth technology, and the motivation for the study.
- Chapter 2 reviews the existing literature on Bluetooth testing and automation, including the advantages and disadvantages of manual and automated testing.
- Chapter 3 this chapter will explain and give a birds eye view of bluetooth low energy.
- Chapter 3 describes the manual testing process for Bluetooth Core 5.3 and the different Bluetooth profiles and use cases tested.
- Chapter 4 discusses why automation is necessary and what makes automated testing superior than manual testing.
- Chapter 5 presents the development of automation scripts for testing different Bluetooth profiles on SoCs.
- Chapter 6 describes my DevOps work and how automation works with it to handle CI/CD pipelines.
- Chapter 7 presents the results of the automated tests and compares them with the manual tests.
- Chapter 8 gives suggestions for future work and enhancements to the testing and automation process.
- Chapter 9 concludes the thesis, summarizing the study's contributions and implications for the industry.

Chapter 2

BLUETOOTH LOW ENERGY

The Bluetooth SIG, one of the major wireless interest groups, created BLE, a power-efficient version of Bluetooth, for short-range control and monitoring applications. BLE was adapted from traditional Bluetooth to enable several novel new use cases. It is clearly clear that smart devices can be upgraded to become even smarter devices making them simple, user-friendly, inexpensive, and compact. The majority of the time, coin-cell batteries are used to power the BLE-enabled devices for communication, and they have a long runtime.[1]

There are many transceivers on the market right now that implement various wireless communication protocols. One recently proposed protocol among them is BLE, a new wireless technology made for cheap, low-power communication. Due to BLE's importance as a foundational technology for the Internet of Things, the market for applications utilising it is constantly expanding.

2.1 Background

Radio frequency (RF) technology called Bluetooth was created more than 20 years ago. It is currently regarded as one of the main IoT pillars. Bluetooth uses radio waves to transmit data, enabling two or more devices to communicate with one another. In order to communicate with these "intelligent" gadgets, Bluetooth has become a highly well-known protocol choice because to familiarity and robust support in all major operating systems. Everything is possible with Bluetooth-enabled gadgets, from playing music to turning on the lights, from sending data to assess your heart rate to turning on the TV.

Most devices' Bluetooth ranges are typically little more than 100 metres. There are three main classifications based on the signal coverage range: Class 1, Class 2, and Class 3. The most potent may go up to 100 metres and is Class 1. The most common is Class 2, which can only operate within a 10 metre radius. Class 3, on the other hand, stops at 1 metres, which is very little used. Although it was seen as dead in 2003, Bluetooth has experienced great growth and success over the past 10 years in a number of application areas, including audio communications and stereo streaming [1]. The Bluetooth market is now thriving and focusing on extending the technology's adoption to short-range wireless communication sectors, notably audio and stereo communications. The Internet of Things (IoT) and Machine-to-Machine (M2M) communications are receiving interest from the Bluetooth business. Bluetooth must have lower power consumption to be appropriate for M2M and IoT applications.

BLE was first introduced by the Bluetooth SIG in 2011 to take full advantage of low energy functionality. Similar to "traditional" Bluetooth, it is a wireless computer networking technology that operates at 2.4 GHz. It was initially created by Nokia as an internal project called "Wibree" before being released by the Bluetooth SIG. BLE's initial Bluetooth 4.0 specification was followed by updates in Bluetooth 4.1, 4.2, and 5. BLE technology was also made appealing for a variety of applications, including vehicular networks.

BLE was created and promoted by the Bluetooth SIG for use in a variety of industries, including security, fitness, home entertainment, and healthcare. It is a relatively new technology that is mainly made for low-power and low-cost operation, which are required by Bluetooth v. 4.2 to support devices and extend battery life. Because the applications it uses don't require the exchange of a lot of data, it can operate for years on just one battery at a lower cost. The Bluetooth SIG is in charge of the Bluetooth specification, which is frequently improved and supported in line with market demands.

For making phone calls, the Classic Bluetooth is perfect for linking cell phones to Bluetooth headsets. It guarantees the data transfer rate to make it appropriate for uses like

the high-quality music is transmitted via Bluetooth headset. The basic rate (BR) and the increased data rate are its two component portions of the traditional kind (EDR). Traditional Bluetooth technology succeeded in eliminating wires for many users as well as in industrial and medical applications by modelling itself as a voice for continuous data flow. Making a safe wireless connection between the devices is the goal of Classic Bluetooth technology. But BLE, also known as Bluetooth Smart, is a type of Bluetooth technology that was created to provide connectivity for small devices, particularly those which are associated with IoT. Small batteries enable Bluetooth Smart-enabled devices to operate for extended durations. Additionally, it can communicate with bigger devices like tablets or smartphones. One of the crucial BLE features include the ability to support devices running at extremely low battery consumption levels while maintaining communication with other Bluetooth devices. For instance, many IoT-related products, such as medical equipment, sports and fitness equipment, mice, keyboards, wearables, and small sensors and actuators, may need to be able to run for a year or longer on a single battery charge. Because BLE is typically in sleep mode and only activates when a connection is made, the power consumption can be reduced to a minimum when connectin is done. Since genuine connection periods are only a few ms, power consumption is kept to a minimum. Only roughly 15 mA and 1 A are used during the peak and average power utilisation, respectively. The standout characteristics of the BLE products include the following characteristics: low average and peak power consumption, long battery life on common coin-cell batteries, multi-vendor interoperability, and improved range. [2]

Bluetooth 5 covers outdoor, commercial, residential, and construction applications as well as the industries that will make it a reality. Additionally, Bluetooth 5 has a unique connection type that was created for long-distance communication. BLE 5's new coded PHY layer operates at 500 kbps and 125 kbps rates, enabling extended distances. In actuality, for outdoor measurements, this range should be up to 490 metres with transmit power of 0 dBm and 780 metres with transmit power of 9 dBm. With coded PHYs, the sensitivity is raised while keeping the Tx and Rx current requirements constant. The number of over-the-air modulated symbols per bit of data increases, making it easier for the receiver to distinguish between a signal and noise. In comparison to the earlier iteration of Bluetooth technology, a more dependable network may be formed with less

power by extending the range of BLE. If you want to increase the range while consuming less power, you might consider lowering the data rate. Range actually relies on the environment, the antennas, and the radio performance.

Factors that affect Bluetooth range are the followings:

- The output power of the transmitter
- Physical obstacles in the transmission path
- The receiver sensitivity and the antennas

A noteworthy aspect is the growth in the rate of data exchange. The data transfer bandwidth of Bluetooth 5 has increased from 1 Mbps to 2 Mbps. Future wearable technology is anticipated to sync at a speed that is twice as fast as it is now. The packet extension function of Bluetooth 4.2 is confirmed by Bluetooth 5. Even though the distance between the packets has not decreased, the data is transmitted more quickly. Bluetooth 5 uses a 2 Mbps mode to increase data transmission over Bluetooth 4.2 by two times. Additionally, it shortens the time needed for data transmission and reception. Because of unchanged time intervals between packets and other factors, calculations in an official blog on the Bluetooth website indicate that Bluetooth 5 is approximately 1.7 times faster than BLE 4.2. [3]

Hardware transmitters known as Bluetooth beacons are a collection of Bluetooth LE devices that broadcast their identity to other nearby portable electronic devices. BLE uses a lot less energy because it delivers data over a shorter distance. Less data is transferred via BLE beacons on a regular basis. The capacity of data broadcasting will grow by 800percent in Bluetooth 5 compared to earlier iterations of the standard. It is anticipated that as a result, the data being sent will be richer, more trustworthy, and more secure. Additionally, Bluetooth 5 enhances the capability of sending unique data packets known as advertising packets.

Technical Specification	BLE 5	BLE 4.2	Classic Bluetooth
Speed	Higher, twice compared to Bluetooth 4.2 version supports 2 Mbps	Higher compared to classic Bluetooth but lowered compared to Bluetooth 5 supports 1 Mbps	1Mbps
Range/distance (theoretical)	Upto 490 m with 0 dBm	Upto 230 m with 0 dBm	~10 – 100 meters
Throughput	2 Mbps gives 1.6 Mbps with overhead	1 Mbps	0.7 Mbps
Frequency channels	40 chanels from 2.4 Ghz to 2.48 Ghz (37 data channels and 3 advertising channels)	40 channels from 2.4 Ghz to 2.48 Ghz (37 data channels and 3 advertising channels)	79 channels from 2.4 Ghz to 2.483 Ghz with a 1 Mhz spacing
Latency (from a non connected state)	<3ms	<6ms	<100ms
Robustness to operate in congested environment	More	Less	Less
Security control	Better compared to Bluetooth 4.2	Less secure compared to Bluetooth 5.0	Less secure compare to Bluetooth 4.2 and 5.0
Nodes / Slave	Unlimited	Unlimited	7
Network Topology	Star-bus, Mesh	Star-bus, Mesh	Piconet, Scatternet
Reliability	High	Low	Low
Channel access method	TDMA	TDMA	TDMA
Power requirement	Low	High	High
Message Size	Large, 255 bytes	Small, 31bytes	358 bytes (max)
Battery life	Longer	Longer	Smaller

Figure 2.1: Comparative Table

2.2 Impact in IoT

The Internet of Things (IoT) is described as a network of interconnected computing devices, mechanical and digital machines, objects, animals, or people that are given unique identifiers and the ability to transfer data over a network without the need for human-to-human or human-to-computer interaction. It is always changing, and the prospects for research that it offers are endless. A wide range of industries and applications are made possible by the "IoT." It has the potential to create a new, interconnected world in which every device in our house, office, and car is interconnected. Numerous businesses and academic institutions have already predicted that BLE will have a significant impact on the Internet of Things during the next 10 years.[4]

Additionally, according to Huawei, there will be 100 billion IoT connections by 2025. The majority of these devices are Bluetooth-enabled. The McKinsey Global Institute estimates that by 2025, the Internet of Things will have a financial impact on the world economy of $3.9 to 11.1$ trillion. Figure 1 depicts an IoT application scenario in many fields. It is clear from the explanation above and Figure 1 how BLE 5 will affect IoT technologies. Bluetooth 5 technology is being used more and more frequently in a variety of industries, including automotive, home automation, healthcare, consumer electronics, mobile phones and smartphones, sports and fitness, and others.[4]

2.3 Functionality

The purpose of BLE 4 and BLE 5 is presented in this section along with an explanation of each layer's key features and operations. Bluetooth wireless technology has two different modes: BR and LE. Alternate media access control (MAC), EDR, and PHY layer extensions are optional for the BR system. The LE system uses less electricity, is simpler, uses lower data rates, and uses fewer duty cycles.

Figure depicts the host and one or more controllers that make up the BLE core system. The BLE protocol stack's top levels, known as hosts, are executed by an application processor. The BLE protocol stack's bottom tiers, including the radio, are called controllers. The logical link control and adaptation protocol (L2CAP), the attribute protocol (ATT),

the security manager protocol (SMP), the generic attribute profile (GATT), and the generic access profile are all higher layer protocols that are included in the host (GAP). The controller includes both the link layer (LL) and the PHY layer. The communication between the upper layer (host) and the lower layer (controller) is handled by the host controller interface (HCI).[5]

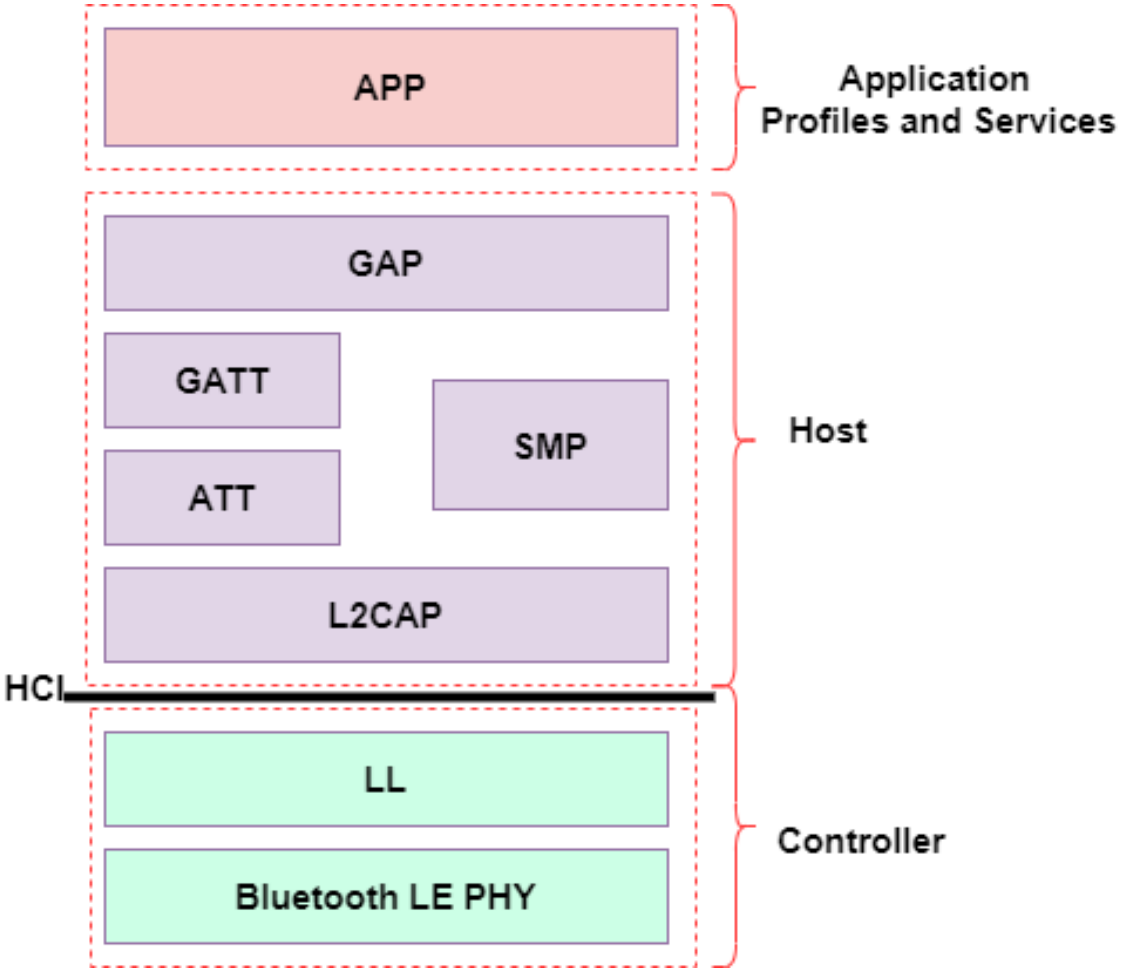

Figure 2.2: Bluetooth Layers

Both Bluetooth controller types are now offensive because some of the functionality of the BLE controller are also found in the traditional Bluetooth controller. As a result, communication between a single-mode device, which only uses Bluetooth Low Energy, and a device that only uses classic Bluetooth is not possible. Dual-mode devices are those that support both the BLE and conventional Bluetooth protocol stacks.

By regulating the radio's link-state, the LL is a sort of communication that takes place between BLE devices. The terms slave, master, scanner, and advertiser are frequently

used to describe different functions that a device may carry out. The LL, which in BLE is typically a combination of a hardware (HW) and a software (SW) part, is the section of the stack that directly interfaces with the PHY. Five states are used to accomplish the state machine activities in the LL: The states of scanning, initiating, promoting, standing by, and connecting. Only one state can be activated at a time using the LL state machine.

Figure 3 displays the LL state's operational state diagram. No packets are sent or received by the LL in the Standby state, which can be accessed from any other state. A device that sends out advertising packets is referred to as an advertiser in BLE. Advertising events are the periodic packet transmissions that take place through advertising networks. This period, which spans from 20 ms to 10.24 s, is known as the 0,625 ms advertising interval because it is a multiple of 0.625 ms. The Standby state can be used to enter the advertisement state. The PDU (protocol data unit) size ranges from 2 to 257 bytes. The size of the cyclic redundancy check (CRC) is three octets. The packets for this kind of connection are identified by a 32-bit access code that is produced at random.[6]

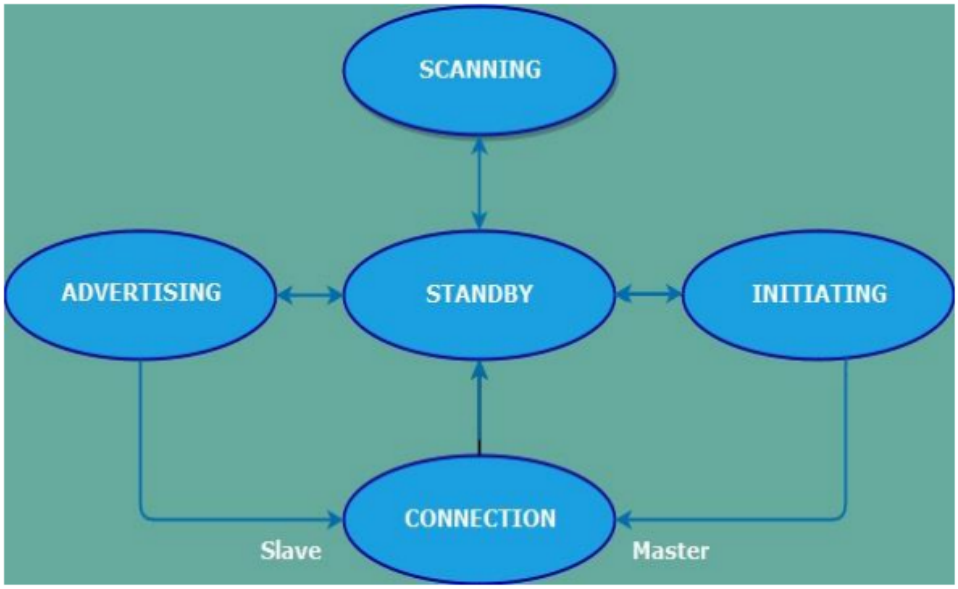

Figure 2.3: State diagram of the link layer state.

The connection state established between the two devices is asymmetrical, with the advertiser indicating its connectability while the other device, known as the initiator, simultaneously hears the adverts. An advertiser can get a connection request message after the initiator has located one. This is the process for linking two devices together at different locations. For both data channels and advertising channels, LL only supports a

single type of packet. Each packet contains four fields: a preamble, an access address, a PDU, and a CRC. The pieces that make up an LL packet are the preamble, access address, PDU, and CRC. PDU size ranges from 2 to 257 octets, with preamble and access address sizesand CRC is 1 Octet, 4 Octets, and 3 Octets respectively.[7]

The connected devices that act as an advertisement and an initiator, respectively, are referred to as the master and slaves. A BLE device can play two LL device roles for a single connection, depending on the application requirements and use-case. While each slave can be attached to one master, a master can be connected to multiple slaves at once. A piconet is a network made up of a master and its slaves that use a star topology. A BLE device currently only has one piconet. Slaves save energy by sleeping by default and waking up periodically to listen for any packets from the master that could be sent. A master uses a time division multiple access (TDMA) technique to manage the medium access. The masters provide information to the slave regarding the frequency hopping algorithm and connection monitoring. The connection request message contains the parameters for connection management. Any device can send a packet with the access address field corrupted. A new data channel frequency is used by the master and slave for a new connection case. This frequency is calculated using the frequency hopping algorithm.

The HCI protocol is the industry standard for keeping track of communications between hosts and controllers. Additionally, the Host is in charge of facilitating communication between the customer implementation and the HW. Its goal is to specify a set of instructions and actions for converting unprocessed data into data packets that may be transmitted via serial port to the host layer, and vice versa.

The main objective of the streamlined and condensed L2CAP protocol is to multiply data from three higher layer protocols. Through the ACL host connection, L2CAP is employed for communication. The connection is established following the creation of the ACL link. In basic mode, L2CAP enables packets with adjustable payloads up to 64 kilobytes in length. The L2CAP delivers information through the lower layers of the Bluetooth stack that has been gathered from higher layers and application layers. L2CAP

sends packets to the hostless system or the link manager via HCI.

The ATT shows how two devices can communicate with one another. A low-level layer called ATT specifies how data should be transferred. It serves as both the client and the server in this scenario. Several properties are managed by the server. The GATT designates the client or server role, which is distinct from the master or slave role. A client requests information from a server, and the server sends the information to the client. For more efficiency, a server may additionally send two types of unsuitable messages to a user, including attributes like unconfirmed alarms and signals that allow the client to submit a reply. For writing attribute values, a user can also issue a server command to the server.[8]

The BLE protocol stack's GAP layer is in charge of connection functions. This describes the device's mode, function, and tactics for finding devices and services, managing connection formation, and maintaining security. Broadcaster, Peripheral, Observer, and Central are the four roles that the BLE GAP plays on the controller, each of which has certain requirements. When acting as a broadcaster, a device is only capable of transmitting data across advertising channels and cannot support connections with other devices. The counterpart to the Broadcaster, the Observer, is in charge of receiving the data that the Broadcaster transmits. The Peripheral function is intended for a dependable device that employs a single connection to a device in the central role. The central role is meant for a device that maintains many connections and is responsible for initiation. Despite a device's ability to execute multiple purposes, only one function can be carried out at once. A high-level profile is an application profile that controls how programmes can communicate with one another.

2.4 Network topology

A piconet is an ad hoc network that connects a wireless user group of devices using Bluetooth technology protocols. A scatternet is a particular type of network that comprises of two or more Bluetooth-enabled items, such as smartphones and household appliances. A collection of piconets called a scatternet contains connections between numerous piconets. A mesh networking protocol called BLE Mesh operates on the idea of a flood network. It is based on the relaying nodes for messages. Huge-scale device networks can be created

using BLE mesh networking, which enables communication between a large number of devices. It is perfect for IoT applications that require tens, hundreds, or thousands of devices to communicate with one another, such as building automation, sensor networks, asset monitoring, and others. Figure depicts several network architectures.[9]

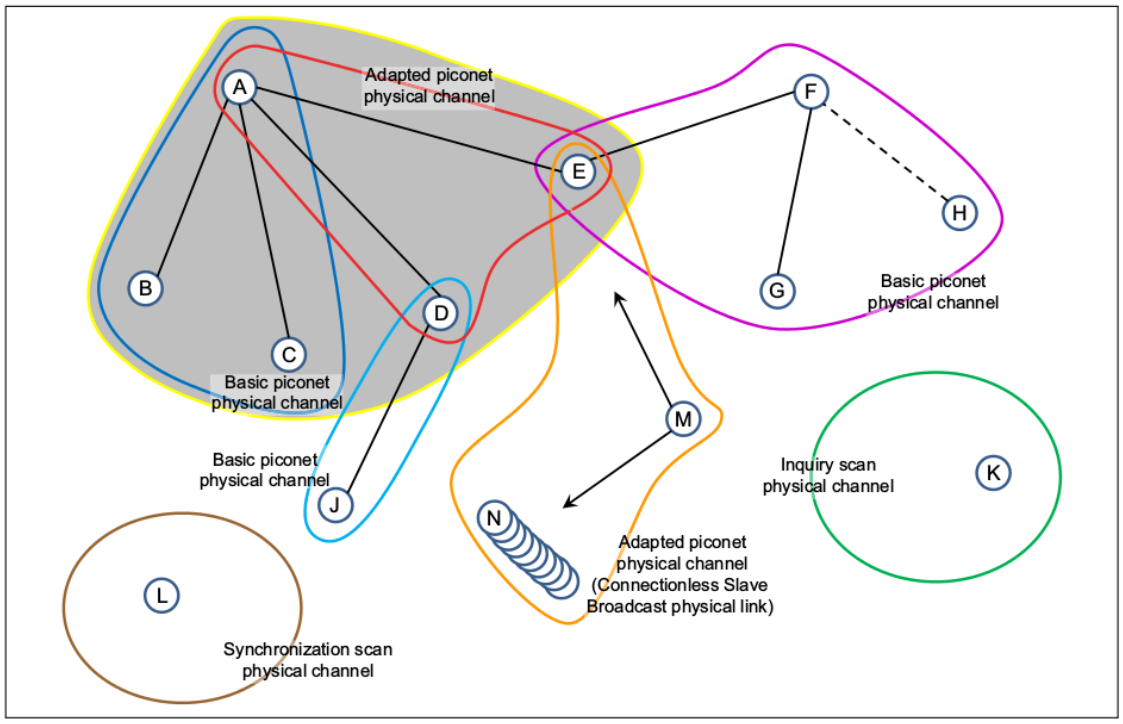

Figure 2.4: Bluetooth Topology

In Figure above, dashed arrows signify connection initiation and point from initiator to responder, while solid arrows point from master to slave. Each device is depicted with a capital letter; linked devices are shown as circles, while advertising-related devices are shown as ellipses. Group (1) in Figure 5 illustrates a straightforward broadcasting topology where A serves as an advertiser while B and C are known as scanners, using a BLE physical channel for advertising. In group (2), D acts as the master and E as the slave in a straightforward piconet with a single physical channel. In group (3), F assumes the role of a master, controlling the slaves G and H through two actual piconet channels. Device F, which is an advertisement with connectable advertising packets on the physical advertising channel, also serves as the connection initiator with Device I. The communication can start with device F adding slave I to its piconet. With only one master and many slaves, this type of network topology is known as a star network. Device J utilises two LE physical channels in scatternet (4), one with

K and the other with L. J serves as L and K's master and slave in this piconet. The BLE device performs communication using two main modalities, such as connections and broadcasting. Data can be easily distributed to multiple customers at once through the broadcasting procedure, however it is improper for sensitive data due to a lack of security measures or privacy. Sending advertising packets to applications that do not need to be completely active is the primary goal of broadcasting packets, which also serve another purpose. Additionally, the second is to recognise slaves when a master sends advertising packets (which are connectable). A connection is a continuous, recurring packet exchange between two devices. The connection is private and can be protected with security measures.

2.5 BLE Operation

BLE devices often only sporadically transfer data and spend the majority of their time in the standby state, which is why it is sometimes referred to as a "largely off" technology. The secret to the extremely low power consumption lies in this. BLE must, however, establish connections very quickly in order to make up for this and continue to be reliable. Three specific advertising channels are employed to establish connections in order to achieve this. Due to this, connection times are 20 times faster than for a Bluetooth Classic connection, coming in at less than 3 ms.

It is crucial to grasp the architecture in order to comprehend the BLE functioning and various connection modalities. Both a connected mode and a connectionless mode of operation are offered by BLE. Before going into detail about the various communication channels that BLE offers, a few words and parameters are introduced.[10]

Advertising packet transmission on the advertising channels is referred to as an advertising event. The advertiser delivers a promotional package before each advertising event. Upon receiving this packet, the associated Scanner may send the Advertiser a request, depending on the type of advertising packet. In the same advertising event, the advertiser then answers to that request. The timing between two advertising events is affected by two factors.[11]

- An integer multiple of 0.625 ms in the range of 20 ms to 10485 s is known as an

advertising interval (advInterval).

- After each advertising interval, a random value in the range of 0 to 10 ms is called the "advertising delay" (advDelay).

As a result, the sum of the advInterval and advDelay is used to define the amount of time (T advEvent) between two consecutive advertising events.

2.5.1 Connectionless Mode

Broadcasting or advertising are terms that are frequently used to describe the connectionless mode of BLE functioning. This is the simplest method of simultaneously sending data to several peers. This method's shortcomings include a lack of privacy, making it unsuitable for sensitive data.

Numerous advertising event types are offered when running in connectionless mode. These events can either be connected to or not. When establishing a connection, connectable events are used, and are better explained in the following section. Without creating a connection, the non-connectable advertising events transmit data directly over the main advertising channels. When the primary channels are not enough, the new secondary advertising channels (data channels) can be used to broadcast larger data packets.

By responding to an advertising packet on the same main advertising channel, the Scanner can make a request for more information for specific ad kinds (both heritage and expanded). As a result, inside the same advertising event and on the same advertising channel, the advertiser sends a scan response packet.

There are two primary categories of adverts that can be used when working in connectionless mode:

- Legacy Advertisements - Sends out a packet of advertisements on the main advertising channels that is only allowed to include 31 octets. The advertising are the same ones that were used in BLE 4.x and can only use LE 1M PHY.

- Extended Advertisements - Compared to historical advertisements, these can send larger data packets. Use any of the three PHYs to send out up to 255 octets-

long large advertisement packets (also known as auxiliary packets) on secondary advertisement channels (LE 1M, LE 2M, LE Coded).

Data is contained in the advertising packet sent over a principal advertising channel in the event of non-connectable packets. Advertisers and scanners are the two different participant categories in this kind of communication.

The main channel is where all advertising events start. The advertiser bursts advertising packets to all three main advertising channels in a typical legacy advertising event with non-connectable packets. Every scan interval, the scanner tunes in to one of the channels before moving on to the next in an effort to gather data. Each of the parameters can be altered to suit a particular application.[12]

The connectionless method using non-connectable advertising packets has been modified to use extended advertising. To accomplish this, data is transmitted over secondary advertising channels without first establishing a link. Like the traditional advertisement, the advertiser uses the three main advertising channels to transmit brief extended advertising packages. This extended advertisement packet contains the time offset for when data is delivered on the secondary advertising channel, as well as a pointer to a secondary advertisement channel randomly selected from the 37 data channels. In order to receive data, the Scanner must then tune the receiver to that channel. When the advertising event concludes, in accordance with a time offset, the so-called auxiliary advertisement packet is transmitted on the secondary channel.

2.5.2 Connected Mode

The linked mode is predicated on creating a special connection between devices to routinely exchange data packets.

In order to connect, a peripheral device (Advertiser) first sends connectable advertising packets to the advertising channels on a regular basis, much like in connectionless

mode but with connectable packets. It's important to remember that this advertising method can be targeted, ensuring that just a particular gadget will react to the advertisement. The central device, which is currently a Scanner, gets the advertisement packet and responds with a connection request packet over the same channel, turning it into an Initiator. Once the connection is made, the peripheral device stops advertising and changes from the master to the slave status. The devices may now transfer data in both directions. Each connection event involves data transfer on the same frequency channel, but an AFH happens at each anchor point.

The initiator, or master, is in charge of the first transmission, connection synchronisation, and communication of the required configuration parameters. Then, either of the participants may end a connection by acknowledging a termination command. Additionally, if a supervisory timeout expires, a connection may be broken.[13]

2.6 Packet Format

The basic building blocks of BLE communication are packets. A chunk of data with a label that is sent from one device to another is called a packet. The device that sent the data and, optionally, which devices should listen to it are identified by the label on the data packet.

Two different basic packet structures are used by BLE. Both uncoded PHYs employ a common packet format (LE 1M and LE 2M). Due to its error correction system, LE coded PHY employs a significantly altered packet format. In BLE communication, only the Little Endian bit ordering is employed.

The packet format specified for LE Uncoded PHYs is shown in Figure. Both connection mode and connectionless communication employ this structure. Each packet has four required fields:

- Preamble: A predetermined pattern of alternately 0 and 1 bits utilised by the receiver to perform automatic gain control (AGC) training, estimate symbol timing, and frequency synchronisation. When utilising the LE 1M PHY, the preamble is 8

bits, and when using the LE 2M PHY, it is 16 bits. The LSB of the preamble and the LSB of the access address must match.

- Access Address (AA): Used by linked devices as a correlation code to avoid confusion between unrelated BLE devices using the same RF channel. The LL produces a 32-bit value called the AA. For each LL connection made between any two devices, each AA must be unique.

- PDUs range in length from 2 to 257 octets, depending on the type of communication. divided into two categories, Data Channel PDU and Advertising Channel PDU, which are further discussed in this section.

- A 24 bit checksum called the Cyclic Redundancy Check (CRC) is generated over the PDU to look for bit mistakes that might occur during packet transmission.

Figure depicts the packet format for the LE Coded PHY, which is utilised for both advertising and data channel packets. This format includes what are known as Forward Error Correction (FEC) blocks, which is the primary distinction between the two forms. The coding scheme used for FEC block 2 is indicated by the Coding Indicator (CI), a two-bit value. FEC block 1 always utilises the S=8 coding scheme. The modulation's termination sequence is formed by the three-bit termination fields TERM1 and TERM2. The remaining fields behave just like the LE Uncoded format.[14]

Chapter 3

BLE 5 Major Enhancements

The most recent Bluetooth core specifications include a number of updates designed to significantly increase performance and add new functionalities. Two new PHYs, LE 2M and LE Coded, are the most fascinating improvements in BLE 5. The former giving a longer covering range and the latter providing a faster transmission speed. It is important to keep in mind that these new PHYs cannot be utilised in tandem to increase speed and increase range. Additionally, a feature that significantly enhances the connectionless functioning mode has been implemented, enabling advertising messages to contain up to 255 bytes of data. This section provides a full description of these improvements and introduces examples of use cases that exemplify how each improvement benefits various IoT applications.

3.1 Increased Speed

In comparison to earlier versions, BLE 5 contains a new radio PHY, LE 2M, that can transfer data at double the speed (BLE 4.x). The LE 2M PHY can transport data at a speed of 2 Msym/s compared to the LE 1M PHY's 1 Msym/s. A single symbol equals one bit because the LE 1M and LE 2M PHYs signals are not modulated (1 sym/s = 1 bps). It's important to note that these data rates represent the on-air data rate and do not take packet overheads, connection intervals, or IFS into account (Inter-Frame Space). The theoretical maximum effective throughput for LE 2M PHY is 1.4 Mbps, or nearly 1.7 times greater than LE 1M, which can reach up to 800 kbps. The radio will need to run for less time due to the faster speed, which has the huge advantage of reducing power usage. When transferring the shortest packets feasible, this difference in

power usage is measured in and claimed to be roughly 15percent. As a result, adopting a BLE packet of the maximum length could result in power savings of up to 40–50 percent.

Although most BLE applications only require a speed of 1 Msym/s, using the new LE 2M may be preferable. A wearable fitness tracker, for instance, does not need a high data rate but instead benefits greatly from lower battery usage and less frequent recharging. The same fitness tracker also offers the advantage of quicker software upgrades, which enhance user experience.

A BLE module's Controller section needs to have its hardware updated in order to use this capability. So it may be predicted that there will be a significant delay before most devices can support this style of operation.

3.2 Increased Range

A new optional PHY called LE Coded is also made available as part of the option for increased range. According to the Bluetooth SIG, this innovation will be able to attain a range that is four times greater than earlier iterations. In order to put it into perspective, the range of BLE 4.x has been reported to be approximately 50–100 m outside and unimpeded, whereas it decreases to 10–20 m in a typical indoor environment. Accordingly, BLE 5 with LE Coded should, in the worst case scenario, be able to reach distances of up to 200 m outside and 40 m inside.

In order to accomplish this, LE Coded uses a reduced packet encoding method in addition to a raw data rate of 1 Msym/s, just like the LE 1M. The two spreading factors S=2 and S=8 can be used with this coding scheme. The number of symbols required to represent one bit is determined by the spreading factor, which results in data speeds of 500 Kbps for S=2 and 125 Kbps for S=8. It is possible to increase the tolerance for a poor Signal-to-Noise Ratio (SNR) by using many symbols. BLE modules require hardware upgrades to support this functionality because the Controller portion of the architecture uses this coding scheme primarily in hardware. The coding procedure is broken down into two parts, which are shown in Figure. The first step is Forward Error Correction (FEC) encoding/decoding, and the second is Pattern mapping/demapping. These actions increase

receiver sensitivity, which results in a better ability to correct faults in the received data without retransmitting it.

By raising the threshold for the maximum transmission power from +10 dBm to +20 dBm, BLE 5 offers the opportunity to substantially extend the range that is already available. This is undoubtedly a disadvantage when aiming for ultra-low power, particularly in the case of LE Coded since it necessitates a much longer radio operation time for the same data amount than LE 1M or LE 2M. For some applications that do not have severe power requirements but still require BLE connectivity, such as mains powered devices in smart homes, this may be recommended.

It's important to note that this method of operation is not appropriate for applications that need to send massive datasets or stream data. However, this operating mode is intended for Internet of Things applications, such as placing inexpensive modules across a building or in open areas to collect data (such as humidity, light, temperature, motion detection, etc.). By switching from BLE 4.x to BLE 5, it would be able to significantly reduce the number of devices covering the same region in this use scenario.[15]

A wearable device might be used in another application. Think of an old person-specific wearable bracelet or watch that, in the event of a fall, sends an emergency message to a smartphone. This circumstance might arise if the wearable's and smartphone's respective ranges are too great for the LE 1M. Since the signal is crucial, sending messages across greater distances has many advantages because the transmission speed or packet size is not as important.

3.3 Advertising Extension

BLE 5's ability to increase broadcasting capacity when in connectionless state is another noteworthy advancement (advertising). Broadcasting does not require a connection between devices, as was discussed in section. Messages are simply transmitted by an Advertiser and one or several scanners within range can pick up the messages. Advertising Extension enables devices capacity to broadcast around 8x larger packets compared to preceding versions. BLE 4.x supports message sizes up to 31 octets, while BLE 5 sup-

ports message sizes up to 255 octets. The single broadcasting mode supported by earlier versions of the technology, Legacy Advertisements, is not backwards compatible with this improvement.

In order to inform scanners about the configurations needed to access the extended advertisement material, the advertiser first broadcasts a packet (31 octets) comprising device address and configuration details. Then, on the secondary advertisement channels (data channels), scanners can receive data packets of up to 255 octets without first establishing a connection. For information on the Advertising Extension procedure, see section.

The advertisement packet delivered on the primary advertisement channel includes a header value instructing these older devices to ignore them so that devices that do not support this functionality are not confused. Without changing the radio hardware, this capability can be supported; all that is needed is for the chipset makers to offer an updated software stack.

Development of BLE beacons can greatly benefit from advertising extensions. Since the introduction of BLE, the widespread use of beacons has rapidly increased. By 2021, forecasts indicate that yearly beacon shipments would exceed 565 million, with practically all of them using BLE 5 and future generations.

The 31-byte message limit imposes a very strict cap on beacon broadcasting. Consider a scenario where a beacon broadcasts a URL to nearby devices to further contextualise the situation. The typical URL size is usually greater than 31 bytes, which forces developers to come up with a workaround. This problem is fixed in BLE 5, allowing for the connectionless transmission of larger amounts of data.[16]

The numerous beacon use cases will gain significantly from this change as well. This data may include things like restaurant menus, traffic statistics, exclusive deals, and promotions. Additionally, since this option simply needs a software update, there is less of a market delay because the majority of current smart devices can support this function following a software update.

3.4 Theoretical performance

It is ideal to talk about how BLE's performance can be assessed now that the theoretical underpinnings of the technology have been presented. A Bluetooth device's performance is solely determined by how it is used and by the hardware configuration, not just by the Bluetooth version it supports. The operation scheme and other performance factors vary between chip suppliers. This part will introduce the theoretical BLE 5 performance in terms of throughput, power consumption analysis, and coverage range.

3.4.1 Throughput

Each wireless technology's achievable throughput serves as an important benchmark. The actual data throughput that can be anticipated from a BLE application depends on a number of variables. However, this may not accurately reflect real-world conditions since if either a master or a slave device in a connection receives two consecutive packets for which the CRC check cannot be confirmed, the connection event stops. In other words, the data won't be sent again until the next connection event utilising a different data channel. Depending on the connection interval, this approach may reduce the effective throughput in locations with a lot of interference, but it also saves energy waste when a particular channel introduces a high bit error rate. One of the many specifics that has been used to reduce the amount of power that BLE communication consumes.

First off, BLE 5 offers three distinct PHYs and four different air data rates, both of which have a significant impact on throughput. These include LE 2M at 2 Mbps, LE 1M at 1 Mbps, and LE Coded at 500 or 125 kbps (S=2 or S=8). However, because this is the rate at which symbols are delivered and because there are a number of reasons that cause the data transfer to be delayed, it is impossible to achieve these data rates. The radio has a limit on the number of packets it can send per connection interval, the Inter Frame Space (IFS) delay between packets is a fixed 150 s, and there is packet overhead in the form of headers and configuration parameters, which means that not all of an octet's data bits are actually usable.[17]

Consider a linked operation mode where the largest data packet is being transferred in order to determine the maximum data throughput for each PHY (255 octets). Figure depicts a whole transmission cycle between two connected devices, during which the slave sends a data packet in response to a blank poll from the master. There is a constant IFS determined by the Bluetooth SIG between each packet. The usable 255 octets of data are simply divided by a single transmission time to determine the data throughput.

The first packet takes 44 s to transmit at 2 Mbps when using LE 2M. It comprises 11 octets. The data packet then takes 1064 s to send and has 255 octets of useful data and 11 octets of overhead. With that said, T2M = 1.45 Mbps can be used to calculate the application data throughput.

The first packet only contains 10 octets when LE 1M is selected because the preamble is shorter and it takes 80 s to broadcast. The data packet transmits in 2120 s and contains 255 octets of useful data and 10 octets of overhead. As a result, T1M = 816 kbps is determined to be the LE1M maximum application data throughput.

Refer to Figure 2.14 for a somewhat different packet format for LE Coded. Here, 255 octets of data are sent in the same quantity. However, the initial empty packet, which is 20 octets in size, is sent much more slowly, taking 462 and 720 milliseconds for S=2 and S=8, respectively. The IFS remains unchanged, however data packet transmission will take substantially longer. To transport the 255 octets of data, it takes 4541 s for S=2 and 17040 s for S=8, respectively. Application data throughputs of TS2 = 384 kbps and TS8 = 115 kbps result from this.[18]

This model does not take into account factors like connection interval, slave delay, maximum packets per connection interval, device restrictions or BER (Bit Error Rate), and RAM available to buffer the data, which can have a substantial impact on throughput. Another noteworthy method for simulating the throughput of a BLE link can be found in, which investigates an older version of BLE and takes the impacts of BER into account.

3.4.2 Power Consumption

As the name suggests, BLE's primary objective is to establish wireless connections while consuming the least amount of power. Since the average power consumption of low power wireless standards truly depends on a number of hardware and software factors, including operation mode, hardware design, power class, etc., it is almost difficult to state. It is necessary to take into account a specific hardware module and operating mode in order to assess BLE's power usage. The average current consumption throughout the active phase of operation must also be assessed, as the peak current can have a considerable impact on battery-powered devices. For the remainder of the process, using a 3V reference, the power usage is practically constant at 1 A.[19]

3.4.3 Covering Range

The covering range is greatly influenced by the working environment, as are the majority of performance attributes. Reflections, obstacles, and RF interference all contribute to real-world usage scenarios and affect the viability of link establishment.[19]

Chapter 4

Bluetooth Testing and Quality Assurance

4.1 Bluetooth Testing Overview

Testing Bluetooth goods is a crucial step in ensuring their dependability and quality. The different facets of Bluetooth operation that are tested include device discovery, pairing, data transfer, and power usage. Depending on the complexity and scope of the testing needs, human or automated Bluetooth testing can be done.

Human testers are used in manual Bluetooth testing, which entails evaluating Bluetooth devices in accordance with specified test plans and processes. Although manual testing is time-consuming and subject to human error, it is effective at spotting user experience problems and edge cases that automated testing might miss.

Using software tools and scripts to run Bluetooth tests automatically is known as automated Bluetooth testing. A greater variety of test cases and scenarios may be covered via automated testing, which is quicker and more effective than manual testing. To enable quicker and more frequent releases of Bluetooth products, automated testing can also be integrated into a continuous integration and continuous delivery (CI/CD) pipeline.

4.2 Bluetooth Testing Challenges

4.2.1 Bluetooth Protocol Stack

The physical layer, connection layer, and application layer are among the various levels that make up the Bluetooth protocol stack. The distinct functionality and requirements of each layer make it difficult to evaluate Bluetooth products thoroughly.

4.2.2 Bluetooth Profiles and Services

Numerous profiles and services are supported by Bluetooth technology, including the hands-free profile (HFP), the advanced audio distribution profile (A2DP), and the serial port profile (SPP). The unique use cases and needs of each profile make it difficult to thoroughly test Bluetooth products across all profiles.

4.2.3 Interference and Noise

The 2.4 GHz frequency band, which is also utilised by Wi-Fi and microwave ovens and many other wireless technologies, is where Bluetooth functions. Bluetooth items' performance might be impacted by interference and noise from other devices, which makes testing difficult.

4.2.4 Compatibility and Conformance

Products that use Bluetooth must adhere to the Bluetooth standard and work with other Bluetooth devices. It is difficult to guarantee complete compatibility and conformity since testing for compatibility and conformance requires extensive testing across various devices and scenarios.

4.3 Bluetooth Quality Assurance

The process of ensuring that Bluetooth goods fulfil the end-users' standards for quality and performance is known as Bluetooth quality assurance (QA). Testing, validation, and verification are just a few of the different tasks involved in Bluetooth QA.

As it enables the detection and correction of flaws and problems in Bluetooth goods, Bluetooth testing is an essential part of Bluetooth quality assurance. All facets of Bluetooth functionality, such as device discovery, pairing, data transfer, and battery usage,

should be tested.

The process of confirming that Bluetooth goods adhere to the stated specifications and use cases is known as validation. Bluetooth products are validated in real-world scenarios and environments to make sure they function as intended.

Bluetooth verification is the procedure used to confirm that Bluetooth items adhere to the Bluetooth standard as well as other pertinent rules and specifications. Verification of Bluetooth devices entails comparing them to established test cases and criteria.

4.4 Bluetooth Test Automation

The technique of using software tools and scripts to automate Bluetooth testing is known as Bluetooth test automation. By minimising the time and effort needed to carry out tests manually, Bluetooth test automation can increase the efficacy and efficiency of Bluetooth testing.

Robot Framework, Appium, and Selenium are just a few of the automation frameworks and tools that may be used to automate Bluetooth tests. Python, Java, or C++ are examples of programming languages that can be used to create Bluetooth test automation scripts.

4.5 Bluetooth Test Automation Framework

A set of standards, instruments, and best practises for creating and running Bluetooth test automation scripts is known as the Bluetooth test automation framework. A framework for Bluetooth test automation can offer a standardised and organised approach to Bluetooth testing, facilitating the creation of scripts that are reusable and maintainable.

These elements make up a typical Bluetooth test automation framework:

4.5.1 Test Environment Setup

Setting up the test environment entails equipping it with the hardware and software elements required for Bluetooth testing. The setup of the test environment should be repeatable and scalable to suit various testing needs.

4.5.2 Test Plan and Test Case Development

Determining the testing objectives, test scenarios, and test cases is a part of developing the test strategy and test cases. The development of the test strategy and test cases should be based on the specifications and use cases for the Bluetooth product.

4.5.3 Test Script Development

The process of developing test scripts entails writing automated test scripts that run the tested scenarios and test cases. To ensure consistency and maintainability, the test script development process ought to adhere to a standardised format and structure.

4.5.4 Test Execution

The automated test scripts are run throughout test execution, and test results are recorded. To provide precise and dependable test findings, the test execution should be carried out in a monitored and controlled environment.

4.5.5 Test Reporting and Analysis

A summary of the test results and the identification of any flaws or problems are included in the test reporting and analysis. The test reports and analysis should offer takeaways and suggestions for raising the calibre of the Bluetooth product.

4.6 Bluetooth Test Automation Best Practices

It is crucial to adhere to a few best practises in order to achieve successful Bluetooth test automation. The following are some of the top Bluetooth test automation best practises:

4.6.1 Define Clear Testing Objectives

For Bluetooth test automation, it is essential to define precise testing objectives. The testing goals should be well-documented and in line with the specifications and use cases for Bluetooth products.

4.6.2 Use Standardized Test Case Formats

The Bluetooth test automation scripts' consistency and maintainability can be ensured by using standard test case formats. The test case description, anticipated outcomes, and test data should all be included in the standard test case forms.

4.6.3 Prioritize Test Cases Based on Risk

It is possible to maximise Bluetooth test automation efforts by ranking test cases according to risk. Prioritise more important test cases over less important test cases when choosing which capabilities and use cases to test.

4.6.4 Use Realistic Test Scenarios and Data

Bluetooth goods can be evaluated in real-world scenarios and environments by using realistic test scenarios and data. The realistic test cases and data should be based on the specifications and use cases for Bluetooth products.

4.6.5 Conduct Regular Maintenance and Review

For Bluetooth test automation scripts to be effective and efficient, continuous maintenance and evaluation are necessary. Regular upkeep and review can assist find and address any flaws or problems and guarantee that the test scripts are current.

In conclusion, Bluetooth testing is an essential step in the creation of Bluetooth goods, guaranteeing that the products are reliable and up to requirements. Bluetooth testing can be streamlined and optimised with the aid of test automation, making the process quicker and more effective. The creation of reusable and maintainable test scripts is made possible by the use of a Bluetooth test automation framework, which can give an organised and standardised approach to Bluetooth testing. In order to automate Bluetooth testing, a number of solutions are available on the market, including Robot Framework, Appium, and Selenium. Clear testing objectives, the use of standardised test case formats, risk-based prioritisation of test cases, the use of realistic test scenarios and data, and executing tests using real-world data are all best practises that must be followed to achieve successful Bluetooth test automation.

In the following chapter, we'll go through how NXP Semiconductors implemented a framework for automated Bluetooth testing of System-on-Chips (SoCs). We'll go over the implementation's specifics, such as setting up the testing environment, creating the test plan and test cases, creating the test script, running the tests, and reporting and analysing the results.

Chapter 5

DevOps for Automation of Bluetooth Profile Testing

DevOps practises have become an essential part of the development process in today's fast-paced software development environment. The automation engineers at NXP Semiconductor were able to streamline the Bluetooth profile testing procedure and guarantee high-quality releases thanks to the usage of DevOps tools like Jenkins, Magnodb, and InfluxDB. In this chapter, we'll talk about the role of DevOps in automating Bluetooth profile testing and show how a testing pipeline can be built using Jenkins, Magnodb, and InfluxDB.

5.1 Overview of DevOps for Bluetooth Profile Testing

Agile software development and continuous software delivery now need the use of DevOps practises. In order to achieve high-quality releases, DevOps focuses on collaboration and communication between the development and operations teams and automates workflows and processes. DevOps techniques can be utilised to fully automate the testing process for Bluetooth profiles, from test execution through reporting and analysis.

5.1.1 Jenkins for Continuous Integration

The development, testing, and deployment of software applications can all be automated using Jenkins, an open-source automation server. Jenkins is used at NXP Semiconductor to automatically run Bluetooth profile checks on SoC devices. Jenkins is set up to get

the most recent code updates from the source code repository, compile the test code, and run the test scenarios on the required hardware. Additionally, Jenkins creates thorough reports of the test findings and notifies the development team.

5.1.2 Magnodb for Continuous Deployment

The data produced when testing Bluetooth profiles is kept and managed in the Magnodb NoSQL database. The results of automated tests, including test case execution status, test coverage, and issue reports, are stored in Magnodb at NXP Semiconductor. Reports and insights into the testing process are produced using the data kept in Magnodb. Magnodb is also used to keep track of and manage test cases and to spot areas that require further testing.

5.1.3 InfluxDB for Data Analysis

A time-series database called InfluxDB is used to store and analyse the data produced when testing Bluetooth profiles. Metrics pertaining to the performance and stability of the SoC devices during testing are stored in InfluxDB at NXP Semiconductor. These data include network activity, CPU use, and memory usage. Additionally, InfluxDB is utilised to produce graphs and charts that shed light on the SoC devices' performance during testing. The performance of the devices can be improved with the use of this data, which can also be used to spot possible problems before they get serious.

5.1.4 Dashboard Output for Bluetooth Profiles

Dashboards are used to show the Bluetooth profile testing procedure in real-time. Grafana, an open-source platform for data visualisation, is used at NXP Semiconductor to produce dashboards. The dashboard shows important testing-related parameters, such as defect reports, test case execution status, and test coverage. The dashboard also shows parameters for the SoC devices' stability and performance throughout testing, such as CPU, memory, and network activity. Developers and stakeholders can track testing progress and see possible problems thanks to the dashboard's centralised view of the testing procedure.

5.1.5 Benefits of DevOps for Bluetooth Profile Testing

The testing of Bluetooth profiles at NXP Semiconductor has benefited in a number of ways from the usage of DevOps tools like Jenkins, Magnodb, and InfluxDB. These advantages consist of:

- The testing of Bluetooth profiles at NXP Semiconductor has benefited in a number of ways from the usage of DevOps tools like Jenkins, Magnodb, and InfluxDB. These advantages consist of:
- Faster time to market: By using DevOps technologies, testing time has been cut down and release cycles have been sped up.
- Greater transparency: The usage of dashboards has improved the testing process's visibility, allowing stakeholders to keep track of developments and spot problems.

DevOps techniques and tools are used to manage the automation process successfully. A software development process called DevOps strives to unite the development and operations teams in order to improve communication and increase productivity across the software development lifecycle. The use of Jenkins, MongoDB, InfluxDB, and Dashboard output for Bluetooth profiles will be covered in this chapter.

5.2 Jenkins

Software projects can use Jenkins, a well-liked open-source automation server, to provide continuous integration (CI) and continuous delivery (CD). To enable the integration of various tools and technologies into the development process, Jenkins offers hundreds of plugins. Jenkins enables developers to test their code in various contexts and supports distributed builds.[20]

Jenkins is employed in the software development, testing, and deployment phases of the Bluetooth automation process. Every time a new code update is committed to the source code repository, Jenkins automatically completes these tasks. This makes sure that any problems are found early in the development process so that developers can address them right away.[20]

5.3 MongoDB

A NoSQL document database called MongoDB stores data as adaptable, JSON-like documents. MongoDB is made to manage big volumes of data and scale horizontally across several servers. MongoDB is renowned for both its usability and flexibility.

The test results and metrics produced during the testing process are stored in MongoDB as part of the Bluetooth automation process. These findings can be utilised to pinpoint problem areas and monitor the development process's advancement. Additionally, MongoDB gives developers the ability to store and retrieve data rapidly and effectively.[20]

5.4 InfluxDB

A time-series database called InfluxDB is designed to store and retrieve data that has been time-stamped. Because of its great performance and scalability, InfluxDB is notable for handling massive amounts of data.

The performance metrics produced during testing are stored in InfluxDB as part of the Bluetooth automation process. These metrics can be used to monitor the software's performance over time and pinpoint areas that require improvement. Developers can view the data in real-time with InfluxDB, which gives them an understanding of the system's performance.

5.5 Integration of Jenkins, MongoDB, InfluxDB, and Dashboard Output

Jenkins, MongoDB, InfluxDB, and Dashboard Output are connected to deliver a seamless development experience for the Bluetooth automation process. To automate the build, test, and deployment processes, utilise Jenkins. The test results and performance metrics produced during the testing process are stored in MongoDB and InfluxDB. Developers can easily spot any problems that need to be fixed thanks to the Dashboard output's graphical depiction of the data.

Through the use of plugins and APIs, these tools are integrated. Jenkins can inter-

face with MongoDB and save the test results thanks to the MongoDB plugin for Jenkins. Developers can view the performance data in real-time with the Grafana InfluxDB plugin. The combination of these instruments offers a powerfull tool set for developers.[21]

Chapter 6

Summary and Conclusion

Since its inception, some 20 years ago, Bluetooth has continued to develop and adapt to new technological developments. With cutting-edge new features like Bluetooth Low Energy (BLE) and Bluetooth Mesh, the technology has a strong chance of becoming the primary wireless protocol for Internet of Things connections for decades to come. Examining studies of related technologies, reviewing the literature, current BLE advancements, and the prevalence of Bluetooth enabled devices—which suggests that the infrastructure for widespread adoption is already in place—can all be used to support this claim.

Additionally, BLE 5's new features broaden the ecosystem of BLE devices by making room for use cases that call for even lower power consumption, a wider operating range, or a better throughput. However, by dynamically altering PHY variants and other connection attributes, these features could all be utilised on the same device for more effective functionality.

During this project, the BellPal watch was aimed at as the use case. Data was acquired for comparison by implementing similar BLE activity as the actual product uses. The results included data that used connection properties limited to prior versions than BLE 5, as well as the new features. These new BLE 5 features consist of utilizing high throughput, long range and decreased power consumption. The benefits that are evident when utilizing new features of BLE 5 will be discussed within this chapter while aiming on answering the research questions proposed early in this thesis.

6.1 Implementation Challenges

It's critical to understand the device's low level capabilities while developing a BLE application. When attempting to implement the needed functionality, a number of difficulties and hurdles were encountered during the project. The issues that most affected the project's work are briefly discussed in this section and what could have been done to avoid them. This section of the discussion aims to underline the value of thorough preparation and efficient literature study, both for academic and practical purposes.

Prior to deployment, the Software Development Kit (SDK) that was first used for software development—which is not the entire official release of this SDK but rather an evaluation version—caused substantially more issues than anticipated. Since this was not the SDK's official version, a lot of time was spent looking for bugs and figuring out solutions, and manufacturer support was sparse.

While examining data flows and connection characteristics, a further issue was discovered. When using wireless connectivity, it might be challenging to determine what information packets include. The quality of measurement results would be significantly improved by having a proper BLE sniffer that can analyse the contents of each packet and measure packet loss while also providing more time-efficient tests and wider analysis possibilities. Sadly, there is no product that fits this project's budget within a fair pricing range.

The initial plan to create an algorithm that can utilise all of the new features in BLE 5 did not work out as planned. The strategy employed to select the PHY is primarily to blame for this. Utilizing RSSI report data to assess the adequacy of connection parameters was the method adopted. Due to the specific usage examined in this study communicating with the central device in daily use so infrequently, excessive power consumption was caused. This might have been avoided and a better strategy could have been used with better planning and analysis prior to deployment.

6.2 IoT Readiness of BLE 5

The objectives of this project were to thoroughly examine BLE 5 and gather data on its potential to standardise IoT communication that demands extremely low power consumption. This thesis provided an overview of the data gathered throughout the project work and included many test scenarios that assessed the advantages of modern BLE technology for a particular use case. During the development of this project, power consumption, covering range, and throughput of a CC2640R2F hardware platform were three key factors that were targeted. Through a literature review, additional crucial aspects like in-depth functionality, scalability, omnipresence, and infrastructure were assessed.

6.3 Scalability

Particularly in the area of IIoT, the scale of an IoT network might be a limiting issue for a system. This can be described in two ways: as a vast network with a huge number of nodes interacting, or as a network requiring a greater distance between nodes. These networks occasionally need for a technology with extremely low power consumption, like BLE.

Although Bluetooth Mesh technology is not the focus of this project, there are certain advantages that it might offer to the field of wireless technology that are worth considering. The use of Bluetooth Mesh in automation, control, or monitoring systems may be suitable. Large-scale device networks that must dependably interact with one another while consuming very little power are frequently seen in these systems. Even though Bluetooth Mesh could be used for high-end industrial applications, it could also have a big impact on private systems like home automation. Compared to other mesh-supporting low power wireless technologies, Bluetooth Mesh has some advantages (such as ZigBee and Thread). These benefits mostly stem from the infrastructure that is already in place because the majority of interface devices, such laptops and smartphones, already support Bluetooth.

Additionally, the seamless use of IPv6 over BLE while using reasonable power could further transform the Internet of Things. Although this strategy has been examined by numerous sources, the market does not yet generally support it.

6.4 Low Power Characteristics

When creating a BLE-based low power system, power consumption is crucial. Every design process must account for the trade-off in range and power consumption between the various PHYs because it can significantly affect the power consumption in a BLE link. The results of the literature that has already been published offer a variety of power measures, but they do not accurately represent consumption in various operating modes. The project's test findings will include precise power consumption measurements for each operational mode. Table 5.2 contains a summary of the findings, which are detailed further.

The application used in this project has a power profile that can be broken down into a number of iterative steps. First, there is advertisement mode, which is activated when a slave device tries to connect to a master and again after a predetermined amount of time if the connection is lost. The results demonstrate power consumption for advertising events utilising three setups, each of which transmitted the same marketing data via a different PHY variation. The advertisement state is not meant to operate frequently for this application, but it should

however be taken into account while assessing the overall power consumption. The two new PHY variants using LE Coded outperform the LE 1M by 40% and 68%, respectively, which is to be expected given the significant difference in power consumption. Due to the implementation of packet structure and various advertising events, as stated in Chapter 2, the power consumption of each coding scheme is not inversely correlated with the data rate.

The device stops advertising and switches to connected mode once it connects to a master. No significant BLE data transition occurs during normal use. Transmission of an alarm message and a massive data exchange that symbolises an OAD are the only relevant BLE communications that have been measured. A notification alarm is set to broadcast a message every second when the alarm is triggered. This message is quite brief and only contains a few bytes of information. For each PHY variant that was on hand, the

power profile was assessed. For each connection event, the PHY with the highest data rate requires the least amount of power, while the PHY with the lowest data rate uses the most.

One of the most crucial aspects for BLE-enabled apps is standby power consumption. BLE is intended to be a mainly off technology, which means that it is primarily in standby mode. This was previously mentioned. The hardware platforms and implementations have a big impact on this attribute. The test results from this study showed that the average amount of power used while in sleep mode was incredibly low. This measurement is somewhat influenced by the connection qualities because it is heavily dependent on the quantity of recharge pulses required to maintain the connection. For the application used, the average standby current was measured to be around 100 nA, giving a theoretical lifetime of about 500 years on a 500 mAh 3V coin cell battery while merely working in standby mode.

6.5 Range & Throughput

If used carefully, the long range PHY option, LE Coded, that BLE 5 introduced can have substantial advantages. The increased power consumption is exchanged for the longer range. In other words, a gadget like the BellPal watch might use this feature sporadically and only when necessary. This would result in more reliable communication and a greater coverage area for the application. When devices are in LoS, connecting over longer distances results in a noticeable improvement. Results indicate that a distance of up to 1 km can be covered while still retaining connectivity. The fact that all range tests were carried out using output powers of 0 dBm rather than the hardware platform's maximum of +5 dBm should be noted.
This implies that the longest range for this gadget may actually be significantly longer.

Chapter 7

Conclusion

This report provides an overview of a literature review and practical application with the aim of addressing the research question and achieving the project's objectives. The implementation phase tried to assess and analyse the advantages of new capabilities added to BLE 5 while the literature study covered in-depth analysis of BLE architecture and functionality.

The new functionalities greatly enhance the complexity of BLE equipped devices while also broadening their potential applications. In a commercial product, this added complexity is invisible to the consumer, but it can present more difficulties during design and development. As a result, the technology is more adaptable and appealing for a wider range of application cases.

The doubled transmission speed, quadrupled range, and eightfold increase in message capacity of BLE 5 were said to be the most significant advancements. The first two qualities were assessed throughout the project's implementation phase for a particular application, and the findings were then presented in Chapter 5. The test results have demonstrated that utilising the LE 2M PHY version, it is possible to almost double the data rate. However, when compared to the normal LE 1M PHY, the results fall short of the quadruple range. The LE Coded PHY variation, which had a coding scheme of S=8, attained the greatest range, which was over 1 km, or twice as far as was feasible with earlier BLE versions (LE 1M PHY). The doubled transmission speed, quadrupled range, and eightfold increase in message capacity of BLE 5 were said to be the most

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If the hardware platform could accommodate the new maximum TX power of +20 dBm, this range might be extended even further. Since it is merely an architectural advancement, the eightfold message capacity is independent of implementation or hardware platform and is present in all BLE 5 equipped devices. Applications that employ one-way topology for broadcasting, like beacons, benefit greatly from this.

The extended range function would at least double the potential range when using such a device in an open environment. However, this is not a likely scenario for this use case, and this change would not be ideal on its own as it roughly doubles power consumption during transmission. However, a long range mode could be employed to increase the robustness of connection, trading it off for increased power consumption, by only employing it when a connection is ended owing to weak received signal strength.

Full-house coverage is the ideal long-range use case for such a gadget. This is difficult since dwellings range widely in size and construction, and RF interference is often unexpected. A pretty large house with strong concrete walls was used in the project's tests since it presented challenging conditions for a clear BLE signal. The results do indicate that a reasonable amount of coverage can be increased by using the LE Coded PHY. It goes without saying that this increases power consumption, and when the range gets closer to its limit, a large rise in the number of retransmitted packages results in even higher power consumption. Sadly, due to equipment restrictions, the retransmissions could not be measured during this research. Having stated that, the extended range function can be useful for increase coverage, however cautious implementation is required to avoid affecting the device's lifespan.

By changing the maximum PDU size, connection and advertisement intervals, and other crucial connection characteristics while dynamically switching between PHYs, all the advantages mentioned above may theoretically be realised simultaneously for a particular use case. Since relying solely on the RSSI value is ineffective for this purpose, careful design and implementation are needed. Since the RSSI value is extremely unstable and inconsistent and uses a lot of power, it must be transferred often between BLE devices to achieve any consistency. This issue might be resolved by adding mesh repeaters to the system or by building a low-power AI that would learn to interpret RSSI report data in the best possible way given the surrounding circumstances.

The Bluetooth SIG is undoubtedly prospering more thanks to BLE 5 and Bluetooth Mesh in terms of low-power, short-range wireless technology. This technology could undoubtedly become the industry standard for low power wireless devices if it integrates well, is widely adopted by manufacturers, and meets all Bluetooth SIG criteria.

7.1 Future works

Developing Bluetooth Low Energy (BLE) into the low power wireless technology industry standard still faces some serious obstacles. This section includes a collection of suggestions and ideas that were discovered while researching this thesis. These suggestions pertain to work that needs to be done by businesses as well as lone academics and developers to better comprehend the practical range of applications where BLE may be the best wireless technology available.

- When using BLE to the boundaries of its range, consider the retransmission rate in relation to the distance between devices to gain more power in actual increments.
- Examine how different BLE IC manufacturers use power when carrying out the same task.
- Look into the technology's IoT readiness from a market perspective. To achieve widespread adoption within the IoT, this can be done by assessing whether the value proposition of the technology outweighs the investment cost, development time, usability, and maintenance cost.

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