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MASTER'S THESIS

BLUETOOTH LOW ENERGY (BLE) DATA STREAMING AND INTEGRATION OF BLE AND 5G MOBILE CONNECTIVITY IMPLEMENTATION

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ABSTRACT

The energy-efficient wireless connectivity is among the crucial enabler technologies for the Internet of Things (IoT) employed throughout a great number of different verticals. The Bluetooth Low Energy (BLE) radio access technology is today among the most widely spread short-range wireless communication technologies for the energy-limited IoT devices available on the market. The thesis focuses on understanding and experimentally assessing the performance of the BLE technology with respect to the maximum communication link throughput and discovering the ways how BLE can be integrated with the 5th Generation Mobile Network (5G). To reach this goal, the study investigates the BLE technology focusing specifically on the parameters affecting the communication throughput, implements and carries the empirical throughput performance measurements for various architectures involving communication between embedded devices and the communication between an embedded device and a mobile terminal, and explore the means of boosting the communication performance range of BLE-enabled devices by integrating BLE with 5G and enabling streaming of the BLE data over 5G. Based on the study, it has been shown that the Nordic UART service achieves a BLE communication throughput of 92 kbps for most of the parameter configurations of connection interval, physical layer configuration, and data lengths. Based on the observed Phone-to-Server mean throughput of 23.11 Mbps, it can be stated that the overall throughput of the end-to-end system, which includes a Board-to-Phone BLE connection and a Phone-to-Server TCP/IP connection, is entirely reliant on the throughput of the BLE connection.

Keywords: BLE, 5G, Throughput Analysis

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PREFACE

This research was carried out at the Centre for Wireless Communications (CWC) of the University of Oulu as a part of the Academy of Finland FireMan project (decision 348008).

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I dedicate this unique academic accomplishment to my parents and brother, who showered me with unconditional love and warmth without diminishing it by the slightest measure, despite being more than 7700 km away from home.

Yasith Wanigarathna Arachchige

LIST OF SYMBOLS AND APPREVIATIONS

1G	1st Generation Mobile Network
2G	2nd Generation Mobile Network
3G	3rd Generation Mobile Network
3GPP	3rd Generation Partnership Project
4G	4th Generation Mobile Network
5G	5th Generation Mobile Network
5GTN	5G Test Network
AFH	Adaptive Frequency Hopping
AMPS	Advanced Mobile Phone System
API	Application Programming Interface
App	Application Layer
ATT	Attribute Protocol
BAN	Body Area Network
BLE	Bluetooth Low Energy
CDMA	Code Division Multiple Access
CRC	Cyclic Redundancy Check
DLE	Data Length Extension
eMBB	enhanced Mobile Broadband
EDI	Electronic Data Interchange
GAP	Generic Access Profile
GATT	Generic Attribute Profile
GB	Gigabyte
GFSK	Gaussian Frequency Shift Keying
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
IDE	Integrated Development Environment
IEEE	Institute of Electrical and Electronic Engineers
IoT	Internet of Things
IP	Internet Protocol
ISM	Industrial, Scientific, and Medical
kB	Kilobyte
KPI	Key Performance Indicator
L2CAP	Logical Link Control & Adaptation Protocol
LBT	Listen Before Talk
LE	Low Energy
LL	Link Layer
LTE	Long Term Evolution
MB	Megabyte
MEMS	Micro Electronic Mechanical Systems
MIC	Message Integrity Check
MIMO	Multiple-Input Multiple-Output
MTU	Maximum Transfer Unit
NFC	Near Field Communication
NFV	Network Function Virtualization
NMT	Nordic Mobile Telephone
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access

PDR	Packet Delivery Ratio
PDU	Protocol Data Unit
PHY	Physical Layer
PRR	Packet Reception Rate
QoS	Quality of Service
RAM	Random Access Memory
SMP	Security Manager Protocol
SSH	Secure Shell
SoC	System-on-a-Chip
SQL	Structured Query Language
TACS	Total Access Communication System
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
UART	Universal Asynchronous Receiver-Transmitter
URLLC	Ultra Reliable Low Latency Communications
USB	Universal Serial Bus
VLC	Visible Light Communication

1 INTRODUCTION

Bluetooth Low Energy (BLE) is a low-power wireless communication technology that uses the 2.4 GHz Industrial, Scientific, and Medical (ISM) band. BLE is widely used in applications with continuous data transmission in power-constrained environments. BLE has a wide range of applications, from smart bands to tags for asset tracking[1]. BLE has shown significant potential in enhancing the efficiency and accuracy of low power Internet of Things (IoT) networks with its reasonable throughput and lower power consumption.

On the other hand, the 5th Generation Mobile Network (5G) has expanded the boundaries of IoT networks with the help of its higher data rates, enhanced reliability and low latency communication. The combination of 5G technology and IoT has paved the way for countless applications, including but not limited to, autonomous cars, remote surgeries, and smart cities. Further, 5G has opened the door for the Internet of Everything (IoE) paradigm, where there will be a massive amount of interconnected devices with enhanced intelligent capabilities[2, 3].

Integrating BLE with 5G provides unmatched capabilities to an IoT network due to the low power consumption of BLE and the higher network capacity of 5G. This research was carried out to examine the possibility of integrating the 5G with BLE to enhance the existing IoT network capabilities. Based on the results of this research, it is planned to apply this concept of integration of BLE with 5G to the ongoing FireMan project and medical sensor integration projects at the University of Oulu[4].

1.1 Motivation

As an ultra-low-power wireless communication technology, adopting BLE in various applications has emerged as a prominent research focus among academia and industry giants. BLE 5 has expanded the boundaries of BLE technology by introducing higher data rates, larger packet sizes, and extended ranges. Even though BLE can be identified as a superior technology for power consumption and achievable throughput under a minimal power constraint, BLE has some limitations compared to other wireless communication technologies, such as the lower range.

Even though the capabilities of BLE are widely discussed among the interested communities, there needs to be more experiments to identify the real-world capabilities of BLE 5 under various conditions. Furthermore, there is a recognized potential in combining BLE with other communication technologies to enhance the efficiency and accuracy of existing IoT infrastructure. However, this research area has not yet been extensively explored.

Among the potential technologies to integrate with BLE to enhance the efficiency and accuracy of the communication process, 5G is a superior technology with higher data rates and ultra-reliable communication ability with low latency. Despite the mention of the integration of 5G and BLE in some literature, there appears to be a lack of valuable information discussing the real-world performance of this integration.

This study aims to fill the research gap by identifying the capabilities of integrating the BLE with 5G technology and evaluating the performance extensively, focusing on the applicability of IoT.

1.2 Contribution/Novelty of the Study

After thoroughly examining the latest developments in BLE and 5G, the potential of integrating BLE with 5G has been explored. Based on that examination, a software solution to integrate the

BLE with 5G technology was derived. For an extensive evaluation of the developed solution, the study has utilized several techniques: an analytical model derived by well-known researchers in the domain of BLE and the standard throughput test given by Nordic Semiconductors, one of the industrial giants in BLE developments. Further, the research has utilized the 5G Test Network (5GTN) at the University of Oulu to have unparalleled connectivity. The combination of these several components provides a novel insight into the capabilities of integrating BLE with 5G to enhance the efficiency and accuracy of the existing IoT infrastructure.

1.3 Objectives of the Research

The main objectives of the research are as follows.

- Examining the previous work that focuses on integrating BLE and 5G in IoT - It is vital to know state-of-the-art developments on 5G and BLE in the IoT area. It is also necessary to examine the recent research projects on integrating the BLE with 5G to have a solid idea about possible considerations when integrating those technologies. By completing this objective, it is planned to derive a feasible solution to integrate 5G with BLE to enhance the efficiency and accuracy of IoT networks.
- Implement an end-to-end software solution that utilizes BLE and 5G to enhance the efficiency and accuracy of communication within an IoT network - Based on the completion of the previous objective, it is a necessity to derive a software solution to address the requirement of integrating BLE with 5G to enhance the capabilities of existing IoT networks. Development is planned to enable the flexibility of testing the implemented solution with various parameters without much effort.
- Test the implemented end-to-end solution with various parameter configurations - Testing the implemented solution's performance is essential to verify its adaptability to various application requirements. It is planned to test the system with different parameters to characterize the throughput of the communication.
- Analyze the obtained results and discuss the performance of the implemented system - Data analysis is crucial to communicate the results to interested parties. Further, data analysis will also help derive conclusions on the implemented solution's different aspects. It is planned to analyze the obtained results with the help of statistical tools and graphical techniques such as graphs.

1.4 Structure of the Thesis

This thesis is arranged as follows.

- Chapter 2 - This chapter extensively studies the state-of-the-art experiments on BLE performance analysis, 5G in IoT communication, and integration of 5G with BLE.
- Chapter 3 - This chapter provides a detailed technical explanation of the BLE technology, 5G, and integrating BLE with 5G.
- Chapter 4 - Using an analytical model, this chapter discusses the theoretical aspect of the concept of throughput in BLE.

- Chapter 5 - Discusses implementing an end-to-end software solution, including the hardware configuration, tools and services used, and mobile and embedded application development.
- Chapter 6 - This chapter provides a detailed explanation of the evaluation of the implemented software solution by focusing on planned tests, testing environment, parameter selection, and test procedure.
- Chapter 7 - This chapter discusses the obtained results for different tests and underlying causes for deviation from theoretical and expected values.
- Chapter 8 - This chapter concludes the overall study and highlights the possible future research avenues.

2 RELATED WORKS

This chapter will delve into previous work that pertains to BLE, 5G in IoT, and the integration of BLE with 5G.

2.1 Previous Studies on BLE Performance Analysis

A group of researchers consisting of Mikhaylov et al.[5] has performed extensive research to experiment with the maximum peer-to-peer throughput, the minimum frame turnaround time, and the energy consumption of BLE 4, Institute of Electrical and Electronic Engineers (IEEE) 802.15.4, and SimpliciTi. They obtained a maximum throughput of 319.5 kbps through the analytical model used for the throughput calculation. That value was obtained in a scenario where the payload was 27 bytes, assuming the existence of only the inter-frame space and the time for transmitting the frame headers and with no payload for the reply frame. For the evaluation with real devices, they utilized CC2510 for SimpliciTi, CC2431 for IEEE 802.15.4, and CC2540 for BLE. The maximum throughput of 122.6 kbps for BLE 4 was observed during the real-world experiment. The significant reduction of the throughput was mainly due to the limitation of the TI BLE stack, which had limited the number of frames sent per connection event based on the frame's payload. The maximum throughput for the advertising channels of BLE 4 was below 10 kbps. Even though the analytical expression resulted in a minimum turnaround time of less than one millisecond for BLE, in the real world, it resulted in 7.6 ms where this happened due to the delaying of the reply frame until the next connection event by the tested BLE transceivers. It was also observed that BLE consumes 2 to 7 times less energy for data communication than IEEE 802.15.4 and SimpliciTi[5].

In 2017, a team of researchers consisting of Tosi et al.[6] analyzed the performance of BLE 4, focusing on throughput, maximum number of connectable sensors, power consumption, latency, and maximum reachable range. They utilized existing literature on BLE to analyze these performances. Maximum throughput was obtained as 236.7 kbps with a payload of 20 bytes. It has been noted that the estimated range for the number of slaves per master was between 2 and 11, particularly when the connection interval was approximately 7.5 ms. It was analyzed that when the connection interval increased to 4 s, the number of slaves could increase to 5900. Even though the theoretical values for the number of slaves per master were significantly higher for higher connection interval values, in the development environment, it was limited due to the availability of heap memory in development boards[6].

After the conclusion of previous research, the same team of researchers performed research to investigate the performance of BLE 4 in general sensor networks focusing on the throughput aspect. Further, they also observed the influence of different nodes with various hardware, software and firmware arrangements on the throughput performance. They utilized the LG Nexus 5, Samsung Galaxy Tab S2, and a stack of two STMicroelectronics boards as the master nodes. There were two topologies for the peripherals. The first peripheral topology was a SensorTile module with some Micro Electronic Mechanical Systems (MEMS) sensors. In contrast, the second peripheral topology was a stack of three ST boards with sensor expansion boards and MEMS sensors. They observed a peak bit rate above 170 kbps with the sensor network when there are five peripheral nodes. They observed that throughput measurements with LG Nexus 5 and Samsung Galaxy Tab S2 showed a significant difference and concluded that newer smart devices with newer hardware arrangements and newer versions of operating systems tend to have higher performance[7].

A team of researchers from Austria consisting of Spörk et al.[8] experimented with the performance of all four Physical Layer (PHY) modes of BLE 5. Their hypothesis was BLE

5 increases the throughput twice and has higher reliability than BLE 4. They performed the experiments in a line of sight channels with 0 dB transmission power and a 1 m distance between the transmitter and the receiver. They utilized nRF52840dk by Nordic Semiconductors for both master and slave devices. It was observed in the experiment that the 2 Mbps PHY mode had the lowest average power consumption, and the coded S8 PHY had the highest average power consumption. It was also observed that 2 Mbps PHY has around 8% lower power consumption than 1 Mbps PHY. Further, the experiment observed that the power consumption increased with the increase in the connection interval. The 62.5 ms connection interval of 2 Mbps resulted in 85% more power consumption than the 500 ms connection interval. It was identified in the experiment that the effect of Protocol Data Unit (PDU) on power consumption was minimal as it was only a 20% increase of the power from 32 bytes PDU to 253 bytes PDU. Further, they obtained throughput measurements for all 4 PHY modes of BLE 5 by sending 10000 notifications from the slave device to the master device. They calculated the throughput based on the total elapsed time for the transmission. They observed around 178% - 212% increase in the throughput for BLE 5 compared to BLE 4. They also observed the Packet Reception Rate (PRR) under -15 dB interference in a line of sight channel with a 10 m distance between the master and slave devices. It was observed the Coded S2 and S8 have higher PRRs which were 67% and 80% respectively, than that of 2 Mbps PHY and 1 Mbps PHY, where the PRRs were around 15% and 32% respectively[8].

Another team of researchers, Ancans et al.[9], measured the BLE performance under various parameters and various interference sources. They utilized (2.1) to calculate the throughput of the application level of BLE. There S_{app} refers to the application level throughput while N refers to the number of data transmissions per connection interval. L_{app} refers to the exchanged application payload in bytes and T_{ci} refers to the connection interval. They utilized an Electronic Data Interchange (EDI) testbed network, 1 CEA sensor platform, 2 WiFi routers, 5 nRF51 development kits, and 5 nRF52 development kits. They experimented considering minimising ISM band interference from external sources, whereas they utilized both 1 Mbps PHY and 2 Mbps PHY in BLE for the measurements. They increased the connection interval from 7.5 ms to 4 seconds and the Attribute Protocol (ATT) Maximum Transfer Unit (MTU) size from 23 bytes to 247 bytes. They also observed that with the increase in the number of Bluetooth devices, the throughput has significantly decreased. The reason for this was explained as when two devices try to operate in the same channel, and transmission should be repeated. They observed that even though higher connection intervals resulted in lower throughput values, the influence of WiFi interference on throughput was around a 30% decrease of the throughput regardless of the connection interval[9].

$$S_{app} = N.L_{app}/T_{ci} \tag{2.1}$$

During the same period, another team of researchers consisting of Bulic et al.[10] observed the effect of connection interval on throughput and compared the power efficiency to throughput for various versions of BLE and transactions like read, write, and notify. They used two Nordic nRF52840dk boards as the central and peripheral devices and the power profiler kit from Nordic semiconductors to measure the power consumption. Because of the possibility of fragmentation of a single ATT packet to several on-air data packets for larger ATT_MTU sizes, the ATT_MTU value was set to 247. The upper bound for the throughput was obtained as (2.2). ATT_MTU in the equation stands for the value of the ATT_MTU where 3 bytes were reserved for the headers. CI stands for the connection interval, where twice it stands for the total duration of the transaction. They observed that the lower connection interval resulted in higher throughputs for read and write operations in all the versions of BLE. Nevertheless, it did not significantly impact notifications and write-without-response transactions. They observed that the radio operation of BLE 5 had higher power consumption than that of BLE 4. However, 2 Mbps PHY helps lower the total power consumption than BLE 4 due to the lower time requirements to transmit data[10].

$$Throughput \leq \frac{(ATT\_MTU - 3)}{2 \times CI} \tag{2.2}$$

Based on the research of Mikhaylov et al.[5], a team of researchers from Aalto University, Finland consisting of Badhini et al.[11] developed a system-level simulator using OMNeT++ to examine the performance of BLE 5 considering the packet error rate, throughput, end-to-end delay, and battery lifetime. They experimented in an open office environment with dimensions of 10 m × 10 m × 4 m. During the point-to-point throughput analysis experiment, it was set to send the traffic by the master node while the slave node always sends the acknowledgement. It was observed that with the increasing number of master-slave pairs, the throughput significantly decreased, whereas the throughput of the master-slave pairs with 2 Mbps PHY showed an average of 40 kbps when there were 100 pairs. It was also observed that 2 Mbps PHY has the highest throughput with the congestion in the network. Coded S8 of BLE 5 showed a higher increase in the packet error rate with the increase in the number of pairs than other PHY options. The average end-to-end delay showed the lowest value in 2 Mbps PHY, whereas coded S8 showed the highest value, more than 30 seconds, when there were 100 pairs. It was observed that battery lifetime decreased with the increasing number of pairs in the network. Coded S8 had the lowest battery life with 100 pairs while 2 Mbps PHY had the highest battery lifetime for the same scenario[11].

A team of researchers consisting of Park et al.[12] developed a mechanism based on local measurements and a small lookup table to adaptively control data rate, transmission power, and connection interval to minimize energy consumption and satisfy the latency requirement under dynamic wireless environments using BLE. The system included tools for estimating latency, calculating connection intervals, and managing data rates and transmission power. The main objective of this research was to reduce energy consumption while meeting the Quality of Service (QoS) requirements. The system was integrated into TI CC2640R2F, and the evaluation focused on two main aspects - the runtime system behaviour and the effects of the channel environment. The experiments were carried out as 90-minute sessions where it was given to the implemented system 3 QoS requirements to satisfy each of the 30 minutes. It was observed that the system could satisfy the QoS requirement in each scenario when experimenting to observe the run time behaviour. However, it could not perform as expected during the experiments to observe the impact of the channel environment. This was mainly identified in non-line of sight channels where the higher number of packets re-transmission resulted in lower QoS[12].

Pang et al.[13] researched to evaluate the performance, mainly focusing on the throughput and reliability of BLE under WiFi interference. BLE uses Adaptive Frequency Hopping (AFH) to mitigate the effect of interference, where it divides the BLE spectrum into 37 data channels and facilitates hopping pseudo-randomly. However, AFH cannot mitigate the effect of interference completely. They used Packet Delivery Ratio (PDR) to measure the reliability of BLE, which is given by (2.3). $ack(c)$ of the equation represents the number of valid acknowledgements at the central device, and $tx(c)$ represents the number of packets the central device sends. They also calculated the throughput of the central device using (2.4). $data(c)$ refers to the total data obtained at the central device. Further, CI and num_{CI} refer to the value of the connection interval and the total number of connection intervals passed during the transmission. They utilized two nRF52840dk boards as the central and peripheral devices, which were placed at a distance of

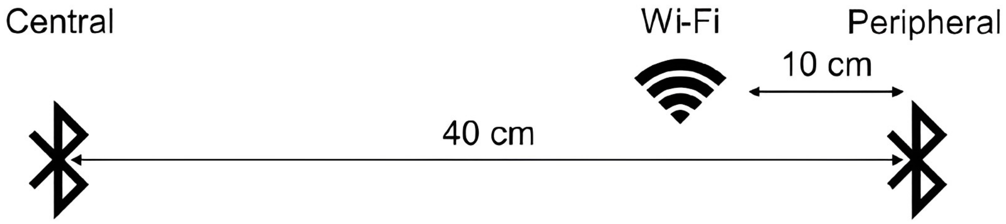


Figure 2.1. Device Arrangement of the Experiment of Pang et al.[13]

40 cm between them. To measure the effect of WiFi interference, they placed Rasberry Pi with WiFi enabled 10 cm from the peripheral in the space between the transmitter and the receiver. The device arrangement is illustrated in Figure 2.1. They used the BLE PHY configuration of 1 Mbps PHY with a connection interval of 7.5 ms. They observed the reliability and throughput under the no WiFi, static WiFi, and dynamic WiFi scenarios. It was observed that even though throughput and reliability decrease with the interference of the channel, the reduction was not proportional to one another, where the throughput reduction was significantly higher than that of reliability[13].

$$PDR = \frac{ack(c)}{tx(c)} \tag{2.3}$$

$$Throughput = \frac{data(c)}{CI \times num_{CI}} \tag{2.4}$$

2.2 Previous studies on 5G in IoT Communication

An extensive survey to identify the IoT application requirements, the capabilities of the 5G new radio, and possible enhancement to the IoT technology with 5G was performed by a team of researchers consisting of Akpakwu et al.[14]. According to them, the main design requirements of IoT networks when considering massive deployments are listed below.

- Low device cost - As it is considered massive development of IoT networks, it is beneficial to make the device cost minimal.
- Low deployment cost - It is required to keep the capital and operational costs at a minimum to enhance the usability of IoT networks.
- Long battery life - As IoT devices are planned to operate for long periods without human intervention, optimizing their battery usage is essential.
- Extended coverage - There are various IoT applications where the sensors are placed in hard-to-reach places. Providing these devices with good network coverage is vital to communicate efficiently.
- Security and privacy - The privacy of mobile IoT users and location privacy should be highly considered to enable a trustworthy network.

- Support for a massive number of devices - The ability to handle a large number of connected devices simultaneously within the network should be considered.

Software-defined wireless sensor networks and cognitive radio networks were identified as the primary enabling concepts of the era of 5G and IoT[14].

A team of researchers consisting of Shancang et al.[15] analyzed the possible advancements in integrating the IoT with 5G networks. They identified the requirements of 5G in IoT networks as high data rate, highly salable networks, poor latency communication, higher reliability, security, long battery lifetime, connection density and mobility. Connection density refers to the number of devices connected and the requirement for a higher network capacity to cater for communication needs. They proposed an architecture for 5G-IoT integration which consists of two planes.

1. Control plane - Used for network management tasks.

2. Data plane - Used for data sensing through software-defined front-haul networks

Network Function Virtualization (NFV) allows scalable and flexible IoT networks by utilizing network slicing. Heterogeneous networks were proposed to be used in 5G-IoT networks for interference management[15].

Potential enhancements to the existing IoT infrastructure with the help of the 5G network were observed by a team of researchers consisting of Agiwal et al.[16]. They identified the requirement of the 5G network due to the shortcoming of the 4G network in the domain of IoT as massive connectivity, extended battery lifetime, sporadic traffic and orthogonality constraints, delay tolerant and delay-sensitive services, narrow band operation, beyond the human interface, heterogeneous connectivity, and disjoint licensed and unlicensed band. Sporadic traffic and orthogonality constraints refer to the expectation to reduce the signalling overhead with the help of synchronous Orthogonal Frequency Division Multiple Access (OFDMA). Disjoint licensed and unlicensed bands referred to the requirement to integrate various licensed and unlicensed bands, which was not catered from 4G networks[16].

2.3 Previous Studies on BLE Integration with 5G

A team of researchers consisting of García et al.[17] researched to observe how BLE, Near Field Communication (NFC), and Visible Light Communication (VLC) affect the development of smart cities. They identified the following possible use cases to integrate BLE with smart cities which utilize the capabilities of 5G and beyond networks.

1. Transport and mobility - BLE beacons, together with cameras, can be utilized for traffic management purposes with the help of advanced algorithms for image processing.

2. Health Care and Social Services - Locating services for hospital patients and smart assistance solutions for the elderly and disabled.

3. Retail and Commerce - Locating people in indoor retail and commercial locations.

4. Sustainability and Smart Building and Homes - Due to the lower power consumption of BLE, it can be adapted as nodes of sustainable smart systems.

Further, they have mentioned that a limited range of BLE will be the primary concern when adapting BLE in the domain of smart cities[17].

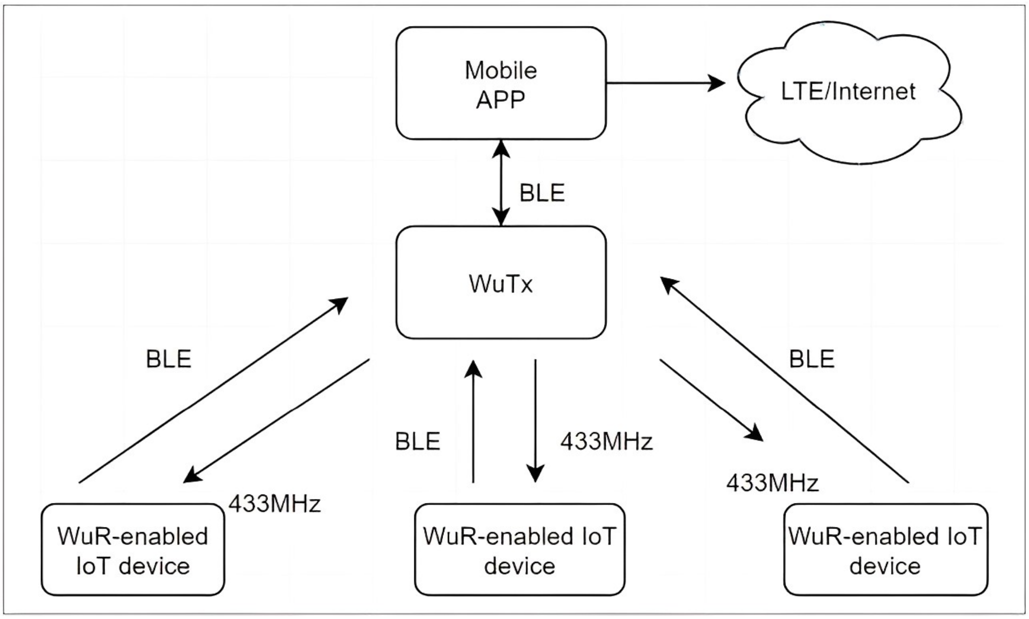


Figure 2.2. System Architecture of Wake-up Radio Enabled Two-tier IoT System [18]

Practical implementation for 5G-BLE integration was performed by a team of researchers consisting of Frøytloget al.[18]. They implemented a wake-up radio-enabled two-tier IoT system as a possible 5G IoT integration which utilizes the BLE for low-power communication. The implemented system consisted of an Android phone as the gateway for BLE devices to connect to the Long Term Evolution (LTE) network. Further, the Android phone was also equipped with an application that initiates the wake-up commands and sends them to the wake-up transmitter. Then the wake-up transmitter sends those commands to the particular wake-up radio-enabled IoT device to which the wake-up command was sent from the mobile phone. The carrier frequency of this wake-up call from the wake-up transmitter to the wake-up radio-enabled IoT device was 433 MHz. The sensed data from IoT devices were transmitted using BLE. The system architecture is shown in Figure 2.2. The targeted average current consumption of IoT devices was less than 1 µA. With the real-world measurements, they were able to achieve the targeted power consumption and latency requirements where the actual current consumption was 390 nA[18].

Muhammad et al.[19] performed research to observe the coexistence with BLE 5 of wireless cellular systems that use Listen Before Talk (LBT) channel access mechanism. The 5G new radio-unlicensed uses the LBT as the channel access mechanism. They have tested this phenomenon using an arrangement as in Figure 2.3 where there were 3 LBT pairs with 2412 MHz, 2437 MHz, and 2462 MHz. The implemented BLE network utilized the nRF52840dk, utilizing ATT_MTU throughout the example provided by the Nordic Semiconductors. In their test, the LBT network acted as the unintended source of interference, while the BLE network acted as the intended signal. They have tested the LBT network with different priority levels. The size of the connection window and channel occupancy time decreased with the increase in the priority level. It was observed that BLE 2 Mbps PHY had the highest reduction of throughput from its general value, and Low Energy (LE) Coded PHY had the most negligible impact from the interference from the LBT network. Further, it was also observed that with the increase in the priority level of the LBT network, the effect on BLE throughput increased. They suggested using LE Coded PHY in BLE applications where the operating environment tends to have higher interference[19].

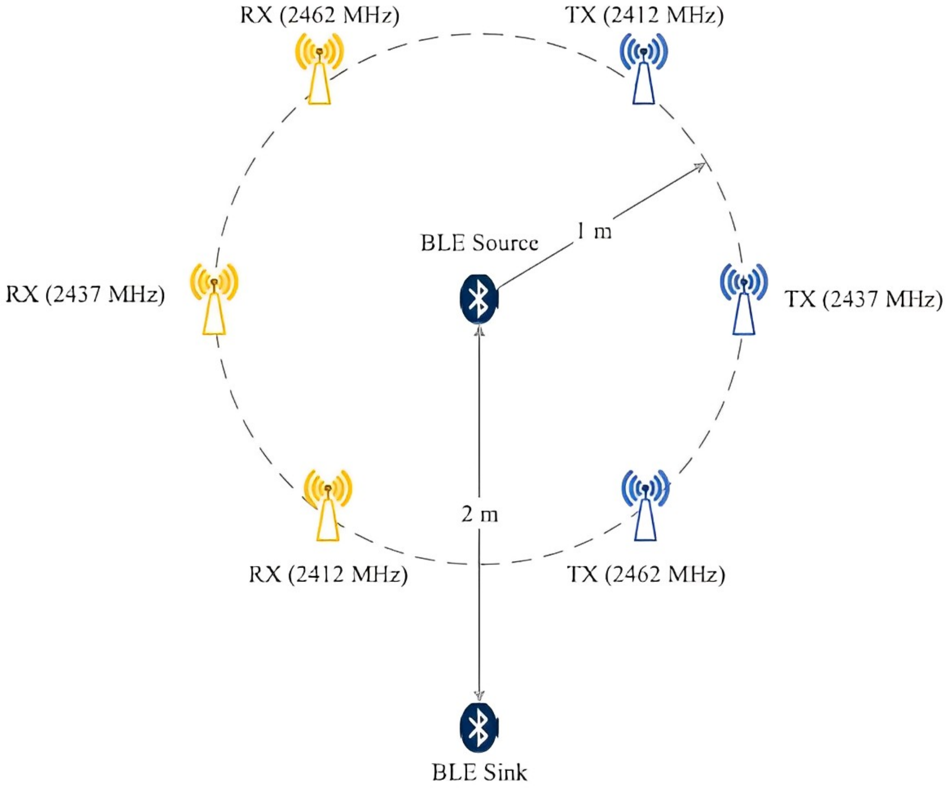


Figure 2.3. Arrangement of LBT Network and BLE Network [19]

3 TECHNICAL BACKGROUND

This chapter refers to the technical concepts related to BLE and 5G technologies, which are the leading technologies utilized in the project.

3.1 Overview of BLE Technology

Bluetooth is a wireless technology that utilizes radio frequency to share data over short distances[20]. Bluetooth Special Interest Group (SIG), which oversees the standards and developments of Bluetooth technology, was initiated in 1998[21]. Currently, the latest revision of Bluetooth technology is Bluetooth 5.4[22]. The timeline of major Bluetooth revisions is as follows.

- Bluetooth 1.0 - 1999
- Bluetooth 2.0 - 2004
- Bluetooth 3.0 - 2009
- Bluetooth 4.0 - 2010
- Bluetooth 5.0 - 2016

Bluetooth Classic and BLE are the two main protocols under Bluetooth technology widely used worldwide. BLE protocol was introduced in 2010 with the release of Bluetooth 4.0. This protocol focuses on the application which has ultra-low power requirements than high throughput. BLE can be used as point-to-point, broadcast and mesh in device communication, whereas Bluetooth Classic can only be used in point-to-point form[23]. BLE protocol can be defined as one of the prominent technology for IoT-related applications due to two main reasons.

1. Low power consumption for communication - Most IoT devices have stringent power requirements due to relying on sources like small batteries.
2. Nature of data - BLE is designed to transmit a small amount of data where the communication happens in short bursts. This perfectly fits the IoT devices, such as sensors that transmit state data.

BLE technology is widely used in home automation applications, fitness tracking, audio devices, contact tracing and inventory management. The main disadvantages of the BLE technology can be defined as,

- Throughput limitation - Currently, the maximum data throughput at the physical BLE Layer is 2 Mbps.
- Range - The BLE technology is designed to operate in short range. This also depends on the operating environment.

Other than the above disadvantages, it is a considerable disadvantage that a BLE-only device has to rely on another BLE device that has Internet Protocol (IP) connectivity to transmit data from the device to the internet[24].

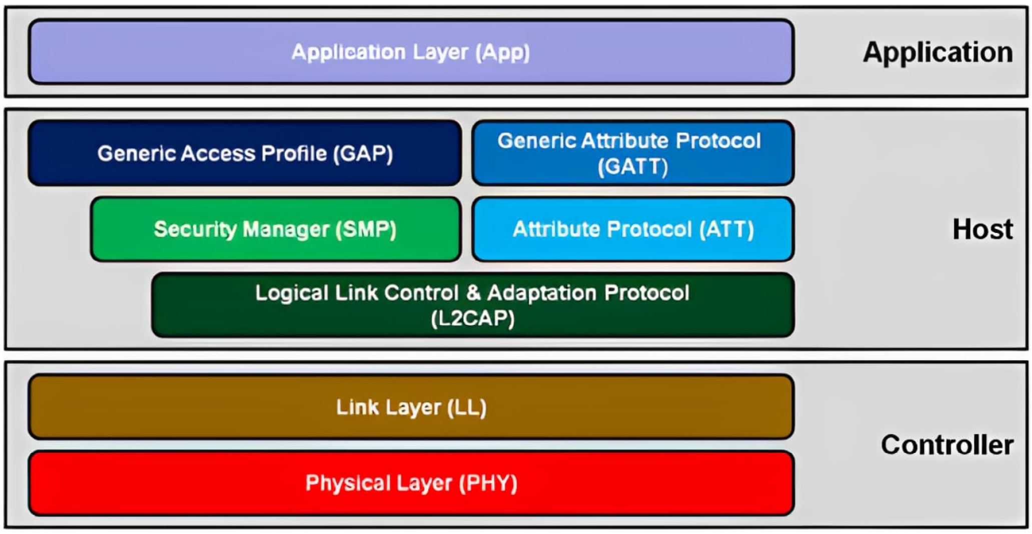


Figure 3.1. BLE Protocol Stack [25]

3.1.1 BLE Protocol Architecture

The functionalities of the BLE protocol are distributed around several layers. This protocol stack is divided into three main subsystems: host, controller and application. Figure 3.1 illustrates the protocol stack of BLE. Each layer of the BLE protocol stack can be described as follows.

- PHY - This layer represents the physical radio used for communication and modulation/demodulation of data. BLE uses the 2.4 GHz ISM band for communication. It has 40 channels with 2 MHz spacing from 2.4000 GHz to 2.4835 GHz. Among those 40 channels are three advertising channels and 37 data channels. Figure 3.2 shows this arrangement of channels. Further, BLE uses Gaussian Frequency-Shift Keying (GFSK) as the modulation scheme and Time Division Duplexing (TDD) as the utilization method of the spectrum.
- Link Layer (LL) - The main functionalities of this layer are scanning, advertising, connection establishment and maintaining the connections. These functionalities are handled as a set of states where the roles of the BLE devices, such as broadcaster, peripheral and central, will define the sequence of states to be followed.
- Logical Link Control & Adaptation Protocol (L2CAP) - This layer obtains data generated using different protocols from upper layers, converts them into the standard BLE packets and transmits them into the lower layer (LL).

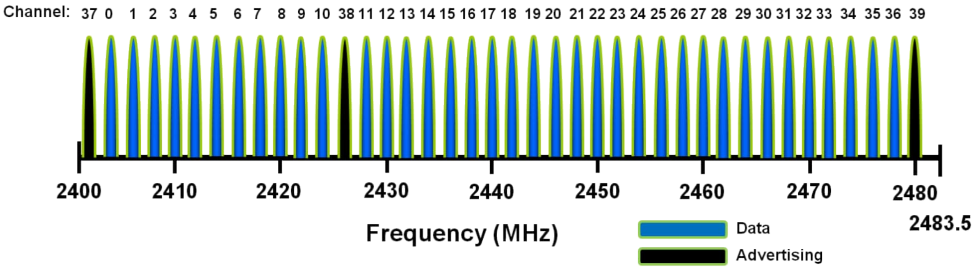


Figure 3.2. BLE Channel Assignment [25]

- Security Manager Protocol (SMP) - This layer is responsible for pairing and key distribution of BLE devices. These keys are then used to encrypt the communication link, verify the signed data and perform random address resolution.
- ATT - This layer is responsible for organizing the data stored, updated and accessed in the server using a data structure called an attribute. ATT has client and server roles similar to the world wide web. Using this concept of roles, this Layer allows the server device to store data uniformly that can be retrieved and modified by the client device. Further, it allows the client device to store the data in the server device similarly.
- General Access Profile (GAP) - This layer is responsible for defining the roles of the devices. There are four main roles: broadcaster, observer, peripheral and central. A few limitations are established during the period of connection by enabling these roles. This layer is also responsible for the initiation of security features.
- Generic Attribute Protocol (GATT) - This protocol defines the types of data a BLE device exposes and the method to access those data. The server exposes data and possible functionalities to the client using the client-server concept. Client device connects with server to read those data or perform those allowed functionalities. These data and allowed functionalities are defined in terms of services and characteristics. Service represents one or more attributes where the characteristics are the data the server needs to expose. These characteristics fall under the service.
  Example: Nordic Universal Asynchronous Receiver-Transmitter (UART) service is a service that has two characteristics named Rx and Tx. Rx characteristics are used to obtain the data transmitted through the service from the transmitter, while Tx characteristics are used to send data to the receiver.
- Application Layer (App) - This layer has the applications that utilize the BLE protocol stack for different use cases[26, 27, 28, 29, 30, 25].

BLE has only one packet structure for both data transmission and advertising. The main components of the packet structure in BLE are the preamble, access address, PDU and Cyclic Redundancy Check (CRC). The structure of the PDU is different for the advertising packets and data transmission packets. Figure 3.3 shows the structure of the BLE packet with different PDU structures for data transmission and advertising. The Message Integrity Check (MIC) of the data channel PDU represents an optional payload that can be added for security purposes[31, 32].

BLE initiates the connection through advertising mode by utilizing broadcasting in advertising channels. Advertising informs the surrounding BLE devices about the presence of the advertising device and the different parameters, such as connection interval and device identifiers. The devices in the scanning mode obtain these advertising packets and establish the connection.

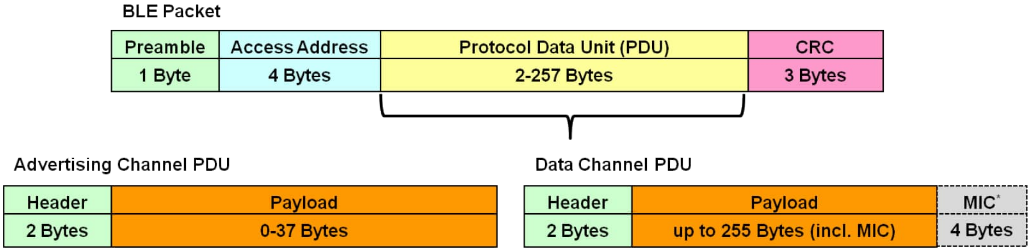


Figure 3.3. BLE Packet Structure [31]

This connection establishment makes the advertising device change its mode from advertising to connected, where in this mode, two devices synchronize their connection with the help of the connection interval. Data exchange of these two BLE devices happens during the connection event of each connection interval.

3.1.2 Bluetooth Range

The Bluetooth connection range can vary from less than a meter to more than one kilometre. The factors affecting this variation of the range are as follows.

- PHY performance - The PHY is responsible for the modulation scheme and related techniques to utilize the radio frequency for data communication. Bluetooth provides various options for the PHY which it can be utilized according to the requirement of the range.
- Receiver sensitivity - This defines the minimum signal strength where the receiver can detect and demodulate the signal while maintaining the connection. The minimum receiver sensitivity of Bluetooth is defined as -70 dBm to -82 dBm, which varies in that range according to the PHY configuration.
- Transmit power - The range probably increases with the transmit power increase. In other words, the range of the device is traded off with its power consumption. Bluetooth supports transmitting powers from -20 dBm (0.01 mW) to +20 dBm (100 mW).
- Antenna gain - The antenna's performance, such as the efficiency of converting electrical energy to electromagnetic energy at the transmitter and vice versa at the receiver, influences the range of the Bluetooth. However, it can be observed that the Bluetooth devices achieve an antenna gain in the range of -10 dBi to +10 dBi.
- Path loss - Path loss can be defined as the reduction of the signal strength due to the environment arrangement. It can be anything from humidity to obstacles like walls[33].

3.1.3 Parameters Affecting the Communication Throughput

Various parameters in Bluetooth define the throughput based on the configuration.

1. PHY configuration - There are three main options that the PHY can be configured into. They are 2 Mbps PHY, 1 Mbps PHY, and coded PHY (with S=2 or S=8) configuration. It is worth noting that the 2 Mbps PHY option helps to reduce power consumption while achieving higher throughput due to the lower on-air time.
2. Connection interval - The connection interval determines how frequently one device requests data from another. Connection interval can be varied from 7.5 ms to 4 s. Even though Android devices can reach the minimum defined value by Bluetooth core specification for the connection interval of 7.5 ms, the minimum value for the connection interval of iOS devices is 15 ms.
3. Data Length Extension (DLE) - The transmission packet's PDU can be increased from 27 to 251 bytes by enabling DLE. In other words, it increases the ATT maximum transmission

unit (MTU) to 251 bytes. This feature was introduced by Bluetooth 4.2. DLE allows transmitting more data in a single packet, resulting in higher throughput and lower power consumption.

4. Operation type - Throughput depends on the type of operation that is performed to transmit data. Write requests, write commands, notifications, and indications are the main operation types that are used to transmit data. Write requests and indications are synchronous operations that depend on the receiver's acknowledgement before the next transmission event. Write commands and notifications are asynchronous operations where it can be sent data back-to-back without waiting for acknowledgements. It is typically observed that asynchronous operations of write commands and notifications have higher throughput than synchronous operations [34, 35].

3.2 Overview of 5G Technology

5G took around 30 years to evolve from 1st generation to 5th generation. 1st Generation Mobile Network (1G) was introduced in the 1980s. 1G used Advanced Mobile Phone System (AMPS), Nordic Mobile Telephone (NMT) and Total Access Communication System (TACS) technologies with voice-only services. 2nd Generation Mobile Network (2G) was introduced in 1990 and utilized Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA) technologies for communication. Global System for Mobile Communication (GSM) was introduced with 2G and became the widely adopted mobile communication standard. The 3rd Generation Mobile Network (3G), introduced in 2004, utilized General Packet Radio Service (GPRS) technology and integrated multimedia services with mobile networks. It obtained data rates of around 2 Mbps with 3G networks. The 4th Generation Mobile Network (4G) was introduced in 2010. With the help of technologies such as Multiple Input Multiple Output (MIMO) and Orthogonal Frequency-Division Multiplexing (OFDM), 4G networks obtained a significant increase in mobile internet speeds compared to previous generations.

Deployment of the 5G was started in 2019. These networks utilize small cells and beamforming to provide ultra-high speed network speed with lower latency. 5G is the pioneer in the concept of the Internet of Everything. This opens the door for applications such as remote surgeries and driverless cars. Further, it will make Virtual Reality (VR), Extended Reality (XR), and cloud-based applications to be everyday interactions of human beings[36].

3.2.1 5G Specification

The 5G specifications can be described using the following terminologies related.

1. 5G New Radio - This describes the air interface of the 5G networks, which is designed to support a wide range of applications and services. 5G NR can operate in a spectrum bandwidth of up to 400 MHz in Frequency Range 1 (FR1) and up to 100 MHz in Frequency Range 2 (FR2). FR1 refers to the spectrum band below 6 GHz, whereas FR2 refers to the spectrum band of 24 GHz and above. Further, FR2 is also referred to as the millimetre wave implementation. Peak network rates of 5G networks are expected to be around 20 Gbps which is 20 times higher than that of 4G LTE.

2. Massive MIMO - MIMO is a method of enhancing the capacity of the radio link by using multiple transmitter and receiver antennas. Massive MIMO is an extension of the MIMO

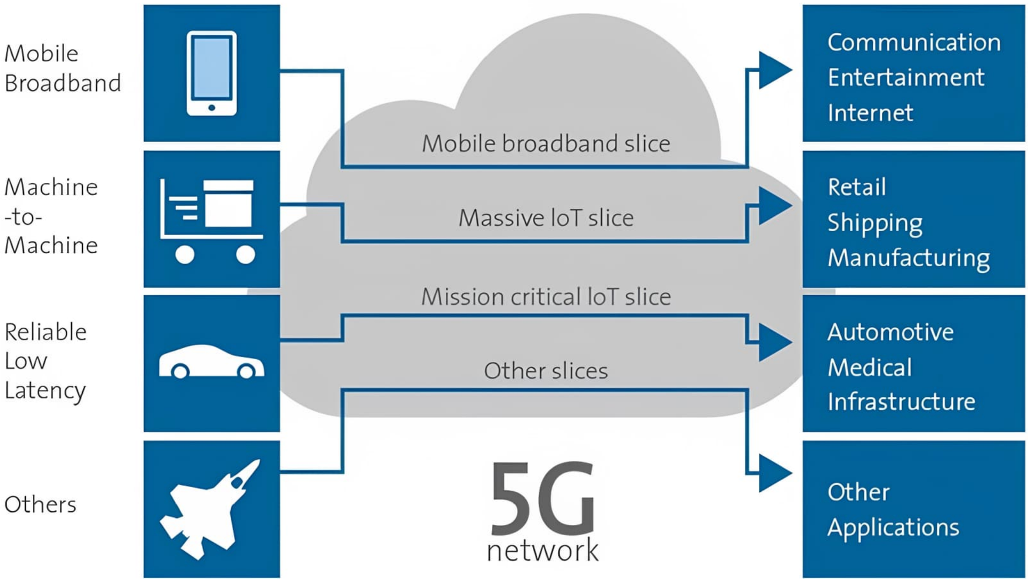


Figure 3.4. Network Slicing Applications [37]

method that utilizes antenna panels and beamforming. Each antenna panel can consist of hundreds of antennas, whereas beamforming refers to steering these antenna panels digitally, resulting in higher signal quality and data rates. Beamforming also helps to use the spectrum efficiently with the help of focused beams where the MIMO panels can use the same frequency for all the mobile devices due to the property that focused beams are less prone to cross.

3. Enhanced Mobile Broadband (eMBB) - This refers to the increase of the existing mobile broadband services with higher data rates and broader coverage in 5G networks. This targets providing a consistent mobile broadband connection indoors and outdoors in densely populated areas such as office premises and conference halls. It also considers providing a consistent mobile broadband connection for highly mobile users, such as users travelling in vehicles.

4. Massive Machine Type Communication (mMTC) - This defines the high density of devices in the 5G network and the requirement of connecting up to 1 million connected devices per square kilometre. This mainly establishes the relationship between 5G and the future IoT ecosystem. This higher number of devices typically requires fewer data rates, typically around 100 kbps.

5. Ultra Reliable Low Latency Communication (URLLC) - This allows addressing the critical application requirements by utilizing hardware and software techniques. According to the 3rd Generation Partnership Project (3GPP) releases of 16 and 17, URLLC should have multiple connections to an attached device with the help of Massive MIMO technology. It is also mentioned that the communication system can utilize edge computing capabilities to enable URLLC.

6. Network Slicing - This allows the creation of virtual networks utilizing the common physical infrastructure where these virtual networks can cater for the specific needs of devices, consumers or applications. Network slicing allows for optimizing the existing 5G network by dividing it into several end-to-end virtual networks by considering the

different business purposes. Figure 3.4 illustrates the application of network slicing[37, 38, 39, 40, 41].

Key Performance Indicators (KPIs) for 5G networks can be listed below.

1. Peak data rate of 20 Gbps for downlink and 10 Gbps for uplink.
2. Data rate experienced by the user of 100 Mbps of downlink and 50 Mbps of uplink
3. Latency of 4 ms for eMBB-related applications and 1 ms for URLLC-related applications. 20 ms for applications other than eMBB and URLLC domains.
4. Connection density of 1 million devices per square kilometre.
5. Mobility of up to 30 km/h for dense urban areas whereas up to 500 km/h for rural areas.
6. Mobility interruption time of 0 ms.
7. Availability and reliability of 99.999% [42, 43].

3.2.2 5G in IoT Communication

It is expected that there will be nearly 75 billion connected devices by 2025. The higher data rates of around 20 Gbps of the 5G networks enable IoT devices to utilize cloud storage and functions instead of relying upon the hardware's capabilities, such as processing power and internal storage. This enhances the capabilities of the IoT networks significantly, which will result in more powerful intelligent solutions. For the following reasons, 5G can be utilized in IoT networks for enhanced efficiency and accuracy.

- Higher network capacity - A lot of IoT-enabled devices are connected to the network, which requires a higher network capacity to communicate efficiently.
- Low latency communication - Applications like driverless cars require low latency communication to ensure optimal performance.
- Higher network speeds - Real-time sensing devices require higher network speeds to provide the most efficient data to decision-makers.
- Higher network reliability - Applications like remote surgery require a highly reliable network to ensure a safe operating atmosphere.
- Network slicing capabilities - Since IoT networks have a wide variety of networking requirements, it is crucial to provide customized network solutions to optimize communication.
- Integration of edge computing for higher efficiency - With the higher amount of IoT devices, it is more efficient to migrate some of the network functionalities to edge computers, which will reduce the capital and maintenance cost of the network.
- Higher energy efficiency of 5G networks - With the increased number of connected devices, it is vital to consider the network's energy consumption to ensure its maintainability and sustainability.

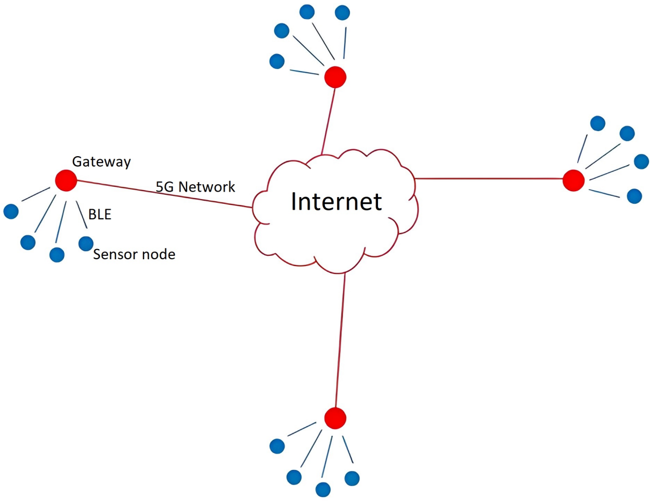


Figure 3.5. Network Topology for 5G and BLE Integration

The most common applications of 5G networks in IoT are,

1. Smart cities - 5G networks can benefit smart city applications such as traffic monitoring and environmental monitoring, which require real-time data transmission to the servers for better resource utilization.
2. Autonomous vehicles - 5G facilitates autonomous vehicles, such as self-driving cars and drones, which utilize the functionalities of URLLC in 5G networks.
3. Smart healthcare - 5G allows applications such as remote patient monitoring, telemedicine and surgical robotics to become more accurate with the ability to have high-speed network connections with extremely low latency.
4. Smart agriculture - Thanks to the increased network capacity of 5G, a greater number of sensors and devices can connect, enabling efficient real-time communication. This technology makes it possible to monitor soil, manage irrigation, and track livestock, among other applications[44].

3.3 Integration of BLE with 5G

The discussion in the two previous sections shows that BLE can be a superior technology for the last mile of the end-to-end IoT network. This integration promotes a wide range of possibilities to enhance the efficiency and accuracy of the existing IoT infrastructures.

Currently, industries and academia are focusing their research efforts on battery-less and maintenance-free IoT development. ON semiconductor's RSL10 multi-sensor platform is one good example of using BLE as the last mile of an end-to-end IoT network. This sensor platform relies on solar cells entirely, and the combination of a 5G network as the back-haul of this type of IoT network will result in a realistic example of achieving higher energy efficiency without compromising a significant amount of capabilities of the IoT network[45].

Integrating Bluetooth with 5G enhances the range of the Bluetooth-based IoT network by utilizing multiple distributed gateways connected to the internet. Adapting to this topology

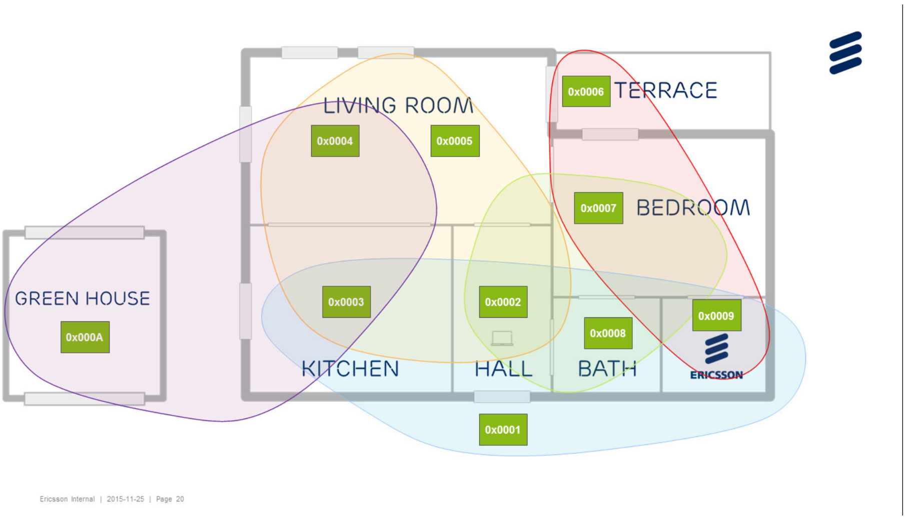


Figure 3.6. Smart Home Solution Utilizing Bluetooth Mesh and a Capillary Gateway [47]

allows for extending the reach of a Bluetooth network to cover a vast geographical area. The gateways establish connections with multiple Bluetooth devices within a specific location. At the same time, the gateways are also connected to the internet. Figure 3.5 illustrates this network topology. Mobile devices like smartphones can be utilized as gateways for this type of network topology. This architecture has several advantages: low-cost implementation, lower power consumption, and higher flexibility. Limited throughput and limited range are the main drawbacks of this type of network since BLE has a maximum throughput of around 2 Mbps and an effective range of around 100 m.

Using mesh network topology allows the connection of many Bluetooth devices into a single network. In this scenario, Bluetooth devices talk to each other directly or via an intermediate node. The broadcasting approach is one of the prominent approaches to passing messages in these networks where the individual nodes act according to their relevance to the passed message[46]. In this type of network, access to the internet can be provided by capillary gateways, which provide seamless integration of wireless sensor networks with cellular networks. Figure 3.6 depicts an innovative home solution by Ericsson using Bluetooth mesh and a capillary gateway to the cellular network. It also illustrates the possible range of each node in the mesh network. It utilizes another node to reach the capillary gateway when it is not accessible directly[47, 48].

4 ANALYTICAL MODEL

It can be observed that BLE throughput analysis experiments which were discussed in the related works section [5],[10],[11] used the concept of analytical modelling to understand the theoretical behaviour of the throughput in different parameter configurations. It was planned to use the concept of analytical modelling in this research to observe the theoretical behaviour of the throughput before the real-world experiment.

Analytical modelling refers to the process of representing a specific process or a system mathematically. This representation helps enhance understanding of that particular system or model by establishing connections between interdependent variables to forecast future behaviour. Analytical modelling is initiated by deriving one or more equations that link every essential parameter required for reliable predictions. Analyzing these parameters helps in predicting performance under varying conditions with high accuracy. This analysis also makes this tool critical for anticipating potential problems and forecasting future trends, thereby assisting in performing effective comparative analysis[49].

Utilizing an analytical model for deriving the throughput of BLE 5 helps to examine the communication protocol's performance under varying conditions accurately. Further, it will help developers to optimize the utilization of BLE 5 under various application needs for higher accuracy and efficiency. Derivation of the analytical model for BLE 5 requires analyzing factors like LL operations while considering different parameters influencing critical performance factors such as device throughput rates. The LL serves an essential role in BLE communication by handling all transmitting-receiving tasks necessitated in ensuring successful data transfers. Different characteristics of BLE 5 need to be taken into account, such as the 2 Mbps PHY for faster data transmission and the coded PHY version for extended-range communication.

4.1 Derivation of the Analytical Model

Throughput can be defined as the effective payload over a transmission period, which can be represented as (4.1). Figure 4.1 illustrates the single transmission period. Here the T refers to the transmission packet, consisting of frame headers, payload, and CRC bits. R refers to the acknowledgement packet from the receiver with a minimum packet size. T_IFS refers to the interframe space, which defines the interval between two consecutive packets. This value is 150 µs for both BLE 4 and 5.

$$Throughput = \frac{Effective\ payload}{Transmission\ period} \tag{4.1}$$

Based on the principle discussed above, a team of researchers consisting of Mikhaylov et al.[5] has performed a performance analysis for BLE 4, discussing the analytical model for BLE 4 as in equation (4.2).

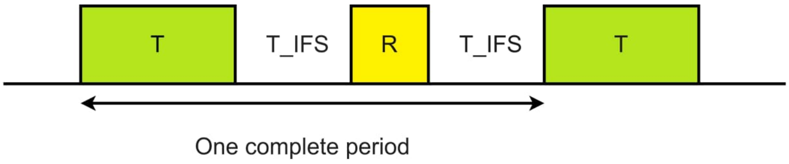


Figure 4.1. Illustration of the Single Transmission Period

$$\begin{aligned} &Throughput_{BLE_DATA}(n, m, T_{TXprep}, T_{RXproc}, \tau) \\ &= \frac{8n}{0.16ms + \frac{8(n+m)}{1000} + 2\tau + 2 \times max(0.15ms, T_{TXprep} + T_{RXproc})} \end{aligned} \tag{4.2}$$

In (4.2), n refers to the payload of the LL packet transmitted from master to slave, whereas m refers to the payload of the acknowledgement packet. Further, in (4.2), 0.16 ms refers to the time to transmit frame headers. τ refers to the signal propagation delay whereas T_{TXprep} and T_{RXproc} refer to the time required to process n byte data frame before and after the reception respectively[5].

Based on the analytical model defined by (4.2), a team of researchers at the Aalto University, Finland consisting of Badihi et al.[11] suggested the analytical model for BLE 5 as in (4.3). Here H refers to the header size in bits, while R represents the bit rate. S refers to the code rate while T_{IFS} which is inter-frame space which is the same as the value of 0.15 ms in (4.2)[11].

$$Th(n, m) = \frac{8n}{\frac{H}{R} + \frac{8(n+m)S}{R} + 2\tau + 2 \times max(T_{IFS}, T_{TXprep} + T_{RXproc})} \tag{4.3}$$

During the research of Mikhaylov et al.[5], they utilized the model as in (4.4) to calculate the minimum turnaround time for BLE 5. The minimum turnaround time is the time required to complete one transmission cycle. To derivate the minimum turnaround time, they have considered the time needed to transmit frame headers, the time required to transmit the payload, signal propagation delay, processing times before transmission and after reception of data packets, switching time, and inter-frame space. Here T_{RPLgen} refers to the time required to process the forward frame and generate the reply frame by the layers above. Considering (4.3), the minimum turnaround time for BLE 5 can be derived as (4.5).

$$\begin{aligned} &T_{turnaround_BLE}(n, m, T_{RPLgen}, T_{TXprep}, T_{RXproc}, \tau) \\ &= 0.16ms + \frac{8(n+m)}{1000} + 2\tau + T_{TXprep} + T_{RXproc} + max(0.15ms, T_{TXprep} + T_{RPLgen} + T_{RXproc}) \end{aligned} \tag{4.4}$$

$$\begin{aligned} &T_{turnaround_BLE}(n, m, T_{RPLgen}, T_{TXprep}, T_{RXproc}, \tau) \\ &= \frac{H}{R} + \frac{8(n+m)S}{R} + 2\tau + T_{TXprep} + T_{RXproc} + max(T_{IFS}, T_{TXprep} + T_{RPLgen} + T_{RXproc}) \end{aligned} \tag{4.5}$$

In (4.3), and (4.5), $\frac{H}{R}$ refers to the time required for the transmission of packet headers while $\frac{8(n+m)S}{R}$ gives the time required for the transmission of the payload. The value of 2τ takes into consideration the time it takes for the signal to travel from the transmitter to the receiver and back again, including the time it takes to reach the transmitter again from the receiver. To tailor the analytical models (4.3) and (4.5) to the BLE 5 PHY configuration, one can use the R and S parameters in (4.3) and (4.5).

- R - Since this represents the bit rate, it would be 2 Mbps for 2M PHY, 1 Mbps for 1M PHY, 500 kbps for coded PHY with S=2, and 125 kbps for coded PHY with S=8.
- S - Both 2M and 1M PHY have the same code rate of 1 due to the absence of forward error correction. This is 2 for coded PHY with S=2 and 8 for coded PHY with S=8.

4.2 Calculation of the Throughput using the Analytical Model

This section analyzes the theoretical throughput values for different parameter configurations with the help of the BLE 5 analytical model defined by (4.3).

4.2.1 Calculation of the Throughput for Different PHY Configurations

Based on the analytical model defined by (4.3), the following throughput values were calculated for different PHY configurations of BLE 5. The data length was 251 bytes to obtain the maximum possible theoretical throughput. It was assumed that the header size of 10 bytes based on the discussion on BLE headers in Chapter 3 and Figure 3.3. Further, it was assumed T_{TXprep} = T_{RXproc} = τ = m = 0 as in the experiment of [5].

1. 2 Mbps PHY

$$Th(n,m) = \frac{8n}{\frac{H}{R} + \frac{8(n+m)S}{R} + 2\tau + 2 * max(T_{IFS}, T_{TXprep} + T_{RXproc})}$$
$$Th(251,0) = \frac{8 \times 251}{\frac{8\times 10}{2000000} + \frac{8\times(251+0)\times 1}{2000000} + 2\times 0 + 2\times max(0.15ms, 0)} = 1.494Mbps \tag{4.6}$$

2. 1 Mbps PHY

$$Th(n,m) = \frac{8n}{\frac{H}{R} + \frac{8(n+m)S}{R} + 2\tau + 2 \times max(T_{IFS}, T_{TXprep} + T_{RXproc})}$$
$$Th(251,0) = \frac{8 \times 251}{\frac{8\times 10}{1000000} + \frac{8\times(251+0)\times 1}{1000000} + 2\times 0 + 2\times max(0.15ms, 0)} = 840.871kbps \tag{4.7}$$

3. LE Coded S2

$$Th(n,m) = \frac{8n}{\frac{H}{R} + \frac{8(n+m)S}{R} + 2\tau + 2 \times max(T_{IFS}, T_{TXprep} + T_{RXproc})}$$
$$Th(251,0) = \frac{8 \times 251}{\frac{8\times 10}{500000} + \frac{8\times(251+0)\times 1}{500000} + 2\times 0 + 2\times max(0.15ms, 0)} = 448.615kbps \tag{4.8}$$

4. LE Coded S8

$$Th(n,m) = \frac{8n}{\frac{H}{R} + \frac{8(n+m)S}{R} + 2\tau + 2 \times max(T_{IFS}, T_{TXprep} + T_{RXproc})}$$
$$Th(251,0) = \frac{8 \times 251}{\frac{8\times 10}{125000} + \frac{8\times(251+0)\times 1}{125000} + 2\times 0 + 2\times max(0.15ms, 0)} = 118.089kbps \tag{4.9}$$

4.2.2 Calculation of the Throughput for Different Payload Configurations

Based on the analytical model defined by (4.3), the following throughput values were calculated for payload configurations of BLE 5. These payload values were planned to be examined through real-world implementation. Based on the calculation of (4.6), the PHY configuration was set to 2 Mbps PHY to obtain the maximum possible theoretical throughput. Further, the header size of 10 bytes was assumed based on the discussion on BLE headers in the Technical Background chapter and Figure 3.3. It was assumed T_{TXprep} = T_{RXproc} = τ = m = 0 as in the experiment of [5].

1. 27 bytes of payload

$$\begin{aligned} Th(n,m) &= \frac{8n}{\frac{H}{R}+\frac{8(n+m)S}{R}+2\tau+2\times max(T_{IFS},T_{TXprep}+T_{RXproc})} \\ Th(27,0) &= \frac{8\times 27}{\frac{8\times 10}{2000000}+\frac{8\times(27+0)\times 1}{2000000}+2\times 0+2\times max(0.15ms,0)} = 482.143kbps \end{aligned} \tag{4.10}$$

2. 139 bytes of payload

$$\begin{aligned} Th(n,m) &= \frac{8n}{\frac{H}{R}+\frac{8(n+m)S}{R}+2\tau+2\times max(T_{IFS},T_{TXprep}+T_{RXproc})} \\ Th(139,0) &= \frac{8\times 139}{\frac{8\times 10}{2000000}+\frac{8\times(139+0)\times 1}{2000000}+2\times 0+2\times max(0.15ms,0)} = 1.241Mbps \end{aligned} \tag{4.11}$$

3. 251 bytes of payload - 1.494 Mbps (Calculation is precisely similar to 4.6)

4.2.3 Summary of the Calculations

The analytical results obtained in Sections 4.2.1 and 4.2.2 are summarised in Table 4.1.

Table 4.1. Results of the Analytical Model

PHY Configuration	**Data Length**	**Throughput**
2 Mbps PHY	251 bytes	1.494 Mbps
1 Mbps PHY	251 bytes	840.871 kbps
LE Coded S2	251 bytes	448.615 kbps
LE Coded S8	251 bytes	118.089 kbps
2 Mbps PHY	27 bytes	482.143 kbps
2 Mbps PHY	139 bytes	1.241 Mbps

5 IMPLEMENTATION

This chapter describes the technical details related to implementing the entities used during the experiment. A discussion of the three main setups for measuring throughput is also provided in this section.

5.1 Design of the BLE Throughput Performance Measurement Setup

The throughput measurements were obtained using three main setups.

1. Board-to-Board throughput measurement using the experimental example of ATT_MTU throughput firmware
2. Board-to-Board throughput measurement using Nordic UART service
3. Board-to-Phone throughput measurement using Nordic UART service

As mentioned earlier, different hardware and software tools were utilized with different configurations for the setups. Below subsections will discuss those tools in more detail.

5.1.1 Hardware Selection and Setup

Two Nordic nRF52840dk development boards were used for the central and peripheral devices. Both ATT_MTU throughput firmware and Nordic UART service were used to test Board-to-Board communication. In the Board-to-Phone throughput measurement setup, the same development board was used as the peripheral device, while the OnePlus 9 Pro 5G Android phone was used as the central device.

Nordic nRF52840dk is a single-board development kit for BLE that utilizes nRF52840 System-on-a-Chip (SoC). This development kit can also be utilized for the developments of Bluetooth mesh, Zigbee, 802.15.4, and ANT. The nRF52840dk development kit is compatible with Bluetooth 5.3 and supports the over-the-air device firmware upgrade. A battery, an external power supply, or a Universal Serial Bus (USB) port can be used as a power source for the board. Further, this board has a flash memory of 1024 kB and Random Access Memory (RAM) of 256 kB. Figure 5.1 shows the Nordic nRF52840dk development kit[50, 51]. Oneplus 9 Pro is a 5G-enabled mobile device on the Android 11 operating system. It has 128 GB of storage and 8 GB of RAM. The phone supports BLE 5.2. The overall architecture of the implemented system is as in Figure 5.2.

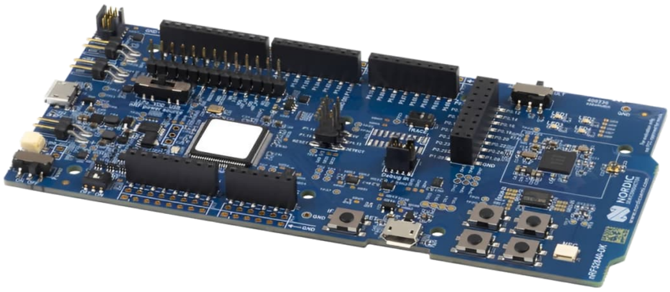


Figure 5.1. Nordic nRF52840dk Board [52]

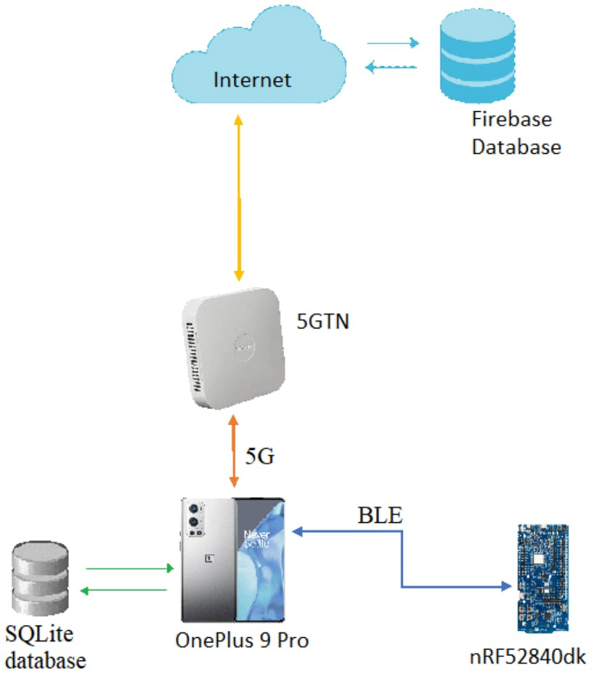


Figure 5.2. Overall Architecture of the Implemented System

5.1.2 Software Tools and Services

Several software tools were utilized for development and debugging purposes.

1. Segger Embedded Studio - This tool can be used to develop, test, deploy, and manage embedded applications. Further, this is a multi-platform application which enables it to be used in Windows operating system, Mac operating system, and Linux operating system. Segger Embedded Studio was mainly utilized in the project to develop and debug embedded applications for the Nordic nRF52840dk boards[53].
2. Putty - An open-source open Secure Shell (SSH) and telnet client developed by Simon Tatham. Putty was utilized in the project to provide inputs to the board and observe the outputs from the board through the serial UART[54].
3. Android studio - This is the official Integrated Development Environment (IDE) for Android development. Android Studio is built using JetBrains' IntelliJ IDEA software for all three main operating systems. The project utilized this to develop and debug tasks related to the mobile application[55].

5.2 Nordic ATT MTU Throughput Test

This is an example firmware from Nordic Semiconductor for its boards. The Nordic ATT MTU throughput test allows us to observe the effect of different parameters on BLE throughput. The following parameters are available to be adjusted and observe the throughput variation.

- Data length - Default data length is set to 27 bytes. The range for this parameter is from 27 bytes to 251 bytes.

- Connection interval - Has a range of 7.5 ms to 4 s. It is expected to observe higher throughput with lower parameter values.
- PHY data rate - This allows us to observe the effect on the throughput of utilizing the different PHY configurations; 2 Mbps PHY, 1 Mbps PHY, Coded S8 PHY, and Coded S2 PHY of BLE 5.
- Connection length event extension - Used to control the scenario where SoftDevice attempts to extend the radio time for connections in connection interval.
- GAP event length - Used to determine the duration of a connection event within a connection interval. This is measured in units of 1.25 ms. The minimum and maximum values mainly depend on the hardware configuration.

Two compatible boards are programmed with the same application to perform the test. At the start of the experiment, it allows the boards to select whether they act as central or peripheral devices. Based on the transmitted data of 1 MB from the peripheral device to the central device, it calculates the throughput[56].

5.3 Nordic UART Service

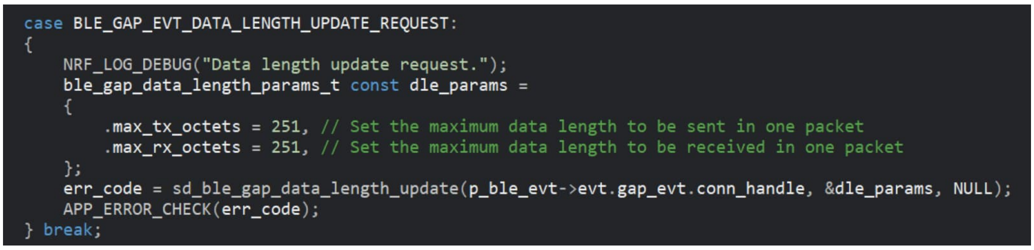
Nordic UART service is a custom GATT service used to transmit and receive data using the UART interface. This service has two main characteristics named RX characteristic and TX characteristic. It can transmit data using RX characteristics by writing the required data. TX characteristics can be utilized to obtain the data transmitted by the transmitter. Data obtained through the UART interface are transmitted as notifications. Nordic has provided source codes for central and peripheral devices to utilize the Nordic UART service[57].

The Nordic UART service starts its operation by initializing the UART and BLE communication parameters. Then the peripheral initiates the advertisement by sending packets to the nearby devices. In contrast with the peripheral device, the central device starts with scanning for advertisements. The possible events related to the Bluetooth connection, such as connection establishment and disconnect from nearby devices, are handled by the event handler defined as ble_evt_handler. When a connection is established with a nearby device, the transmission and reception of data over Nordic UART service are handled by the event handler uart_evt_handler.

The project utilized this service to implement Board-to-Board and Board-to-Phone communication. The source code for the Nordic UART peripheral was utilized, but with a modification that allows for setting the data length during the connection establishment process. This modification was done by defining the case for data length update request during the connection establishment process as in Figure 5.3. The ble_nus_chars_received_uart_print function of the Nordic UART Service central source code was modified to observe the BLE connection throughput through the receiving data over UART service as in Figure 5.4.

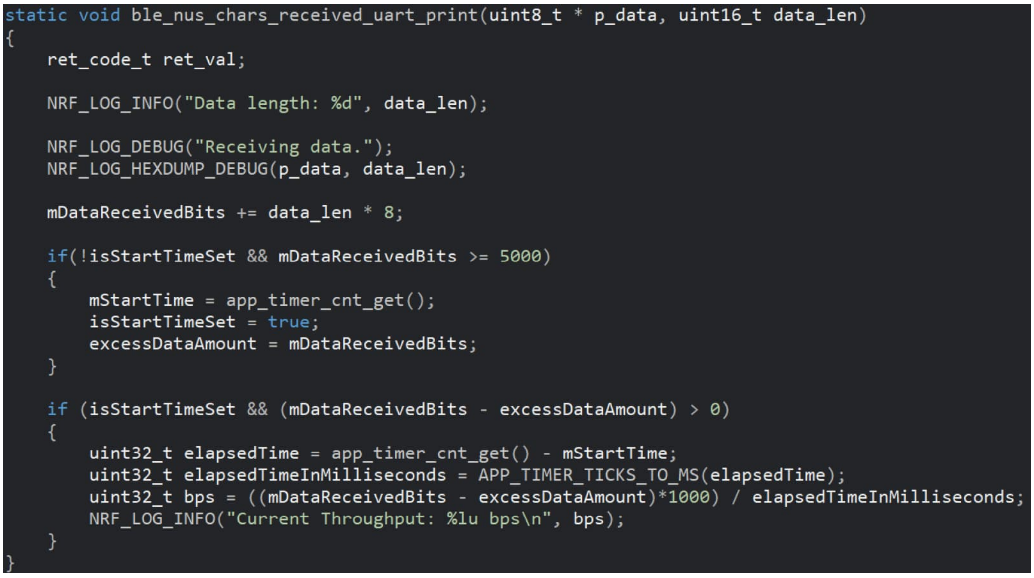
5.4 Android Application for BLE and 5G Integration and Database

Android application was developed using Android Application Programming Interface (API) version 30, released in 2020 under the code ”Red Velvet Cake”[58]. It was the same API version used by the OnePlus 9 Pro phone, which was used as the mobile terminal. The user interface of the mobile application is as shown in Figure 5.5, which consists of one button to start the



```
case BLE_GAP_EVT_DATA_LENGTH_UPDATE_REQUEST:
{
    NRF_LOG_DEBUG("Data length update request.");
    ble_gap_data_length_params_t const dle_params =
    {
        .max_tx_octets = 251, // Set the maximum data length to be sent in one packet
        .max_rx_octets = 251, // Set the maximum data length to be received in one packet
    };
    err_code = sd_ble_gap_data_length_update(p_ble_evt->evt.gap_evt.conn_handle, &dle_params, NULL);
    APP_ERROR_CHECK(err_code);
} break;
```

Figure 5.3. Data Length Update Request Implementation



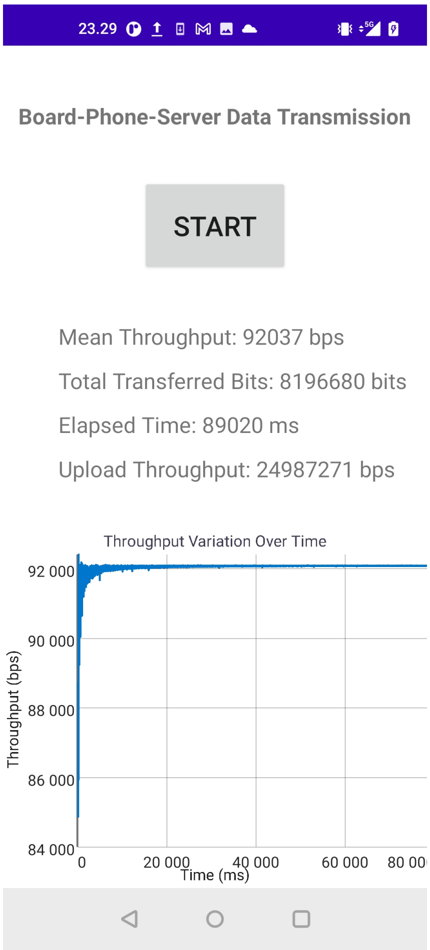
```
static void ble_nus_chars_received_uart_print(uint8_t * p_data, uint16_t data_len)
{
    ret_code_t ret_val;

    NRF_LOG_INFO("Data length: %d", data_len);

    NRF_LOG_DEBUG("Receiving data.");
    NRF_LOG_HEXDUMP_DEBUG(p_data, data_len);

    mDataReceivedBits += data_len * 8;

    if(!isStartTimeSet && mDataReceivedBits >= 5000)
    {
        mStartTime = app_timer_cnt_get();
        isStartTimeSet = true;
        excessDataAmount = mDataReceivedBits;
    }

    if (isStartTimeSet && (mDataReceivedBits - excessDataAmount) > 0)
    {
        uint32_t elapsedTime = app_timer_cnt_get() - mStartTime;
        uint32_t elapsedTimeInMilliseconds = APP_TIMER_TICKS_TO_MS(elapsedTime);
        uint32_t bps = ((mDataReceivedBits - excessDataAmount)*1000) / elapsedTimeInMilliseconds;
        NRF_LOG_INFO("Current Throughput: %lu bps\n", bps);
    }
}
```

Figure 5.4. Modification in the Nordic UART Service Central Code

communication process, several text views to display the required parameters, and a graph to display the variation of the throughput over time. After pressing the start button, the application initiates an instance of a BluetoothManager system-level service. It defines an object called a ”Bluetooth Adapter” to perform all the tasks related to the Bluetooth connections. After the initiation of the Bluetooth adapter object, it connects to the remote device with the given MAC address. After the connection to the GATT server, it sets the priority level to high for the connection with the GATT server to enable low latency communication with the GATT server. After that, it discovers the available GATT services of the remote device. Among the available services, it gets the service of Nordic UART Service and checks for the TX characteristic of it. This TX characteristic has the data that is transmitted from the embedded device. Based on this continuous receiving data from TX characteristics, it calculates the throughput. In the meantime, the obtained data are stored in an embedded server-less database until the Bluetooth connection is disconnected. After the disconnection, it sends the stored to a remote server using Transmission Control Protocol (TCP)/IP connection.

There were two types of data storage utilized:

1. SQLite - SQLite is an embedded database which does not rely on a separate server for data processing and storing tasks where it directly reads and writes to ordinary disk files. The file format of SQLite database is cross-platform, where it can be copied between 32-bit system and 64-bit system or big-endian and little-endian architecture-based system without additional configurations. It is claimed that the performance of the SQLite



Board-Phone-Server Data Transmission

Mean Throughput: 92037 bps

Total Transferred Bits: 8196680 bits

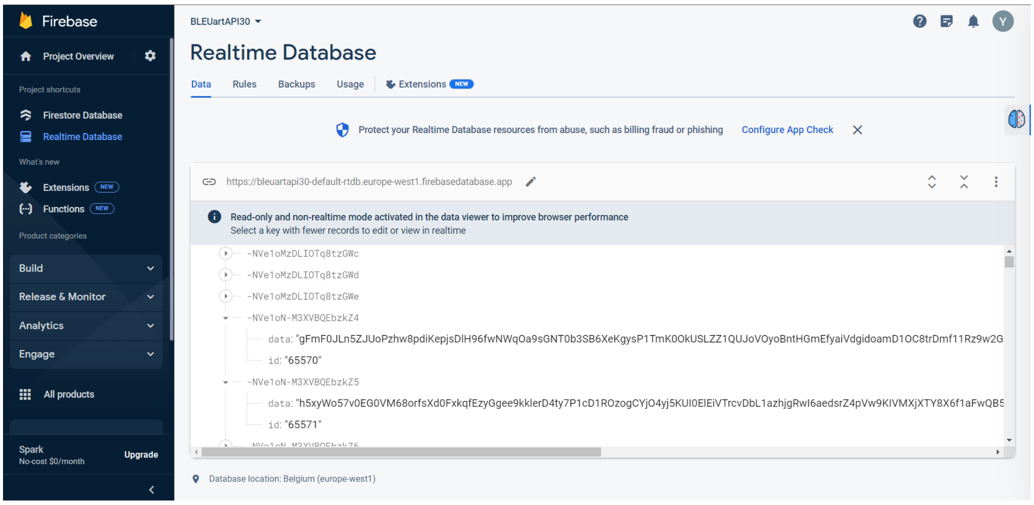
Elapsed Time: 89020 ms

Upload Throughput: 24987271 bps

Figure 5.5. User Interface of the Android Application

database is quite good in low-memory environments. As of 16th May 2023, over 1 trillion SQLite databases are in active use. SQLite database was utilized in the project to store the data in mobile-phone which were transmitted from the embedded device. Here, it was used to store two attributes in the SQLite database; one attribute was ID, and the other was received data. The ID refers to the primary key of the database that increments automatically[59, 60].

2. Firebase - Firebase is a Back-end-as-a-Service (BaaS) platform developed by Google. This has various features, such as a real-time database, authentication, and performance monitoring. The real-time database of the Firebase platform is a No-Structured Query Language (SQL) database where the data are stored in the way of key-value pair, graph database, document or column family. This No-SQL database helps the mobile applications store and synchronize the data in real-time across all user devices, which enables the mobile applications to be continuously updated even without user influence. After the Bluetooth disconnected, the stored data in the SQLite database were sent to the Firebase database. The data stored in the firebase database as key-value pairs as in Figure 5.6[61, 62, 63].



Protect your Realtime Database resources from abuse, such as billing fraud or phishing

https://bleuartapi30-default-rtdb.europe-west1.firebasedatabase.app

Read-only and non-realtime mode activated in the data viewer to improve browser performance
Select a key with fewer records to edit or view in realtime

```
-NVe1oMzDLIOTq8tzGWc
-NVe1oMzDLIOTq8tzGWd
-NVe1oMzDLIOTq8tzGWe
-NVe1oN-M3XVBQEbzkZ4
    data: "gFmF0JLn5ZJUoPzhw8pdiKepjsDlH96fwNWqOa9sGNT0b3SB6XeKgysP1TmK0OkUSLZZ1QUJoVOyoBntHGmEfyaiVdgidoamD1OC8trDmf11Rz9w2G
    id: "65570"
-NVe1oN-M3XVBQEbzkZ5
    data: "h5xyWo57v0EG0VM68orfsXd0FxkqfEzyGgee9kklerD4ty7P1cD1ROzogCYjO4yj5KUI0ElEiVTrcvDbL1azhjgRwI6aedsrZ4pVw9KIVMXjXTY8X6f1aFwQB5
    id: "65571"
```

Database location: Belgium (europe-west1)

Figure 5.6. Data in Firebase Database

6 EVALUATION

This chapter provides a detailed description of the evaluation procedure. It also discusses the factors which were considered during the evaluation process.

6.1 Planned Tests

Three main tests were performed to observe the throughput variation in BLE communication by changing different parameters.

1. Board-to-Board throughput test using Nordic ATT_MTU throughput firmware - This test utilized the ATU_MTU throughput test firmware provided by Nordic Semiconductors. Two Nordic nRF52840dk boards were used for this test to calculate the throughput.

2. Board-to-Board throughput test using Nordic UART service - It used the Nordic UART service peripheral and central applications provided by Nordic Semiconductors with the throughput calculation modification, as discussed in the implementation section.

3. Board-to-Phone throughput test using Nordic UART service - This test utilized the Nordic UART service peripheral application and the developed Android application to calculate the throughput of BLE communication. The Nordic nRF52840dk board served as the peripheral device, sending data to the OnePlus 9 Pro phone which was the central device.

Besides the tests mentioned above, another test was carried out to measure the Phone-to-Server throughput where the phone was connected to the 5GTN at the University of Oulu. The Android application was designed to automatically send the data received from the Nordic nRF52840dk to the Firebase database without the need for user intervention. After the Board-to-Board throughput test was successfully completed, a corresponding throughput test was conducted for Phone-to-Server.

6.2 Environment

All the tests were performed in the TS455 room of the Faculty of Information Technology and Electrical Engineering (ITEE) of the University of Oulu. The Arrangements of the tests were as follows.

1. Board-to-Board ATT_MTU throughput test - This test was performed using the Nordic nRF52840dk board with a 1 m distance between them and placed on top of a working desk as illustrated in the Figure 6.1.

2. Board-to-Board Nordic UART service throughput test - This test was performed similarly to the Board-to-Board ATT_MTU throughput test, where two Nordic nRF52840dK boards were placed on top of a working desk with a 1 m distance between them. The arrangement was the same as in Figure 6.1.

3. Board-to-Phone Nordic UART service throughput test - This test was performed using a Nordic nRF5284dk board and a OnePlus 9 Pro phone where the distance between the phone and the board was set to 1 m. The arrangement is depicted in Figure 6.2.

Figure 6.1. Board-to-Board Arrangement

Figure 6.2. Board-to-Phone Arrangement

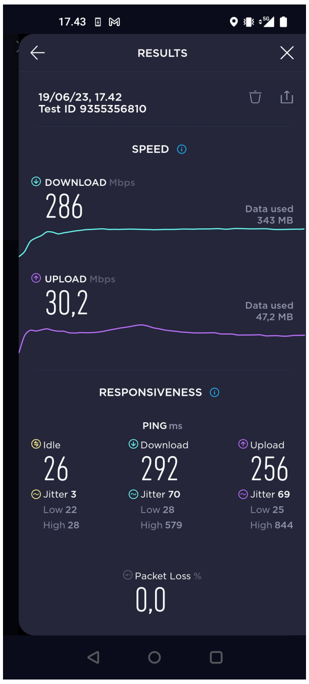
4. Phone-to-Server throughput test - Since this test was performed soon after completing the Board-to-Phone Nordic UART service throughput test, the arrangement was similar to Figure 6.2. The connection with the remote server was established through the TCP/IP protocol using the 5GTN. 5GTN is the widest 5G test network with open access in the world. 5GTN utilizes both the standalone and non-standalone 5G architectures. 5GTN has its own cloud-based core network and sim cards for the mobiles that utilize the 5GTN. The OnePlus 9 Pro mobile, utilized in this experiment, is one such mobile equipped with a 5GTN sim card. Figure 6.3 illustrates a throughput test performed on 5GTN using the Speedtest by Ookla.

It should be noted that the BLE throughput tests mentioned above were carried out in an office-like indoor environment where there can be possible interference from other communication systems, such as WiFi access points and BLE indoor navigation systems that are operating the same 2.4 GHz ISM band as BLE. The measurements are taken using a line of sight channel, with a distance of 1 meter between the transmitter and receiver. This distance is significantly lower than the distance to the potential sources of interference. Therefore, it is assumed that any effects from those sources are minimal.

6.3 Prameter Selection

This section highlights the selected parameters for each test and the reasons for those parameters to be chosen.

The procedure for parameter selection is primarily utilized for conducting the Board-to-Board ATT_MTU throughput test, Board-to-Board Nordic UART service throughput test, and Board-to-Phone Nordic UART service throughput test. Phone-to-Server throughput test did not



17.43

RESULTS

19/06/23, 17.42
Test ID 9355356810

SPEED

DOWNLOAD Mbps
286
Data used
343 MB

UPLOAD Mbps
30,2
Data used
47,2 MB

RESPONSIVENESS

PING ms

Idle	Download	Upload
26	292	256
Jitter 3	Jitter 70	Jitter 69
Low 22	Low 28	Low 25
High 28	High 579	High 844

Packet Loss %
0,0

Figure 6.3. Results of the Speedtest by Ookla for 5GTN

fall into this procedure because there were no parameters to be adjusted in the Phone-to-Server throughput test, and it solely relied on the capabilities of the 5G network utilized for the test.

During the testing procedure, the following parameters were adjusted to observe the influence of those parameters on the throughput. Five repetitions of each parameter configuration were performed and the average throughput value was obtained for that parameter configuration.

1. BLE PHY configuration
2. Connection interval
3. Data length
4. UART TX and RX buffer size of the boards - Only with Tests that utilize Nordic UART Service

6.3.1 Testing with Different BLE PHY Configurations

The following BLE PHY configurations were planned to test the influence of throughput on BLE communication during the experiments.

1. 2 Mbps PHY
2. 1 Mbps PHY
3. LE Coded S2
4. LE Coded S8

The other parameters were kept as below while observing the throughput under the above parameters.

1. Connection interval - 7.5 ms
2. Data length - 251 bytes
3. UART TX and RX Buffer size - 32768 bytes

The reason behind the selection of the above values can be explained as,

- In ideal channel situations, the maximum throughput can be obtained with the highest connection interval. But with the assumption of possible interference and continuous data transmission, it was planned to observe the throughput with the minimum possible value for the connection interval, which is 7.5 ms. The effect of the connection interval will be experimented with immediately after this test process for different PHY configurations. If a higher throughput is observed at a different connection interval than 7.5 ms, that value will be adapted for later experiments.
- During the Technical Background section, it was discussed that the higher data lengths result in lower packet header overheads. This will ultimately result in higher throughput values to set the data length to the maximum possible value.
- The buffer size was to set a higher value than the default value of 256 bytes to eliminate the influence of hardware limitations on throughput due to insufficient buffer size to transmit and receive data with higher throughput values.

6.3.2 Testing with Different Connection Interval Configurations

The following connection intervals were planned to test the influence of throughput on BLE communication during the experiments.

1. 7.5 ms - The tests were planned with minimum connection interval to mitigate the effects of interference.
2. 15 ms - Some applications and operating systems, such as iOS, have a minimum connection interval of 15 ms. It was planned to observe the throughput with 15 ms to understand whether Android devices get a significant advantage of a lower connection interval of 7.5 ms than Apple devices.
3. 4 s - The throughput behaviour of the highest possible value was planned to be examined to understand how significant connection intervals can influence the throughput of BLE and how far the channel follows the characteristics of an ideal channel condition.

The other parameters were kept as below while observing the throughput under the above parameters.

1. BLE PHY configuration - 2 Mbps
2. Data length - 251 bytes
3. UART TX and RX Buffer size - 32768 bytes

The reason behind the selection of the above values can be explained as,

- It was expected to obtain the highest throughput with the 2 Mbps PHY of BLE. If the earlier test on different PHY configurations showed a different configuration for the highest throughput, it would be adapted instead of 2 Mbps PHY.
- Reasons for the buffer size and data length selection were the same as the previous test.

6.3.3 Testing with Different Data Length Configurations

The following data length values were planned to test the influence of throughput on BLE communication during the experiments.

1. 27 bytes - This was the minimum possible value that could be used for the data length. It was planned to examine the amount of throughput observed with the minimum possible data length.
2. 139 bytes - This was the average value of the range of possible values for the data length in BLE. By observing the effect of the throughput with the average value for the data length, it was expected to get a clear idea of the variation of the throughput with the range of possible values for the data length.
3. 251 bytes - This was the maximum possible value that could be used for the data length. It was planned to examine the effect on the throughout with the maximum possible data length.

The other parameters were kept as below while observing the throughput under the above parameters.

1. BLE PHY configuration - 2 Mbps
2. Connection interval - 7.5 ms
3. UART TX and RX Buffer size - 32768 bytes

The reason behind the selection of the above values can be explained as,

- It was expected to obtain the highest throughput with the 2 Mbps PHY of BLE and 7.5 ms connection interval. Suppose the earlier test on different PHY configurations and connection intervals showed different configurations for the highest throughput. In that case, they would be adapted instead of 2 Mbps PHY and 7.5 ms connection interval
- Reason for the buffer size selection was the same as the previous tests.

6.3.4 Testing with Different Buffer Size Configurations

The following buffer size configurations were planned to test the influence of throughput on BLE communication during the experiments. This test was only available with the Board-to-Board Nordic UART service throughput test and the Board-to-Phone Nordic UART service throughput test since they were the only tests that utilized the Nordic UART service.

1. 256 bytes - This was the default buffer size provided in the example code. It was expected to observe the effect on the throughput with this default value.
2. 4096 bytes - This was the 16 times increase from the default value. It was expected to obtain a clear idea of where there is any considerable increase throughout, increasing the buffer to 16 times its default value.
3. 32768 bytes - This is 128 times the default buffer size. It represents a significant increase, and it was expected to observe how the throughput varies when scaled up from the default value to a large multiple.

The other parameters were kept as below while observing the throughput under the above parameters.

1. BLE PHY configuration - 2 Mbps
2. Connection interval - 7.5 ms
3. Data length - 251 bytes

The reason behind the selection of the above values can be explained as it was expected to obtain the highest throughput with the 2 Mbps PHY of BLE, 7.5 ms connection interval, and 251 bytes of data length. Suppose the earlier test on different PHY configurations, connection intervals, and data lengths showed different configurations for the highest throughput. In that case, they would be adapted instead of 2 Mbps PHY, 7.5 ms connection interval, and 251 bytes of data length.

6.3.5 Summary of Test Cases

The above-discussed test cases can be summarized as Table 6.1.

Table 6.1. Summary of the Test Cases

Test	**Fixed parameters**	**Changing parameters**
Testing with different BLE PHY configurations	Connection interval = 7.5 ms Data length = 251 bytes UART buffer size = 32768 bytes	PHY configurations of 2 MBPS PHY, 1 MBPS PHY, LE Coded S2, LE Coded S8
Testing with different connection interval configurations	PHY configuration = 2 Mbps PHY Data length = 251 bytes UART buffer size = 32768 bytes	Connection interval of 7.5 ms, 15 ms, and 4 s
Testing with different data length configurations	PHY configuration = 2 Mbps PHY Connection interval = 7.5 ms UART buffer size = 32768 bytes	Data lengths of 27 bytes, 139 bytes, and 251 bytes
Testing with different UART buffer size configurations	PHY configuration = 2 Mbps PHY Connection interval = 7.5 ms Data length = 251 bytes	UART buffer sizes of 256 bytes, 4096 bytes, and 32768 bytes

6.4 Test Procedure

This section focuses on the aspect of the procedure of the experiments with the test cases, as mentioned earlier.

6.4.1 Procedure of Measurements

The process of obtaining measurements was comparatively different for the considered tests, which can be described as follows.

1. Board-to-Board throughput test using Nordic ATT_MTU throughput firmware - The measurements for this test were obtained through the console interface connected with the board using serial UART. The different parameters were configured through the console using the ’config’ command. After each test, the throughput results were displayed at the console interface. This value was taken as the measurement of the particular configuration.
2. Board-to-Board throughput test using Nordic UART service - The measurements for this test were obtained through the debug console of the Segger embedded studio. The code was modified to show the throughput of each connection event at the debug console as a log message. At the end of the transmission, it provides a log message with the average throughput over all the connection events. This value was taken as the measurement of the particular configuration.
3. Board-to-Phone throughput test using Nordic UART service - The measurements for this test were obtained through the user interface of the developed Android application. The Android application was designed to provide the throughput of each connection event as an output to a text field. Further, it updates the average throughput over all the connection events at the end of the Board-to-Phone data transmission. This value was taken as the measurement of the particular configuration.
4. Phone-to-Server throughput test - This was measured from the Android application’s user interface, which provided the upload speed to the server after storing all the data in the Firebase database.

The above-mentioned tests were performed five times with each configuration except the Phone-to-Server throughput test. During the Phone-to-Server throughput test, 15 iterations were performed.

6.4.2 Analysis of the Results

The data analysis process is performed for different tests as follows.

1. Board-to-Board throughput test using Nordic ATT_MTU throughput test - Results of this test were mainly analyzed by comparing them with the results of the analytical model. Further, statistical measures such as the mean and standard deviation were taken to understand the parameter configuration’s representative value and the measurement distribution. The possible reasons for the differences were considered with the results obtained from the analytical model. Further, graphs were used to observe the measurements showing comparatively higher variation.
2. Board-to-Board throughput test using Nordic UART service - Results of this test were mainly analyzed by comparing them with the results of the analytical model and the results obtained for the Board-to-Board throughput test using Nordic ATT_MTU throughput firmware. It was considered the possible reasons for the differences with the results obtained from the analytical model and Board-to-Board throughput test using Nordic ATT_MTU throughput firmware.

3. Board-to-Phone throughput test using Nordic UART service - The analysis procedure of the obtained measurements was exactly similar to the Board-to-Board throughput test using Nordic UART service.
4. Phone to Server throughput test - The results obtained for this test were verified by performing several repetitions of the speed test provided by Ookla.

6.4.3 Throughput Calculation

In the Nordic ATT_MTU throughput test, the throughput is calculated by the application considering the elapsed time to receive the 1 MB of transmitting data. But in the scenarios where the Nordic UART service is used for data transmission, the throughput is calculated with a custom-defined function, which considers the effective payload utilized and elapsed time for the transmission. It can be represented as (6.1). Further, in scenarios that use the Nordic UART service, 1 MB of data was manually provided to the peripheral device to transmit to the central device. To overcome that issue of elapsed time taking the delay of data input, the start time is set when the application gets 5000 bits from the transmitter where the effective payload was to be calculated as (6.2).

$$Throughput = \frac{Effective\ payload}{Elapsed\ time} \tag{6.1}$$

$$Effective\ payload = Total\ number\ of\ received\ bits - 5000 \tag{6.2}$$

7 RESULTS AND DISCUSSIONS

This section summarises the obtained results for each throughput test with different parameter configurations. Further, this chapter also discusses the possible reasons for those results in detail.

7.1 Board-to-Board Throughput Using Nordic ATT_MTU Throughput Test

7.1.1 Testing with Different BLE PHY Configurations

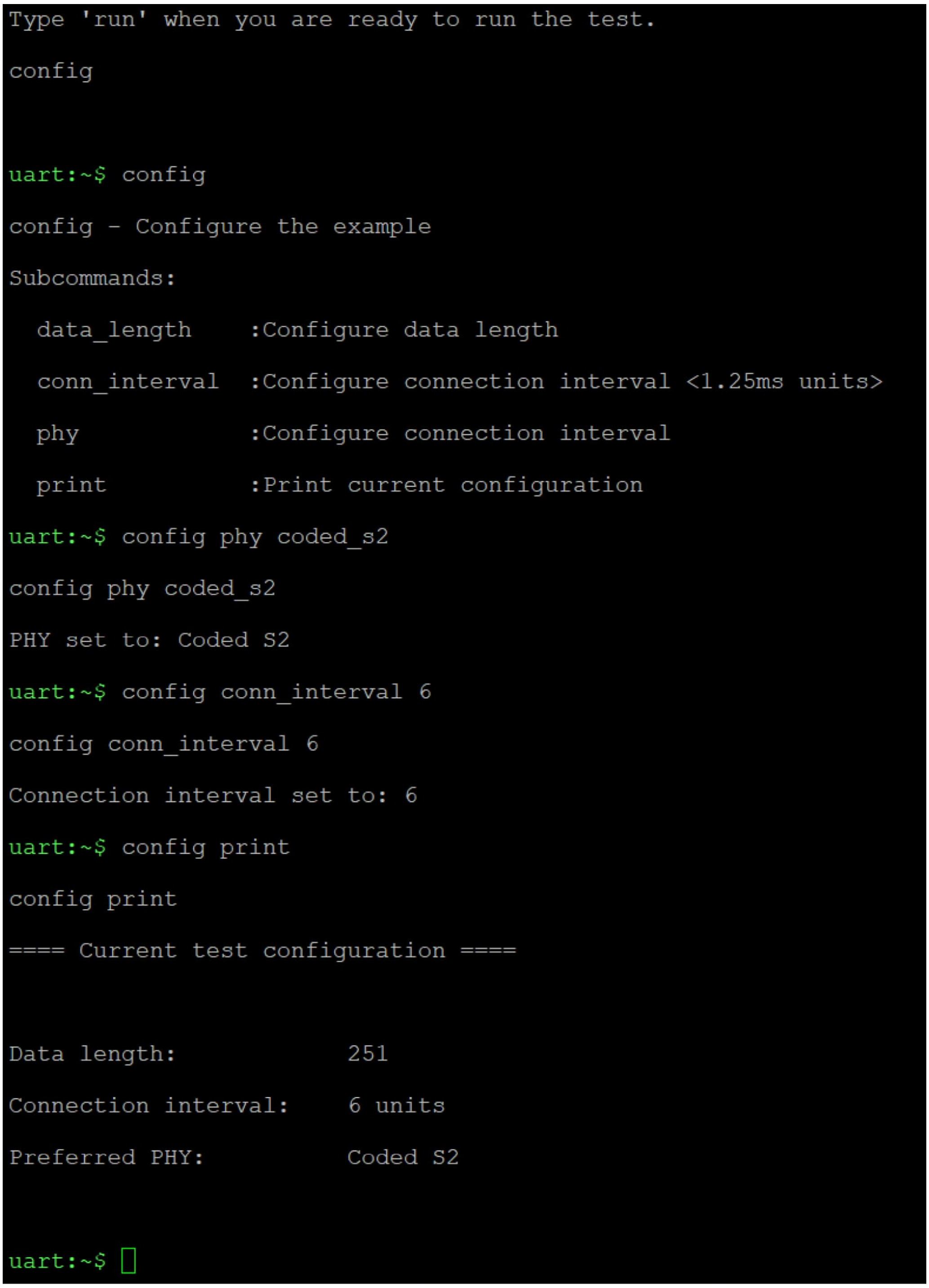
Table 7.1. Results for Different PHY with ATT_MTU Board-to-Board Throughput Test

	2 Mbps	**1 Mbps**	**LE coded S2**	**LE Coded S8**
1st Measurement	1051 kbps	527 kbps	26 kbps	26 kbps
2nd Measurement	1052 kbps	527 kbps	26 kbps	26 kbps
3rd Measurement	1052 kbps	527 kbps	26 kbps	26 kbps
4th Measurement	1050 kbps	528 kbps	26 kbps	26 kbps
5th Measurement	1050 kbps	527 kbps	26 kbps	26 kbps
Mean	1051 kbps	527.2 kbps	26 kbps	26 kbps
Standard Deviation	0.894 kbps	0.447 kbps	0 kbps	0 kbps

Table 7.1 displays throughput values for different PHY configurations using a 7.5 ms connection interval and a 251 byte data length. The PHY configuration of the 2 Mbps PHY was observed to have the highest throughput with a mean value of 1051 kbps. Compared to the analytical model results in Table 4.1, this is a 29.64% decrease. 1 Mbps PHY showed a mean throughput of 527.2 kbps, which was a 37.19% decrease compared to the analytical model. Most importantly, the throughput for LE Coded S2 and LE Coded S8 showed the same throughput with a mean of 26 kbps. Considering the results of the analytical model, it can be assumed that, even though in both the tests for LE coded S2 and LE Coded S8, respective PHY configurations were set as Figure 7.1, the board has used the LE Coded S8 configuration for the BLE communication. This phenomenon was observed in the results illustrated in Figure 7.2 where the PHY configuration of the receiver and transmitter was configured as LE Coded. It was observed in the Nordic UART service source code using Nord nRF5 SKD version 16.0 that the PHY configuration for BLE connection was limited to 2 Mbps, 1 Mbps, and LE coded where the coded mode will be assigned based on the hardware configuration. With that assumption, we can conclude that even though the PHY configuration of LE Coded S2 or LE Coded S8 was set through the console, switching between LE Coded S2 and LE Coded S8 modes mainly depend on the relevant hardware configurations in the Nordic ATT_MTU throughput firmware. Further, in the given console configuration, the board has used LE Coded S8 irrespective of the LE Coded mode.

Considering the difference in the throughput values from the results obtained from the analytical model in Table 4.1 and real-world values as in Table 7.1, it can be assumed that this difference in throughput was mainly caused due to the following reasons.

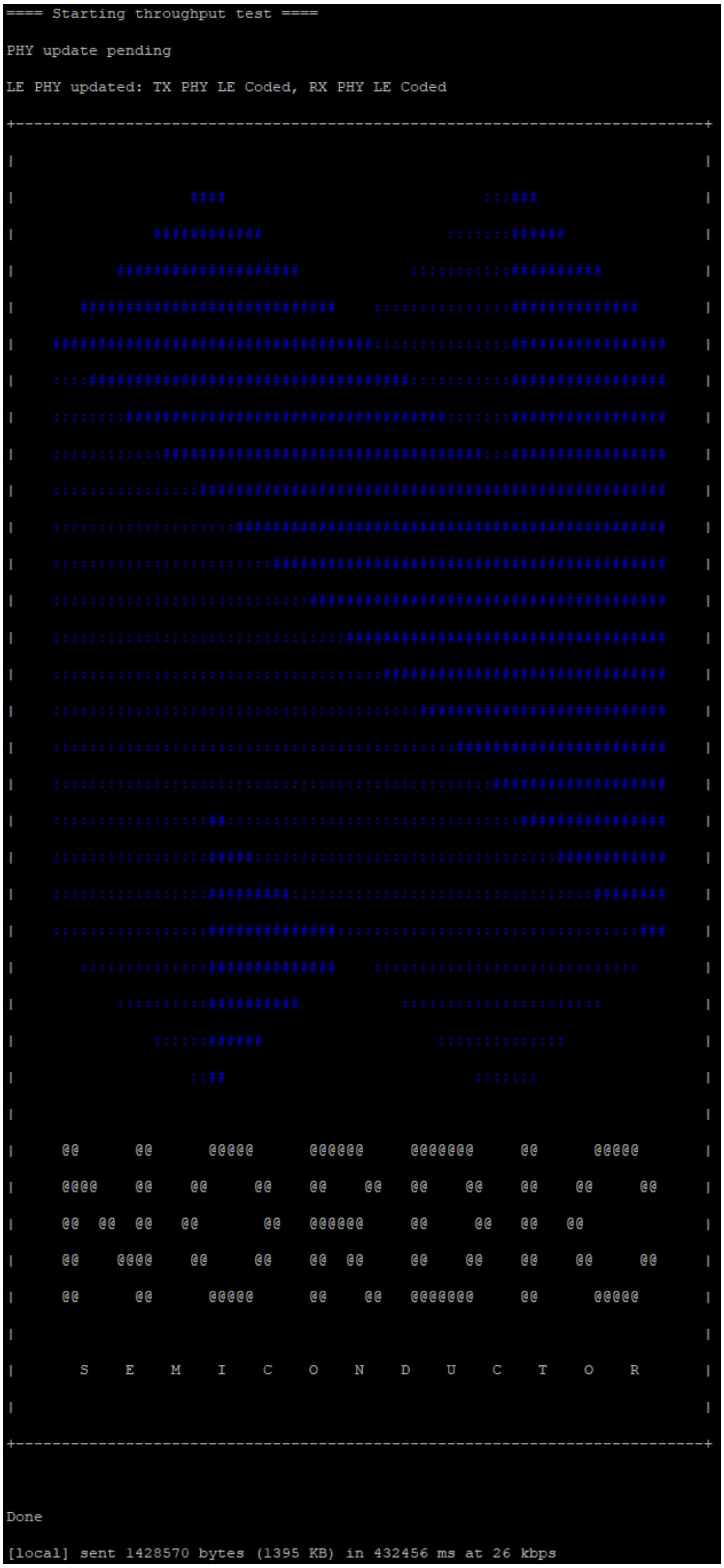
- Effect of connection interval has not been considered in the analytical model.
- Effect of the interference and packet losses have not been considered in the analytical model.



```
Type 'run' when you are ready to run the test.

config


uart:~$ config

config - Configure the example

Subcommands:

  data_length     :Configure data length

  conn_interval   :Configure connection interval <1.25ms units>

  phy             :Configure connection interval

  print           :Print current configuration

uart:~$ config phy coded_s2

config phy coded_s2

PHY set to: Coded S2

uart:~$ config conn_interval 6

config conn_interval 6

Connection interval set to: 6

uart:~$ config print

config print

==== Current test configuration ====


Data length:            251

Connection interval:    6 units

Preferred PHY:          Coded S2


uart:~$ 
```

Figure 7.1. Configuration of LE Coded S2 PHY in ATT_MTU Throughput Test

- Assumption of zero roundtrip time and zero process time of n byte data frame before and after the reception may not be precisely accurate.
- The analytical model considers only the throughput at the LL and does not account for overheads at higher layers. The L2CAP adds headers for channel IDs and packet lengths. As a consequence, BLE's effective throughput is significantly affected by these overheads.



```
==== Starting throughput test ====
PHY update pending
LE PHY updated: TX PHY LE Coded, RX PHY LE Coded
+---------------------------------------------------------------------------+
|                                                                           |
|                   ####                            :::###                  |
|               ############                    :::::::######               |
|           ####################            :::::::::::##########           |
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|     @@      @@      @@@@@      @@    @@   @@@@@@@     @@      @@@@@       |
|                                                                           |
|       S    E    M    I    C    O    N    D    U    C    T    O    R       |
|                                                                           |
+---------------------------------------------------------------------------+

Done
[local] sent 1428570 bytes (1395 KB) in 432456 ms at 26 kbps
```

Figure 7.2. ATT_MTU Throughput Test for LE Coded S2 PHY

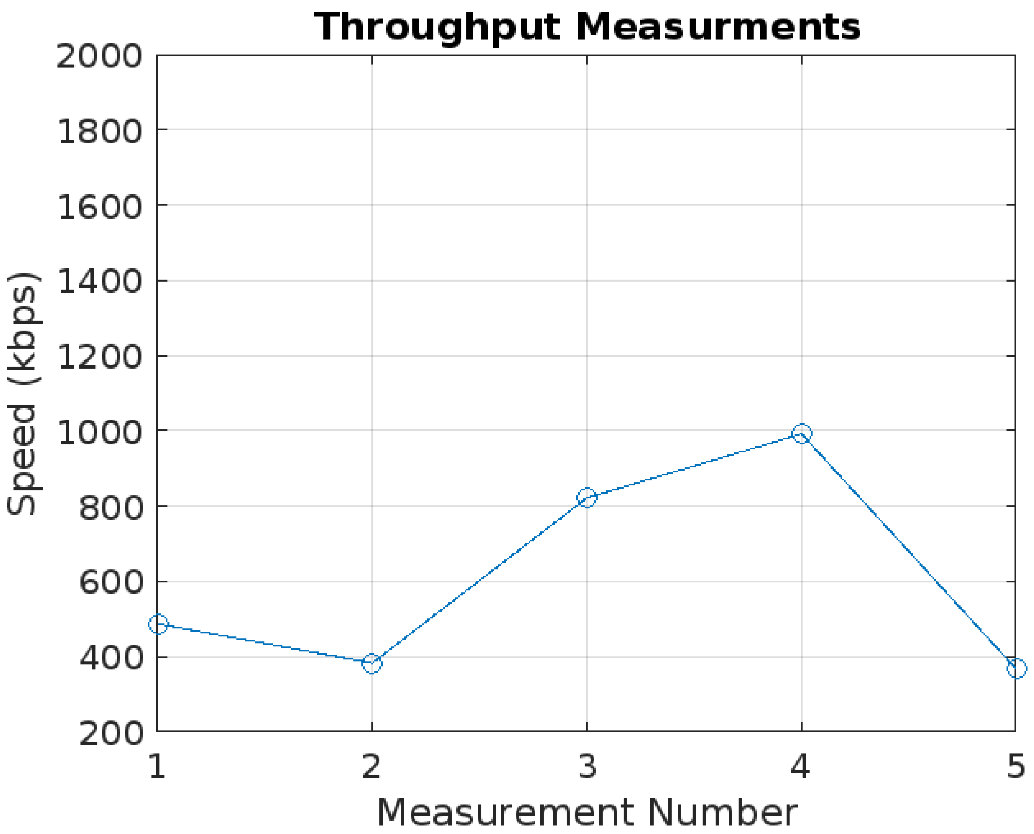

Figure 7.3. Variation of the Throughput with the 4 s Connection Interval

7.1.2 Testing with Different CI Configurations

Table 7.2. Results for Different CIs with ATT_MTU Throughput Test

	7.5 ms	**15 ms**	**4 s**
1st Measurement	1037 kbps	1177 kbps	487 kbps
2nd Measurement	1023 kbps	1182 kbps	383 kbps
3rd Measurement	1035 kbps	1178 kbps	822 kbps
4th Measurement	1019 kbps	1168 kbps	992 kbps
5th Measurement	1031 kbps	1182 kbps	367 kbps
Mean	1029 kbps	1177.4 kbps	610.2 kbps
Standard Deviation	6.83 kbps	5.73 kbps	274.72 kbps

As in Table 7.2, a mean throughput of 1029 kbps was observed with a 7.5 ms connection interval. 15 ms connection interval resulted in the highest mean value among the three values of connection interval, where it was 1177.4 kbps. 4 s connection interval showed a significant variation in throughput value with a mean value of 610.2 kbps. This variation is shown in Figure 7.3.

In an ideal channel, the throughput is expected to be higher with the increase of the connection interval. This is mainly due to utilizing one channel for a longer period, where lower connection intervals switch between the channels more often. But in the real-world scenario of BLE, the longer connection interval results in lower throughput due to interference and collision. This can be elaborated as when there is collision, the packet must wait until the next connection event to re-transmit the packet to the receiver. So, when the connection interval is higher, the re-transmission of the collided packet gets delayed further, resulting in lower throughput. As stated in the above paragraph, throughput values in higher connection intervals are more susceptible to the different channel conditions than in low connection intervals. This relationship is observed in Figure 7.3, showing a significant variation among other obtained results.

A lower throughput in higher connection intervals may also be caused by the Bluetooth software stack limiting the number of packets per connection event. Despite a higher number of packets being transmitted in a relatively longer connection interval, this limitation limits the connection's throughput artificially.

The obtained results show that a 15 ms connection interval gives higher throughput than a 7.5 ms connection interval. It can be assumed that the main reason for the decreased throughput for 7.5 ms over 15 ms is the increased switching of channels with a 7.5 ms connection interval.

Initially, it was planned to proceed with a 7.5 ms connection interval for obtaining measurements of the rest of the tests. But considering the obtained results, throughput measurements of the rest of the tests were performed with a 15 ms connection interval.

7.1.3 Testing with Different DL Configurations

Table 7.3. Results for Different DLs with ATT_MTU Throughput Test

	27 bytes	**139 bytes**	**251 bytes**
1st Measurement	353 kbps	970 kbps	1177 kbps
2nd Measurement	351 kbps	973 kbps	1184 kbps
3rd Measurement	351 kbps	974 kbps	1180 kbps
4th Measurement	352 kbps	979 kbps	1175 kbps
5th Measurement	352 kbps	977 kbps	1180 kbps
Mean	351.8 kbps	974.6 kbps	1179.2 kbps
Standard Deviation	0.84 kbps	2.88 kbps	2.86 kbps

As in Table 7.3, it was observed that with the lower data length, the throughput decreased. In contrast to the lower data length, it was observed that the throughput is higher with higher data length. The reason for this phenomenon can be explained with the help of BLE packet structure which was discussed in Section 3.1.1. The BLE packet has a constant number of bytes reserved for headers illustrated in Figure 3.3. This number is fixed irrespective of the data length. So, when transmitting BLE packets with lower data lengths, the portion of the packet's headers becomes higher than that with higher data lengths. It results in lower throughput in data transmission because a higher number of packets is needed for the data transmission when the data length is lower compared to that with higher data lengths. This results in higher transmission time. Due to this higher transmission time, the throughput becomes lower. This is the exact situation observed in throughput with lower data lengths.

7.2 Board-to-Board Throughput Using Nordic UART Service

7.2.1 Results for Different PHY, DLs, CIs and UART Buffer Sizes

As shown in Table 7.4, the throughput was 92 kbps at each time even though five measurements were taken. Due to the inputs being provided over a serial UART connection with a baud rate of 115200 bps, the main hypothesis was whether the serial UART connection limited the actual test performance. In this test, the connection interval of 4 s could not be configured from the peripheral board, resulting in an error related to data transmission after the connection establishment. It is assumed that since the connection interval is higher, there could be possible re-transmission in the packets due to the interference of the channel. This re-transmission causes an overflow in the buffers used for the communication due to continuous data feed from the serial UART.

Table 7.4. Results for Different PHY, DLs, CIs and UART Buffer Sizes

PHY Configuration	**Connection Interval**	**Data Length**	**UART Buffer Size**	**Mean Throughput**
2 Mbps	15 ms	251 bytes	32768 bytes	92 kbps
1 Mbps	15 ms	251 bytes	32768 bytes	92 kbps
LE coded	15 ms	251 bytes	32768 bytes	92 kbps
2 Mbps	7.5 ms	251 bytes	32768 bytes	92 kbps
2 Mbps	4 s	251 bytes	32768 bytes	-
2 Mbps	15 ms	27 bytes	32768 bytes	92 kbps
2 Mbps	15 ms	139 bytes	32768 bytes	92 kbps
2 Mbps	15 ms	251 bytes	256 bytes	92 kbps
2 Mbps	15 ms	251 bytes	4096 bytes	92 kbps

7.2.2 Testing with Different UART Baud Rate Configurations

With the hypothesis that the serial UART connection limits the performance of the BLE throughput, an experiment was performed to observe the behaviour of the throughput with different baud rates for the serial UART connection. This experiment was not previously planned and performed due to the unforeseen results obtained during the previous experiments of Board-to-Board communication with Nordic UART service. The results obtained for different baud rates are in Table 7.5.

The baud rate can be defined as the rate at which the transmitted signal changes during the transmission medium. Simply, this can be defined as the maximum rate at which data transmits in a channel between two devices. The baud rate can be represented with (7.1). This is frequently defined in devices that communicate with other devices using serial communication[64, 65].

$$Baud\ rate = \frac{Number\ of\ Changes\ of\ the\ Transmismitted\ Signal}{Total\ Time\ in\ Seconds} \tag{7.1}$$

The serial UART utilized in the experiment has a 115200 baud rate equal to 115.2 kbps. So, the maximum data transmission rate is limited to 115.2 kbps. Considering hardware capabilities and signal processing delays, the maximum value achieved is less than 115.2 kbps. This can be

Figure 7.4. UART Packet Structure

elaborated with the UART packet structure as in Figure 7.4. Two bits are reserved as a start and stop bit on either side of the 8-bit data block. So this limits the effective throughput by 80% due to the actual amount of data transmitted in the 10-bit packet being limited to 8-bit. Based on this reduction, the effective throughput for different baud rates can be calculated as follows.

1. For 115200 baud rate (115200 bps)

$$115200 \times 0.8 = 92160\ bps$$

2. For 76800 baud rate (76800 bps)

$$76800 \times 0.8 = 61440\ bps$$

3. For 38400 baud rate (38400 bps)

$$38400 \times 0.8 = 30720\ bps$$

Based on these calculations, it can be observed that the effective baud rate is much closer to values that were obtained during the experiments as in Table 7.5. It can be observed that when lowering the baud rate, the BLE connection's throughput decreased accordingly.

As per the results of Section 7.1, it can be observed that the throughput values were way higher than 92 kbps, except for the LE Coded S2 and LE Coded S8 tests. But again, the hardware limitation of LE Coded modes when switching between them was discussed in Section 7.1. It also discussed the restriction of BLE PHY configurations into 3, namely 2 Mbps, 1 Mbps and LE Coded in the Nordic UART service. Based on that discussion, it is assumed that the PHY configuration of LE Coded mode in Nordic UART service uses the LE Coded S2 mode, where it has 500 kbps throughput. As a result of that assumption, it is possible to conclude that the throughput was limited because of the serial UART connection's limitations.

Table 7.5. Results for Different Baud Rates with Nordic UART Service

	115200 bps	**76800 bps**	**38400 bps**
1st Measurement	92 kbps	61 kbps	30 kbps
2nd Measurement	92 kbps	61 kbps	30 kbps
3rd Measurement	92 kbps	61 kbps	30 kbps
4th Measurement	92 kbps	61 kbps	30 kbps
5th Measurement	92 kbps	61 kbps	30 kbps
Mean	92 kbps	61 kbps	30 kbps
Standard Deviation	0 kbps	0 kbps	0 kbps

7.3 Board-to-Phone Throughput Using Nordic UART Service

7.3.1 Results for Different PHY, DLs, CIs and UART Buffer Sizes

As in Table 7.6, the results of the Board-to-Phone throughput test using the Nordic UART service showed a consistent throughput of 92 kbps in the five measurements taken for each parameter configuration. It was assumed that the same scenario of limiting the throughput values was due to the serial UART connection as it was in the Board-to-Board throughput measurements with Nordic UART service. In this test, the connection interval of 4 s could not be configured from the peripheral board, resulting in an error related to data transmission. The same assumption can be made as earlier that the possibility of UART buffers overflow due to continuous data stream and a higher number of packet re-transmissions.

Table 7.6. Results for Different PHY, DLs, CIs and UART Buffer Sizes

PHY Configuration	**Connection Interval**	**Data Length**	**UART Buffer Size**	**Mean Throughput**
2 Mbps	15 ms	251 bytes	32768 bytes	92 kbps
1 Mbps	15 ms	251 bytes	32768 bytes	92 kbps
LE coded	15 ms	251 bytes	32768 bytes	92 kbps
2 Mbps	7.5 ms	251 bytes	32768 bytes	92 kbps
2 Mbps	4 s	251 bytes	32768 bytes	-
2 Mbps	15 ms	27 bytes	32768 bytes	92 kbps
2 Mbps	15 ms	139 bytes	32768 bytes	92 kbps
2 Mbps	15 ms	251 bytes	256 bytes	92 kbps
2 Mbps	15 ms	251 bytes	4096 bytes	92 kbps

7.3.2 Testing with Different UART Baud Rate Configurations

As in Table 7.7, obtained results were exactly similar to those obtained for similar tests in the Board-to-Board throughput test using the Nordic UART service. Based on the discussion of Section 7.2.2, it can be concluded that the baud rate of the serial connection used to provide input to the peripheral board is the main limiting factor of the observed throughput values.

Table 7.7. Results for Different Baud Rates with Nordic UART Service

	115200 bps	**76800 bps**	**38400 bps**
1st Measurement	92 kbps	61 kbps	30 kbps
2nd Measurement	92 kbps	61 kbps	30 kbps
3rd Measurement	92 kbps	61 kbps	30 kbps
4th Measurement	92 kbps	61 kbps	30 kbps
5th Measurement	92 kbps	61 kbps	30 kbps
Mean	92 kbps	61 kbps	30 kbps
Standard Deviation	0 kbps	0 kbps	0 kbps

7.4 Phone-to-Server Throughput Test Using 5GTN

As part of the Board-to-Phone throughput test that uses Nordic UART service, 15 measurements were obtained for Phone-to-Server throughput as in Table 7.8. The throughput results were obtained through the user interface of the Android application illustrated by Figure 5.5. At the end of each test, the database was observed to ensure that all the transmitted data had been updated to the database correctly. There was considerable variation in the connection throughput, as shown in Figure 7.5 with a mean value of 22.77 Mbps and a standard deviation of 3.11 Mbps. By performing several repetitions of the Speedtest by Ookla, it was confirmed that the obtained mean value for the uplink of the 5GTN through the developed Android application is within the typical observable value for the uplink of 5GTN. These results indicate that the Phone-to-Server connection does not limit the throughput. At the same time, the Board-to-Phone data transmission capacity solely determines the throughput of the end-to-end system.

Table 7.8. Results for Phone to Server Throughput Tests

Measurement	**Throughput**
Measurement 1	24.93 Mbps
Measurement 2	23.09 Mbps
Measurement 3	29.02 Mbps
Measurement 4	19.28 Mbps
Measurement 5	22.14 Mbps
Measurement 6	23.57 Mbps
Measurement 7	18.72 Mbps
Measurement 8	16.41 Mbps
Measurement 9	22.93 Mbps
Measurement 10	24.47 Mbps
Measurement 11	21.29 Mbps
Measurement 12	25.75 Mbps
Measurement 13	21.40 Mbps
Measurement 14	27.26 Mbps
Measurement 15	21.52 Mbps
Mean	23.11 Mbps
Standard Deviation	3.11 Mbps

7.5 Discussion of the Results

When considering the results of the Board-to-Board throughput using the Nordic ATT_MTU throughput firmware, it can be observed that the 2 Mbps PHY configuration has the highest mean throughput of 1051 kbps with a connection interval of 7.5 ms and a data length of 251 bytes. In contrast, LE Coded S2 and S8 show the lowest throughput with a mean of 26 kbps. 1 Mbps PHY configuration of BLE 5 showed a mean throughput of 527.2 kbps. The measured values were significantly lower than the values obtained through the analytical model. Specifically, the 2 Mbps physical layer configuration demonstrated a 29.64% decrease, while the 1 Mbps configuration showed a 37.19% decrease. The main reason for this decrease can be assumed as the lack of examining the effect of connection interval, interference, and packet losses in

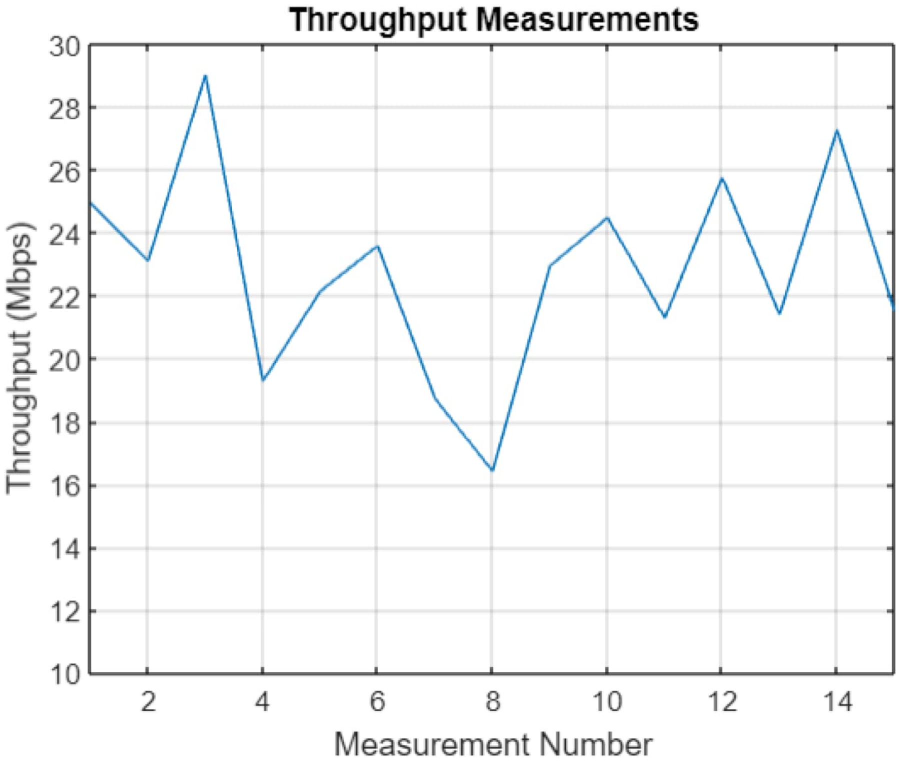

Figure 7.5. Variation of the Throughput Phone to Server Connection

the analytical model, the assumption of zero overheads in the upper layers from the LL on the packet when calculating the throughput, and the assumption of zero round trip time, and zero process times of the packet. Results highlighted the hardware limitation where the LE Coded mode would be switched based on the hardware configuration even though it was set to either LE Coded S2 or LE Coded S8. Results for the connection interval showed that the throughput is maximized neither at the lowest value nor the highest value. The reason behind this phenomenon was assumed as the highest connection intervals tend to have a significant amount of delay due to the re-transmission of the collided packets when the delay between two consecutive connection events is higher. The lowest connection intervals are assumed to have a lower throughput due to increased channel switching. The results obtained for the connection interval pave the way for future research to determine the optimal connection interval maximizing throughput. A significant variation of the throughput values for the 4 s connection interval was observed, where the standard deviation was 274.72 kbps. Regarding BLE communication, higher connection intervals are more vulnerable to channel conditions like interference in real-life situations. This can be considered the reason behind the higher throughput variation with a 4 s connection interval. Results with the different data lengths showed that the mean throughput was higher when the data length was higher, where there was around 70% throughput increase with 251 bytes of data length than that with 27. This phenomenon can be discussed as a higher number of packets is needed for the data transmission when the data length is lower than that with higher data lengths, resulting in higher transmission time.

The same results were observed during the Board-to-Board and Board-to-Phone throughput tests that utilized the Nordic UART service. All the tests, except those with 4 seconds connection interval, resulted in the same mean throughput of 92 kbps. Tests with the 4 seconds connection interval could not conclude successfully due to an error related to data transmission after the connection establishment. It is assumed that the increased number of packet re-transmissions resulting from a higher connection interval leads to a buffer overflow during communication due to the constant stream of data from the serial UART. With the hypothesis the serial UART connection limited the throughput with each configuration, another test was performed to examine the effect of the baud rate on the BLE throughput. During the test, it was observed that the results were limited by the effective throughput of the serial UART connection that was utilized to provide inputs to the peripheral board. The effective throughput of the serial UART connection was derived considering the UART packet structure. Based on the results of the Board-to-Board and Board-to-Phone throughput tests utilizing the Nordic UART service, it can be concluded that the minimum BLE communication throughput is at least 92 kbps for all parameter configurations, except for the 4 s connection interval.

Phone-to-Server throughput test resulted in a mean throughput of 23.11 Mbps. The values obtained for the throughput varied considerably, with a standard deviation of 3.11 Mbps. Several repetitions of the Speedtest by Ookla confirmed that the obtained mean value for the upload throughput is within the range of possible values for the throughput of the uplink in 5GTN.

Based on the results of the four tests performed with different parameter configurations, it can be observed that the throughput of board-to-board connection bottlenecks the end-to-end throughput.

8 CONCLUSIONS

Based on the study's results, BLE is a superior technology for communicating with low-power devices in the era of 5G and beyond. This can be further elaborated with the results obtained for the ATT_MTU throughput test and Nordic UART service throughput test. The ATT_MTU throughput test proves that the 2 Mbps PHY configuration has an achievable throughput of around 1.2 Mbps. Based on the throughput results with the Nordic UART service, it can be observed that even the LE Coded configuration gives a throughput higher than 92 kbps. As the LE Coded mode was designed to have a higher range and provide more reliable transmission by utilizing forward error correction mechanisms, the results of the study show that BLE has the potential to be one of the key enablers in a wide range of IoT networks from Body Area Network (BAN) to widely spread IoT networks like smart farming. It's worth noting that smartphones equipped with BLE can be viable gateway options for IoT networks, like BAN, which rely on BLE to transmit sensor data. The study's results also show the potential of integrating the 5G network with BLE, which enables the IoT network to communicate with remote servers with significant throughput. Integrating 5G with BLE also paves the path to highly scalable IoT networks with reasonable QoS. Further, it expands the boundaries of the IoT networks where reduced power consumption is the primary consideration.

The findings of this research can be highly applicable when designing new network architectures utilizing BLE and 5G. The results of the Board-to-Board and Board-to-Phone throughput tests that utilize Nordic UART service have been limited by the capabilities of serial UART communication that provide the input to the peripheral device. This gave a clear insight into the practicalities of adapting several communication protocols in an IoT network and potential causes that will limit the performance. Although the throughput limitation of approximately 92 kbps hindered our ability to fully observe the behaviour of Nordic UART service in BLE communication, we gained a clear understanding of its potential lower throughput limits. The results obtained during the study are limited to a line of sight channel. The measurements did not take into consideration the interference from the surrounding environment. The results of the study can be slightly different with different arrangements of the data transmission.

This study paves the path for several research avenues that can be considered in future. Exploring the performance of BLE 5 under various channel conditions is one such research avenue that will surely help the potential designers of IoT networks that utilize BLE. It will help to identify the suitability of BLE in different application domains. Further, such research will also help the development of the BLE protocol by identifying the possible loopholes. As another research avenue, it will provide significant insight into different technologies, such as WiFi and NFC if they can be tested similarly to the study, by integrating a similar network architecture with 5G. This will surely cater to the requirement of identifying prominent technologies enabling massive Machine-Type Communication (mMTC) with 5G and beyond networks. Further, observing the Board-to-Phone throughput variation with an iOS device will also significantly contribute to future network designers deciding the optimal network architectures for their specific needs.

As the final remarks, with the achievement of all the expected objectives of the study, it can conclude that BLE has a significant capability of redefining the future low-power IoT networks with its advanced capabilities, such as different PHY configurations for different application requirements. Integrating BLE with 5G and beyond networks can produce more scalable low-power IoT networks with elevated QoS.

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