UNIVERSITY
OF OULU

FACULTY OF INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING
DEGREE PROGRAMME IN WIRELESS COMMUNICATIONS ENGINEERING

# MASTER'S THESIS

# ENERGY EFFICIENCY EVALUATION OF BLE 5 TECHNOLOGY

| | |
|---|---|
| Author | Md Moklesur Rahman |
| Supervisor | Dr. Heikki Karvonen |
| Second Examiner | Professor Jari Iinatti |

December 2019

**Rahman M. (2019) Energy efficiency evaluation of BLE 5 technology.** University of Oulu, Faculty of Information Technology and Electrical Engineering, Degree Programme in Wireless Communications Engineering. Master's Thesis, 65 p.

# ABSTRACT

**As the demand for consumer electronic gadgets keep on growing rapidly day by day, a class of wirelessly connected digital accessories is getting to be built up. In this case, energy efficiency is considered as an essential basic necessity for a wireless communication system to be well adapted for the internet of things (IoT) application. The protocol parameters must be optimized for a given application in order to minimize power consumption. An energy model is therefore required, which can predict the energy consumption of a wireless device based on, Bluetooth low energy (BLE), e.g., for different parameter values. In this case, the BLE 5 technique can be a very effective solution. Lately, the Bluetooth 5 specifications have been introduced in order to offer remarkable improvements in comparison to the previous versions of the protocol. Bluetooth 5 coded is a new special kind of connection that comes with reliable communication features that varies in speed, range, and energy consumption aiming at providing better long-distance connections, but at a lower bit rate. Bluetooth 5 targets to improve twice the speed, four times range, and eight times the advertising in comparison to Bluetooth 4. This thesis describes the evaluation of the energy efficiency of recently specified BLE 5 technique's coded mode. This work analyses both the analytical, and experimental performance of the energy efficiency of BLE 5 (S = 8) coded mode solution. It includes analytical modelling, Matlab programming, and real-life measurement using Nordic semiconductor nRF52840 development kit. The performance of lately revealed BLE 5 coded technique is compared to the performance of the BLE 4, which is seen today to be mostly used in case of commercial wireless devices.**

**To improve the communication range of this low-power technique for IoT purposes, BLE 5 coded mode uses a forward error correction (FEC) method. Because of coding overhead, the packet length increases, and the throughput decreases. In this thesis, the frequency 2.4 GHz is considered. The LE Coded PHY is responsible for adding two steps into the packet transmissions, and reception. Firstly, FEC method is applied to the packet so that the receiver can make a correction of bit errors when the packet is received, and would be capable to improve the packet error rate (PER). Secondly, a pattern mapper method is applied to the packet. This FEC, and pattern mapping results in getting better sensitivity. The experimental results from this thesis show that BLE 5 technique provides better packet error rate (PER) performance, communication range performance, and received signal strength indicator (RSSI) performance than BLE 4, and BLE 5 consumes less energy than BLE 4, which was found out using analytical modelling.**

**Key words: Bluetooth low energy, Forward error correction, Pattern mapper, Packet error rate, Symbol error rate, Received signal strength indicator.**

# TABLE OF CONTENTS

# FOREWORD

I would like to thank Professor Jari Iinatti – the head of CWC-NS unit at the University of Oulu and Academic Coordinator of WCE Programme – Dr. Kari Kärkkäinen for giving me the golden opportunity to study in this department on an exciting and challenging programme. Special appreciation is expressed to my supervisor – Dr. Heikki Karvonen and the technical advisor – Dr. Konstantin Mikhaylov for allowing me to work in this project and for their time, patience and understanding. Their support was immensely valuable to me throughout my thesis work. My thoughts, opinions, and ideas were given the freedom to express them.

My gratitude also goes to a number of other staffs at CWC, Professors for their outstanding lectures and their support and also thanks to the graduation committee for their invaluable advice and support.

I am also grateful to Dinesh Acharya for helping me during conducting thesis measurements.

I respectfully appreciate my parents for their unconditional support, encouragement, and inspiration during my entire studies. Finally, I want to express my profound thankfulness to my dear wife – Tauhida Jahan and my beloved daughter – Jannatul Mawa for their endless support and continued patience during this process to accomplish the master degree.

Oulu, December 17, 2019

Md Moklesur Rahman

# LIST OF ABBREVIATIONS AND SYMBOLS

| | |
|---|---|
| ABI | allied business intelligence |
| ATT | attribute protocol |
| AWGN | additive white Gaussian noise |
| BLE | Bluetooth low energy |
| BER | bit error rate |
| BR | basic rate |
| BWT | Bluetooth wireless technology |
| BD | bit data |
| CRC | cyclic redundancy check |
| CI | coding indicator |
| CS | cellular systems |
| CSI | channel state information |
| DC | direct current |
| DWA | data whitening algorithm |
| EDR | enhanced data rate |
| EPL | extended packet length |
| ECC | error correcting code |
| FEC | forward error correction |
| GATT | generic attribute profile |
| GAP | generic access profile |
| GFSK | Gaussian frequency shift keying |
| GATT | generic attribute profile |
| GFSK | modulation scheme |
| HCI | host controller interface |
| PHY | physical layer |
| HWSW | hardware and software |
| IoT | internet of things |
| ISM | industrial scientific medical |
| IFS | inter-frame space |
| LE | low energy |
| LC | link control |
| LM | link manager |
| L2CAP | logical link control and adaptation protocol |
| LOS | line-of-sight |
| LFSR | linear feedback shift register |
| M2M | machine to machine communications |
| MAC | media access control |
| MIC | message integrity check |
| MD | more data bit |
| NLOS | non line-of-sight |
| OSI | open systems interconnection |
| OTA-DFU | over-the-air device firmware upgrade |
| PER | packet error rate |
| PDU | protocol data unit |
| PED | portable electronic devices |
| RF | radio frequency |

| | |
|---|---|
| RSSI | received signal strength indicator |
| SER | symbol error rate |
| SDK | software development kit |
| SOC | system-on-chip |
| SNR | signal-to-noise ratio |
| SER | symbol error rate |
| SIG | Bluetooth special interest group |
| SMP | security manager protocol |
| TDMA | time division multiple access |
| TF | termination field |
| ULP | ultra low power |
| URL | uniform resource locator |
| USB | universal serial bus |
| WBAN | wireless body area network |
| WSN | wireless sensor network |

| | |
|---|---|
| $B_{n1}$ | number of information bits for BLE 4 |
| $B_{n3}$ | number of information bits for BLE 5 |
| $C$ | velocity |
| $d$ | measurements distance |
| $d_{h0}$ | reference distance |
| $E_s$ | energy per symbol |
| $E_T$ | energy consumption of transmitter |
| $E_R$ | energy consumption of receiver |
| $E_{cdp(1)}$ | energy consumption for BLE 4 in different distance |
| $E_{cdp(3)}$ | energy consumption for BLE 5 in different distance |
| $E_{cd}$ | energy consumption per number of information bits |
| $f$ | frequency |
| $N_0$ | noise power spectral density |
| $N_{tx}(d)$ | number of required transmission for success in different distance |
| $n$ | path loss exponent |
| $k$ | constraint length |
| $PL(d)$ | path loss in different distance |
| $PL_0$ | reference path loss |
| $P_R$ | power consumption of receiver |
| $P_T$ | power consumption of transmitter |
| $P_{rx}$ | received signal power |
| $P_{tx}$ | transmit power |
| $t_b$ | duration of transmitted bit |
| $T$ | noise temperature of receiver circuit |
| $X$ | packet length |

| | |
|---|---|
| $\alpha$ | symbol error rate |
| $\lambda$ | wavelength |

# 1 INTRODUCTION

This master's thesis project work has been carried out in the Centre for Wireless Communications (CWC) at the University of Oulu, Finland as a research part of master's degree programme in Wireless Communications Engineering. The idea to evaluate energy efficiency analysis of Bluetooth low energy (BLE) 5 coded technique was originated based on huge demands of applications in the internet of things (IoT) field as BLE 5 seems to be more reliable candidate among various technologies in the industrial, scientific and medical (ISM) band. According to the forecasting of Allied business intelligence (ABI) research, by 2021, 48 billion devices will be connected to the internet and 30% of those devices are forecasted to be Bluetooth devices [1]. BLE has been actively developed so that it can work as an IoT's key enabler. Bluetooth 5 brings significant technological advancements and makes it ideal for a wider range of IoT applications than ever before. It is noticed, in the case of many applications, data transfer using wired media is not considered more efficient than wireless data transfer [1]. Therefore, during the present years, energy-efficient short-range wireless communication technologies have become an essential subject for research and development. By continuous efforts, the researchers and engineers have become capable of increasing the energy efficiency of and reducing the economic costs for wireless data transmission.

## 1.1 Motivation

Energy-efficient communication has become a major issue due to increasing the demand of various types of new technology which are used in wireless communication. In this case, the BLE 5 [2] coded technique is aimed at providing significantly decreased power consumption and costs compared to the previous version of BLE technology (BLE 4.2), while keeping up same communication range. According to the Bluetooth special interest group (SIG), BLE 4 version has two main drawbacks: too low speed, and too short range. In this case, the BLE 5 technology represents a further evolution of the BLE technology, which deals with the problem of increasing the communications range and the maximum throughput by introducing three new physical layer (PHY) options. BLE 4 can only perform detection of error instead of correcting error. However, BLE 5 has an error correction capability. The significant benefit of correcting error using developed error correction methods is that information can be properly decoded at a lower signal-to-noise ratio (SNR) and hence, at a larger distance from the transmitter. In addition to faster speeds, BLE 5 provides remarkable improvements for energy efficiency and wireless coexistence with reduced radio communication time. Without increasing power consumption, BLE 5 offers data transfers up to 2 Mbps, which is twice the speed of Bluetooth 4.2. With the feature of faster transmit speed, BLE 5 spent less time with the radioactive, which potentially results in decreasing battery consumption.

In this thesis, the main focus is to evaluate energy efficiency analysis of BLE 5 coded technique by evaluating packet error rate (PER) performance and symbol error rate (SER) performance. The goal of this work was to evaluate PER performance at different distance, and to evaluate communication range performance. It also was focused on an analytical model to observe the performance of PER and SER in case of both BLE 4 and BLE 5 with varying distance and the energy efficiency for both cases was evaluated. The research method of this master's thesis includes a literature review, analytical modelling, simulations with the help of the Matlab software, and real-life measurements using Nordic semiconductor nRF52840 development kit [3]. The future work could include, e.g., developing analytical modelling, following proper antenna direction and improving design of the equipment.

## 1.2 Thesis outline

The structure of the thesis is organized as follows. The thesis work provides the overview of BLE technology, and the impact of BLE 5 technology in terms of IoT which is explained in Chapter 2. Background of BLE technology, functions of BLE, and BLE network topology are also described in Chapter 2. Furthermore, the main focus of Chapter 2 is on BLE 5 PHY, packet format, forward error correction (FEC), and pattern mapper. Chapter 3 introduces the analytical model for energy efficiency evaluation of BLE 5 technology where the performance of PER, SER, and energy consumption per number of information bits are described. Chapter 4 represents experimental performance evaluation where the measurements results at different distance for both BLE 4, and BLE 5 are shown. The analytical results and comparison of both BLE technology are introduced in Chapter 5. It also provides future work possibilities of BLE 5 technology. Finally, the summary of this thesis work is given in Chapter 6.

# 2 BLUETOOTH LOW ENERGY

BLE is the power-friendly version of Bluetooth wireless technology developed for short-range control, and monitoring applications, which was adopted from classical Bluetooth to make many innovative new use cases possible by one of the largest wireless interest group-the Bluetooth SIG. It is already evident that smart gadgets can be turned into smarter gadgets by making them compact, affordable, user-friendly and less complicated. The devices equipped with BLE for communication are generally powered by coin-cell batteries and it can be operated for an extended period of time off [4].

At present, numerous transceivers are available on the market that implements different wireless communication protocols. Among them, recently suggested protocol is BLE which is an emerging wireless technology designed for low power, and low-cost communication. The market for applications using BLE is continually increasing because of its popularity as a building block for the IoT technology.

## 2.1 Background

Bluetooth is a radio frequency (RF) technology that was developed more than twenty years ago. At present, it is considered as one of the major pillars of the IoT [5]. Because of radio waves, Bluetooth is used for data transmission allowing two or more devices to connect with each other. Familiarization and strong Bluetooth support in all major operating systems have made it a very well-known protocol choice in order to communicate with these “intelligent” devices. From listening to music to controlling the lights, from sending data for performing a measurement of the heart rate to controlling the TV, everything is possible with enabled Bluetooth devices.

The Bluetooth range of most of the device does not generally exceed 100 meters. According to the signal coverage range, there are three distinct classes: Class 1, Class 2, and Class 3 [6]. The most powerful is Class 1 which can go up to 100 meters. The most popular is Class 2 which can operate only within a range of 10 meters. However, Class 3, does not go beyond 1 meter that is especially least used. In the last ten years, Bluetooth has gained popularity and success tremendously in several application areas, such as audio communications, and stereo streaming though, in 2003, it was considered to be dead [7]. At present, the Bluetooth industry is flourishing and giving attention to prolonging the technology's implementation to short-range wireless communication sectors, like audio and stereo communications. Bluetooth industry are giving attention to the IoT and Machine-to-Machine (M2M) communications [8]. To make Bluetooth suitable for M2M and IoT applications, power consumption requires to be reduced [9], [11].

The Bluetooth SIG introduced BLE in 2011 to make benefit excessively with low energy functionality. It is a wireless computer network technology that works on the same 2.4 GHz frequency as ‘classic’ Bluetooth [9]. Initially, Nokia designed it as an in-house project named ‘Wibree’ before being introduced by the Bluetooth SIG. Bluetooth 4.0 was the first specification of BLE, and then it was updated in Bluetooth 4.1, 4.2 [10], and 5 [2]. Also, BLE technology was made attractive for many uses including vehicular networks [11].

The Bluetooth SIG designed and marketed BLE for the following application: in the healthcare, security, fitness, home entertainment and so forth. It is a comparatively new technology and is primarily designed for low-power and low-cost operation, which are specified in Bluetooth v 4.2 for supporting devices to increase battery life. It can run on battery power for years at a cheaper cost because, in the case of its used applications, there is no need to exchange large amounts of data. Bluetooth SIG supervises the Bluetooth specification that is regularly upgraded and promoted according to market needs [12], [13].

The Classic Bluetooth is ideal for connecting cell phones to Bluetooth headsets for phone calls. It assures the data transmission rate to make it suitable for applications like as the Bluetooth headset transmitting high-quality music. In the classic type, it is subdivided into two parts: the basic rate (BR) and the enhanced data rate (EDR). Classic Bluetooth technology was modeled as a voice for continuous streaming of data and succeeded in disposing of wires in many users as well as in industrial and medical applications. The aim of Classic Bluetooth technology is to make a secure wireless connection among the devices. However, BLE or Bluetooth Smart is a form of Bluetooth technology that was developed to supply available connectivity for the small devices, especially those associated with the IoT. Devices with small batteries, those use Bluetooth Smart technology, can run for long periods. Also, it can communicate with larger devices like smartphones or tablets. One of the key aspects of BLE is that it can support devices running with very low levels of battery consumption until still being able to communicate with existing Bluetooth devices. For example, many devices that are associated with the IoT like healthcare devices, sports & fitness devices, mice, keyboards, wearables, along with small sensors and actuators that may need to be able to operate for a year or more on a single battery charge. The power consumption can be kept to a minimum because most of the time BLE is in sleep mode and only wakes up when a connection is initiated. Consumption of power is kept minimum as the real connection times are only a few ms. The peak power usage and the average power consumption are only about 15 mA and 1μA, [13] respectively. The highlight features of the BLE products are the followings: average and idle mode power consumption, ultra-low peak, ability to run for years on standard coin-cell batteries, multi-vendor interoperability, and enhanced range [13].

The Bluetooth SIG has announced the specifications of Bluetooth 5 [12] on 16th June 2016 which feature is, compared to the prior specification, to make the speed in double, range in fourfold, provide an eightfold increase in the capacity of data broadcast, and its launch helps define the role of Bluetooth technology in implementing the IoT over the next decade. It's new functions are in particular focused on the emerging IoT. Bluetooth 5 standard will take part in contributing to the development of existing use cases, consisting of better coexistence, quicker consumer reports, and larger coverage. It also gives an exclusive variety of connection which is designed for long distance communications. Bluetooth 5 will likely grow to be the de-facto version of Bluetooth over the following few years. The classic version of Bluetooth 5 is similar to the previous versions, where the enormous improvements pay attention to the BLE version. According to the Bluetooth specification hardware boards are able to support three kinds of Bluetooth connections: BLE 4.x, Bluetooth 5 2 Mbps, and Bluetooth 5 coded [14]. The connection model named BLE 4.x is used by the BLE specification: 4.0, 4.1 and 4.2. This type of connection is known as BLE at 1 Mbps, as this is its estimated speed at the lowest layer before introducing any protocol overheads. Bluetooth 5 is the new high-speed connection that is, at the Physical (PHY) layer, rated at 2 Mbps. Bluetooth 5 coded is a new version of the world's most popular wireless connection solution which goal is to provide better connections in long-distance [15]. The initial aim of the BLE 5 coded is, therefore, to cover a broader range rather than just speed. It is obvious that the new version of BLE technology has been designed to produce a communication network that provides a short-range communication bandwidth, which permits data sharing between the connected IoT devices, and other intelligent devices [16]. The LE long-range feature of

Bluetooth 5 can deliver reliable connections. Therefore, it covers the home and building, as well as outdoor, commercial applications and industries that will make it a reality. Bluetooth 5 also provides a different type of connection that was designed for long-range communication. New coded PHY layer of BLE 5 rates of 500 kbps and 125 kbps, which results in achieving a long distance. In fact, in the case of outdoors measurement, with transmit power of 0 dBm, this range should be up to 490 meters and 780 meters with transmit power of 9 dBm [17]. The sensitivity is increased with coded PHYs while maintaining the same current consumption of Tx and Rx. For each bit of data, the number of over-the-air modulated symbols is improved, making it simpler for the receiver to differentiate a signal compared to noise. By increasing the range of BLE there is less retransmission required which forms a more reliable network with lower power compared to the previous version of Bluetooth technology. Decreasing the data rate would be a possible solution in case of extending the range without increasing the power consumption. Actually, range depends on surroundings, antennas, and radio performance [18].

Factors that affect Bluetooth range are the followings:

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

The development in the data exchange rate is a remarkable feature. Bluetooth 5 increases the bandwidth of data transfer to 2 Mbps from 1 Mbps [18], [19]. Future wearable devices are expected to synchronize with twice the current speed. Bluetooth 5 corroborates the packet extension feature of Bluetooth 4.2. The data is transmitted more rapidly, though the distance between the packets has not been declined. Bluetooth 5 uses 2 Mbps mode to double the data throughput compared to Bluetooth 4.2. It also reduces the time needed for transmitting and receiving data. According to calculations in an official blog on the Bluetooth website, Bluetooth 5 is approximately 1.7 times faster in comparison to BLE 4.2 because of unchanged time intervals between packets and so on [20]. The new high-speed mode permits data transfers up to 2 Mbps, twice the speed of Bluetooth 4.2, and five times the speed of Bluetooth 4.0 [20].

Bluetooth beacons are hardware transmitters – a group of Bluetooth LE devices, which broadcast their identifier to nearby portable electronic devices [21]. BLE transmits less data over a shorter range, which considerably reduces energy consumption. At regular intervals, BLE beacons transfer less amounts of data. Compared to the earlier versions of the Bluetooth standard, Bluetooth 5 will showcase an 800 % [22] increase in the capacity of data broadcasting. As a result, it is expected that the data being transferred will be richer, reliable, and more secure. Bluetooth 5 also improves the ability of transferring special data packets, named advertising packets. The Bluetooth 4.x beacon has ability sending 31 bytes messages. The message is small in size. Therefore, 31 bytes are not sufficient when it is essential to introduce more substantial information, such as uniform resource locator (URL) or telemetry data. Bluetooth 5 can resolve this problem by expanding the size of the messages from 31 bytes to 255 bytes [23]. Bluetooth 5 can consume approximately two times less power in comparison to the earlier version of Bluetooth technology. Usually, when a wired device doubles the speed, energy consumption becomes doubled. By enabling exchanging twice the amount of data, Bluetooth 5 devices consume “half power” to transmit the same data [24].

Another feature of Bluetooth 5 is the support of mesh networking that was already introduced in November 2015. With this feature, BLE 5 would become a stronger candidate compared to the previous version of BLE technology for more efficient use cases: tracking and smart waste management [23]. The Bluetooth mesh specification was published with the aim of extending the range of Bluetooth networks and summing up support for more industrial purposes using BLE.

All communication within the network is message-oriented in Bluetooth Mesh, and nodes send messages to each other to control or relay information. Messages are the mechanism through which node operations are invoked. Mesh topology allows devices to interact with each other and to relay messages. With Mesh, it is possible to extend coverage and establish enormous connections. Furthermore, when its nodes fail, mesh topology can endure less damage compared to a star topology, improving network reliability.

A flooding mechanism is utilized to interact in a Bluetooth Mesh network. By default, a flooding mechanism guarantees that incoming messages are repeated by each node in the network so that they are further relayed until the target node is reached. Routing mechanisms are used in many mesh networks to relay messages across the network.

A comparison between classic Bluetooth and Bluetooth Low Energy is shown in Table 1 [12], [13], [17], [26]. From the Table 1, it is seen that the data speed of BLE 5 is higher and twice compare to Bluetooth 4.2 version, and BLE 5 supports 2 Mbps, whereas BLE 4.2 and classic Bluetooth support 1 Mbps. In fact, in the case of BLE 4.2 and BLE 5, the number of frequency channels is 40 where it is 79 in terms of classic Bluetooth. Also, the connection duration between devices with BLE 5 is reduced by 3 ms as compared to BLE 4 which is a significant improvement in the case of BLE 5. In addition, the previous version BLE 4.2 and classic Bluetooth do not support IoT devices, while BLE 5 technology supports IoT devices. Further, The Battery life of BLE 5 is longer in compassion to BLE 4 and classic Bluetooth. Moreover, BLE 5 can support Bluetooth Mesh network technology where BLE 4 and classic Bluetooth do not have this feature. The security control of BLE 5 is better to secure as compared to BLE 4 and classic Bluetooth that is also noticed from the Table 1.

Table 1. A comparison between classic Bluetooth and BLE

| **Technical specification** | **BLE 5** | **BLE 4.2** | **Classic Bluetooth** |
|---|---|---|---|
| Speed | Higher, twice compared to Bluetooth 4.2 version supports 2 Mbps | Higher compared to classic Bluetooth but lower compare to Bluetooth 5 supports 1 Mbps | 1Mbps |
| Range/distance (theoretical) | Upto 490 m with 0 dBm | Upto 230 m with 0 dBm | ~10 – 100 meters |
| Throughput | 2 Mbps gives 1.6 Mbps with overhead | 1Mbps | 0.7 Mbps |
| Frequency channels | 40 channels from 2.4 GHz to 2.48 GHz (37 data channels and 3 advertising channels) | 40 channels from 2.4 GHz to 2.48 GHz (37 data channels and 3 advertising channels) | 79 channels from 2.4 GHz to 2.483 GHz with a 1 MHz spacing |
| Latency (from a non connected state) | <3 ms | <6 ms | <100 ms |
| Robustness to operate in congested environment | More | Less | Less |
| Security control | Better compare to Bluetooth 4.2 | Less secure compare to Bluetooth 5.0 | Less secure compare to Bluetooth 4.2 and 5.0 |
| Nodes/salves | Unlimited | Unlimited | 7 |
| Network topology | Star-bus, Mesh | Star-bus, Mesh | Piconet, scatternet |
| Reliability | High | Low | Low |
| Channel access method | TDMA | TDMA | TDMA |
| Power requirement | Low | High | High |
| Message size | Large, 255 bytes | Small, 31 bytes | 358 bytes (max) |
| Battery life | Longer | Longer | Smaller |
| Peak current consumption | Less than 15 mA or 20 mA | Less than 15 mA | Less than 30 mA |
| Support for IoT devices | Yes | No | No |

Table 2 shows a summary of BLE 4.2, BLE 5, and BLE 5 (S = 2, S = 8) [17], [26]. From the Table 2, it is noticed that FEC technique is used for error correction in terms of BLE 5 long range (S = 2) and BLE 5 long-range (S = 8) where BLE 4.2 does not use FEC. The data throughput is seen as 109 Kbps in case of BLE 5 (S = 8), whereas it shows 380 Kbps when S = 2. However, it is 800 Kbps in the case of BLE 4.2. In case of BLE 5 (S = 2), the data rate is found as 500 Kbps which is four times more than that of BLE 5 (S = 8). The data rate, however, is 1 Mbps more in case of BLE 5 as compared to BLE 4.2.

Table 2. The summary of BLE 4.2, BLE 5, and BLE 5 (S = 2, S = 8)

| **Types** | **BLE 4.2** | **BLE 5** | **BLE 5 Long-range (S = 2)** | **BLE 5 Long-range (S = 8)** |
|---|---|---|---|---|
| Data rate | 1 Mbps | 2 Mbps | 500 Kbps | 125 Kbps |
| Data throughput | 800 Kbps | 1400 Kbps | 380 Kbps | 109 Kbps |
| Error correction | None | None | FEC | FEC |

## 2.2 Impact in IoT

IoT has been defined as a system of interrelated computing devices, mechanical and digital machines, objects, animals or people that are given with unique identifiers and the data transfer ability over a network where human-to-human or human-to-computer interaction is not required. It is continuously evolving and its research area with infinite opportunities is continuously expanding. The “IoT” creates a vast scope of industries and applications. It can make a new global world where it is ensured that every device in our home, workplace, and vehicle are connected with each other. A number of different companies and various research organizations have already anticipated the strong impact of BLE on the IoT during the following ten years. For instance, Cisco anticipated more than 24 billion Internet-connected devices by 2019 [26]; however, according to Morgan Stanley, there will be 75 billion networked devices by 2020 [27].

Searching out furthermore, Huawei forecasts a hundred billion IoT connections by 2025 [28]. Among these devices most of the devices are Bluetooth. According to the McKinsey Global Institute, by 2025, the financial impact of IoT on the global economy may be as much as \$3.9 to \$11.1 trillion [29]. Figure 1 shows the scenario of the IoT application in different field [30]. From the Figure 1 and above discussion, it is seen that how will BLE 5 impact the IoT technology. The use of Bluetooth 5 technology in different field (automotive, home automation, medical and health, consumer electronics, mobile phones and smartphones, sports and fitness etc.) is increasing rapidly.

Figure 1.The application of the IoT in different field.

Due to the fact, new improvements in IoT have made its scope more enormous. IoT generation blessings not one but all i.e. people, society, agencies, etc. IoT is tagging our everyday items with the help of machine-readable identity tags. Sensors can be a couple of tags to gather more information about the condition of everyday objects and those around them. IoT advanced from M2M communication that happens through machines connecting to each other via a network without human interaction. M2M communication is a system where a device is connected to the cloud and it manages by accumulating data. Taking M2M to the next level, IoT is considered as a sensor network of billions of smart devices that connect people, systems and other applications to collect and share data [31], [32]. The IoT market is thriving rapidly, and people are tracking the news on this new technology. This technology has a significant impact on the corporate sector. By applying the technology for home automation, at present, the IoT has become a household name. The recently published Bluetooth version will be not only enhanced IoT but also make it more efficient. It is projected that with the help of BLE 5 feature – extended range WiFi will be as a communication technology for most IoT applications [33].

Power consumption contributes to a significant role in the wearables sector. Moreover, this improves the efficiency of a device that results in a reduction in power consumption to half [33].

## 2.3 Functionality

This section presents the function of BLE 4 and BLE 5 and describes the main mechanisms and features of each layer. There are two types of modes of Bluetooth wireless Technology: BR and LE. The BR system involves optional alternate media access control (MAC), EDR, and PHY layer extensions. The LE system involves less current consumption, less complication, less data rates, and fewer duty cycles.

The BLE core system includes a host and one or more controllers which is shown in Figure 2 [35]. The upper layers of the BLE protocol stack are called host which runs on an application processor. Controllers are the lower layers of the BLE protocol stack, including the radio. The Host includes upper layer functionality, i.e., the logical link control and adaptation protocol (L2CAP), the attribute protocol (ATT), the security manager protocol (SMP), the generic attribute profile (GATT), and the generic access profile (GAP). PHY layer and the link layer (LL) all are included in the controller. The host controller interface (HCI) is liable for the communication between the upper layer (host) and the lower layer (controller) [34], [35].

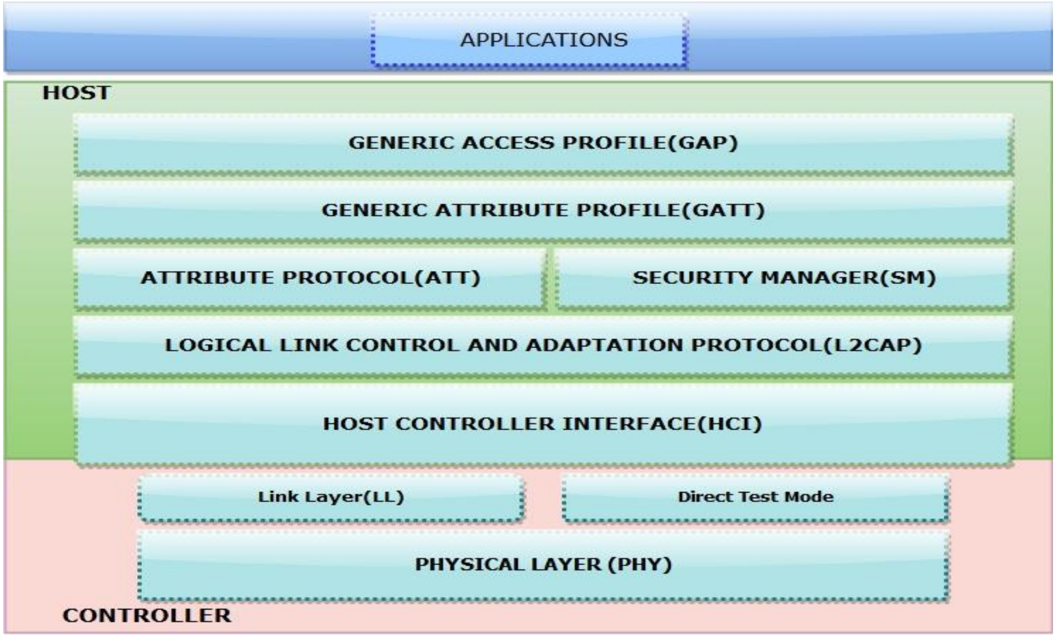


Figure 2. BLE protocol stack.

Since some of the BLE controller's features belong to the classical Bluetooth controller, both controller types are presently repugnant. Therefore, communication is not possible between the device which implements only a BLE device called a single-mode device and the device that performs only classic Bluetooth. Multiple devices are supposed to implement both BLE protocol stacks, and classic Bluetooth, known as dual-mode devices [36], [37].

The LL is a type of communication, which takes place between BLE devices by controlling the radio's link-state. LL also refers to various roles that a device can perform, i.e., slave, master, scanner, and advertiser. Generally in BLE, the LL is the portion of the stack that interfaces directly with the PHY, and it is a combination of a hardware (HW) and a software (SW) part. The state machine operations in the LL are completed through five states:

Scanning state, Initiating state, advertising state, Standby state, and Connection state. LL state machine enables the activation of only one state at a time.

The operation of state diagram of the LL state is shown in Figure 3 [35]. The LL in the Standby state that can be accessed from any other state does not transmit or receive any packets. In BLE, an advertiser is a device that transmits advertising packets. Advertising events are the transmission of packets that happens in intervals of time through the advertising channels. This interval is called the 0,625 ms advertising interval, meaning that it is a multiple of 0.625 ms. and it ranges from 20 ms to 10.24 s [38]. The advertising state can be taken entered from the Standby state. The protocol data unit (PDU) range is between 2 and 257 bytes. The cyclic redundancy check (CRC) is three Octets in size. A randomly generated 32-bit access code recognizes the packets for this type of connection.

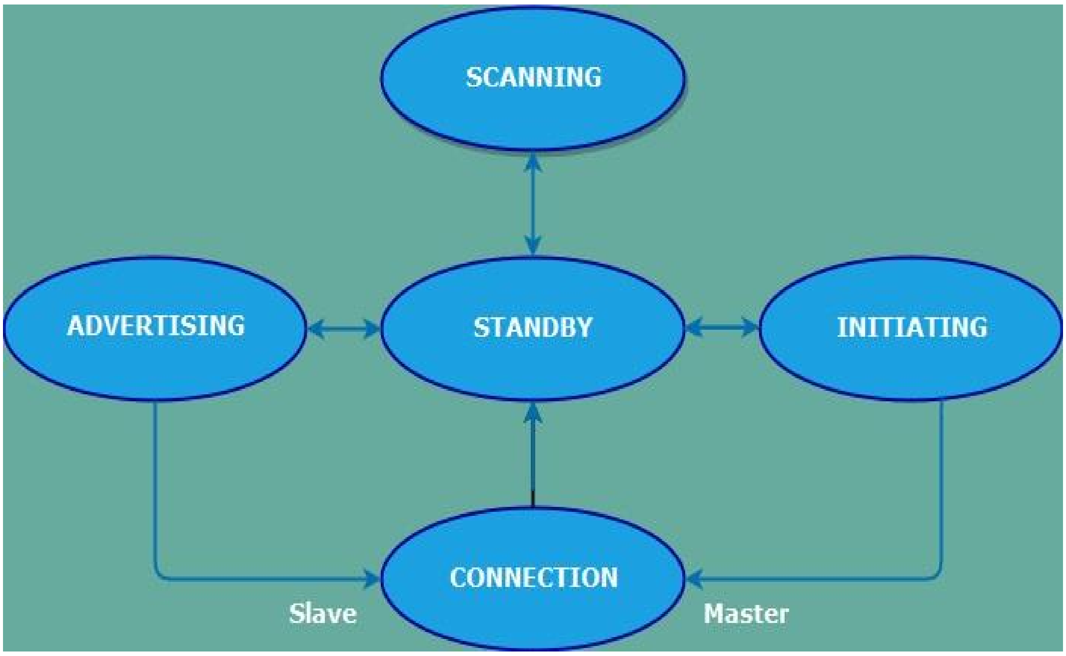


Figure 3. State diagram of the link layer state.

The connection state created between the two devices is an asymmetric process, through which the advertiser shows that it is a connectable device, while the other device, called the initiator, listens to these advertisements at a same time. Once an initiator finds an advertiser, a connection request message can be sent to an advertiser. This is the method for connecting two devices from one point to another. LL only has one type of packet for both advertising channels and data channels packet. There are four fields in each packet: preamble, access address, PDU, and CRC. The LL packet is formed with elements: preamble, access address, PDU and CRC. The size of PDU is from 2 to 257 Octets where the size of preamble, access address, and CRC is 1 Octet, 4 Octets, and 3 Octets respectively.

The master and slaves are the connected devices that serve respectively as an initiator and an advertiser. Depending on the application requirements and use-case, a BLE device serves two LL device roles for a fabricated connection. A master is connected to various slaves at the same time, whereas each slave can be linked to one master. The network constructed of a master and its slaves is known as a piconet that follows a star topology. At present, a BLE device has one piconet. By default, slaves are in the state of sleep, and wake up in a periodic order to listen for receiving master's possible packet, saving energy on the slave side. The medium access is coordinated by a master through a time division multiple access (TDMA) scheme. The slave gets information from the masters regarding the frequency hopping algorithm and for monitoring of connection. The parameters for connection management go to the connection request message. Corruption of a packet's access address field is sent via any device. Master and slave utilize a new data channel frequency for a new connection case. To compute this frequency, the frequency hopping algorithm is used.

HCI is the standard protocol for monitoring the communication between the Host and the Controller. The Host is also responsible for communication between the HW and the customer implementation. Its purpose is defining a collection of commands and events for the translation of raw data into data packets transmitting to the host layer via serial port, and vice versa [38].

The L2CAP is an optimized and simplified protocol which primary purpose is to multiply data from three higher layer protocols. L2CAP is used for communicating through the ACL host connection. The connection is formed after the ACL link has been established. L2CAP offers packets with up to 64 kilobytes in length of configurable payload in basic mode. The L2CAP collects data from the Bluetooth stack's higher layers and application layers and passes it over the stack's lower layers. L2CAP transfers packets to the link manager through HCI or to the hostless system.

The ATT illustrates the communication between two devices. ATT is a low-level layer defining how information is to be transmitted. In this case, it plays the roles of server and client respectively. The server manages a set of attributes. The role of client or server is identified by the GATT, and it is independent of the master or the slave role. A client asks for information from a server and a server transmit data to clients. A server may also transmit two forms of inappropriate messages to a user for better efficiency, including attributes: alerts that are not confirmed, and indications that allow the client sending a response. A user may also give a server command to the server for writing attribute values. Response or request, and confirmation transactions or indication are done following a scheme of stop-and-wait [39].

The GATT characterize a framework, and the exchange of characteristics. The framework uses the ATT for the discovery of services. A characteristic is known as a set of data, which covers a value and properties. The exchange of characteristics happens from one device to another. In attributes, the data that is related to services and characteristics are stored. The main role of the GATT is to set up how to interchange all profile's information and data in a BLE link. GATT describes two connection roles: client, and server. Profiles include possible applications. It specifies general behaviors for communicating with other Bluetooth devices via Bluetooth devices. Profiles are constructed based on the Bluetooth standard technology to expressly describe what types of data are transmitted by a Bluetooth device. These types of data are formed into a hierarchical structure consisting of parts known as services. A service is usually a container that conceptually groups related attributes, while characteristics are the attributes included in a service, and each of them is used to communicate a specific type of data. The server reveals its services and functionality to the user during the creation of a connection to define how the connection will be constructed. The GATT server profile's logical structure consists of server, property, characteristic, value, and descriptor which is shown in Figure 4 [40]. Characteristics involve the value of data, a descriptor which provides extra information regarding the characteristic.

The properties that are noticed in the technology are the followings:

- Broadcast: This property allows the sending of data through advertisement packets to BLE devices.

- Readable: Through this property, the user is able to read only the characteristic value.
- Writeable: Through this property, the user is able only to write a new value on the characteristic.
- Notifiable: With this property, the client is notified when the server updates the feature to read the new value.

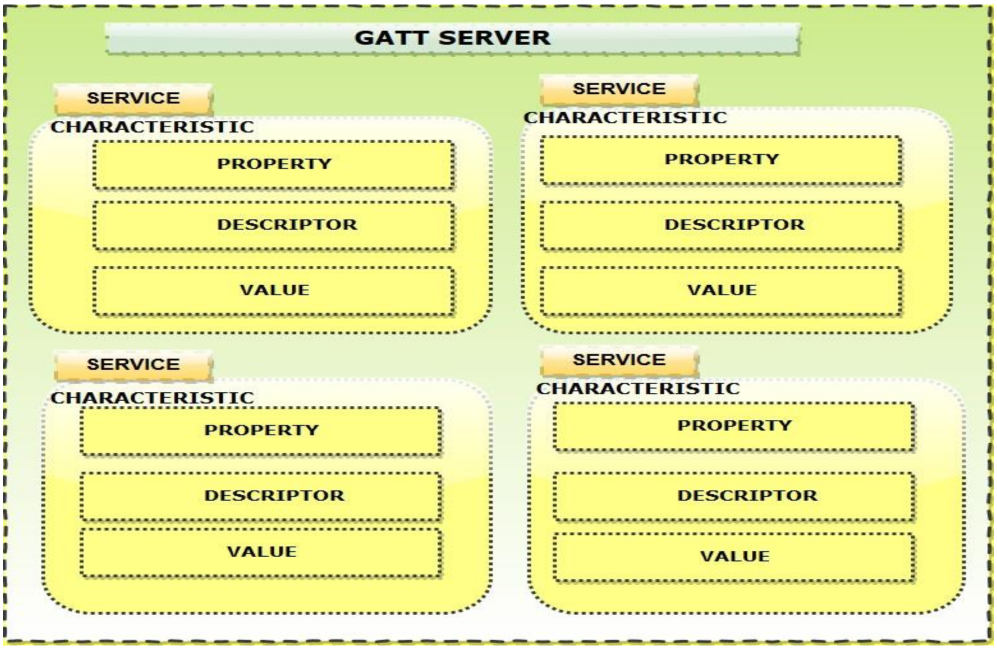


Figure 4. The logical structure of the GATT server profile.

The GAP layer of the BLE protocol stack is accountable for connection functionality. This indicates devices mode, role, and strategies for the discovery of devices and services, the management of connection formation, and security. The BLE GAP plays four functions with individual needs on the controller: Broadcaster, Peripheral, Observer, and Central. When a device plays the role of a broadcaster, it solely transmits data via the advertising channels and is not able to support connections with various devices. The Observer is the Broadcaster's counterpart, which is responsible for receiving the transmitted data from the Broadcaster. The central role is designed for a device, which manages multiple connections and is responsible for initiation, whereas the Peripheral function is designed for a reliable device that uses a single connection to a device in the central role. A device might allow numerous functions; however, at a given time only one function can be performed. An application profile is called a high-level profile that determines how applications can interact.

## 2.4 Network topology

A piconet is an ad hoc network that uses Bluetooth technology protocols to connect a wireless user group of devices. A scatternet is a kind of network, which consists of two or more Bluetooth-enabled devices, like home appliances, and smartphones. The scatternet is a group of piconets where there are connections between various piconets [41]. BLE Mesh is a mesh networking standard that works on the principle of flood network. It is based on the messages relaying nodes. BLE mesh networking allows communication among many devices and is optimized to create large-scale device networks. It is ideal for building automation, sensor network, asset monitoring, and other IoT solutions that needs tens, hundreds, or thousands of devices to interact with each other. Different network topologies are shown in Figure 5 [41].

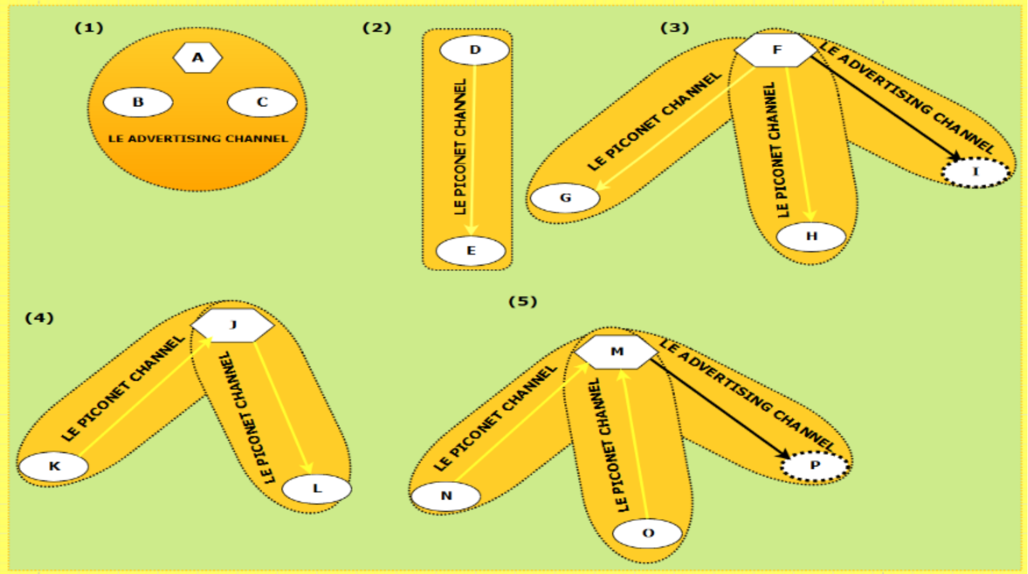


Figure 5. Example of BLE topology.

In the above Figure 5, solid arrows point from master to slave; dashed arrows indicate a connection initiation and point from initiator to responder. Each device is illustrated with a capital letter; devices that are connected are represented by a circle, whereas devices that are advertising are illustrated using ellipses. A simple broadcasting topology is shown in Group (1) in Figure 5, where A acts as an advertiser, while B and C are known as scanners, utilizing a BLE physical channel for advertising. Group (2) is a simple piconet with a single physical channel in which D functions as a master and E as a slave. In group (3), F plays a role of a master, utilizing two physical piconet channels with slaves G, and H. Device F also acts as the connection initiator with device I, and is an advertisement with connectable advertising packets on the physical advertising channel. The device F can begin the communication and include slave I to its piconet. A network topology such as this one is called a star network, with only one master, and several slaves. In scatternet (4), device J uses one LE physical channel with K, and another one with L. Here, in the piconet, J acts as a master and slave with L and K. In scatternet (5), M acts as a slave of two physical channels, where N and O are the masters. Using a connectable advertising event on the advertising physical channel, device P is advertising. And the device M acts as the initiator; when the connection is constructed, M will result in being the master of this link [42]. There are two key modalities such as broadcasting and connections, which are used to perform communication in the BLE device [39]. Through the broadcasting process, data can be transmitted quickly to more than one customer at the same time, though it is inappropriate for sensitive data due to a lack of security controls or privacy. The purpose of broadcasting packets are two: the primary one is sending advertising packets to application that do not have to be fully active. And, the other is to identify slaves when a master transmits advertising packets (which are connectable). A connection between two devices is a continuous, periodic packet exchange of data. The connection is confidential, which with security protections can be secured [39].

## 2.5 Physical layer

The physical layer known as PHY is the lowest layer of the BLE protocol stack, which includes the analog communications circuitry accountable for translation of digital symbols over the air. The summary of BLE frequency channels is shown in Figure 6 [43]. It has 40 channels of radio frequency (RF) with a channel spacing of 2 MHz. There are two different kinds of BLE RF channels, such as advertising and data channels. Advertising channels can be utilized to discover the device, establish a connection and broadcasting transmission, where data channels are used to communicate directionally between the connected devices. Three channels (37, 38, and 39) are allocated to advertise packets, whereas the rest of the 37 channels can be used to exchange data packets in connections. The x-axis indicates that how channels are placed in the frequency band. The first channel, 37, is at a frequency of 2402 MHz, whereas the last channel, 39, is centered at 2480 MHz. The center frequency of these channels is (2402+k × 2) MHz, where k= 0,…, 39 [43]. The mandatory working requirement of PHY is 1 Mbps (LE 1M PHY) [43]; in this case, uncoded transmission happens when each bit is sent corresponds to a single symbol. The LE Coded PHY can be operated with two different data rates: LE coded S = 2 mode, and LE coded S = 8 mode. Each bit is defined by two symbols in LE coded S = 2 mode. The data rate is therefore 500 kbps. The range is approximately twice in this mode compared to the LE 1 M PHY. Conversely, in LE coded S = 8, S = 8 means that eight symbols code include one bit. This provides 125 kbps data rate. The range is nearly fourfold in this mode compared to the LE 1 MPHY. The optional data rate for radio is 2 Mbps, though only with uncoded data is used in this situation. BLE PHY also specifies the radio transmission power limits, from a minimum of -20 dBm (0.01 mW) to a maximum of + 10 dBm (10 mW), respectively [38], [44], [45]. In BLE, the sensitivity of the receiver is usually considered to be the signal level of the receiver to get a bit error rate (BER) of $10^{-3}$. The sensitivity requirements of BLE specification is either higher than or equivalent to -70 dBm. The coverage distance is usually over several tens of meters.

Gaussian frequency shift keying (GFSK) modulation is a simple implementation that is used in case of all physical channels. The range of the modulation index is from 0.45 to 0.55, allowing decrease peak power consumption.

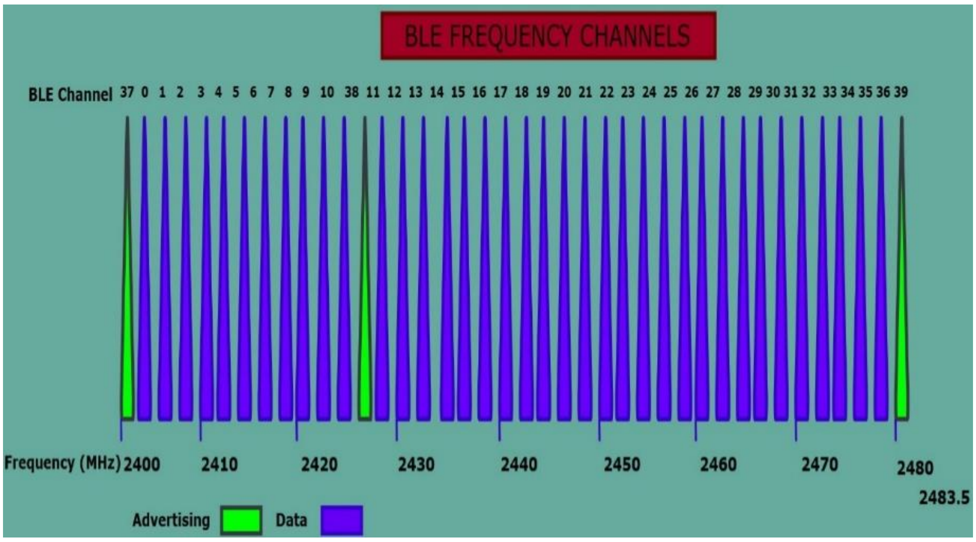


Figure 6. BLE frequency channels.

A summary of BLE 5 PHYs is shown in Table 3 [17]. From the Table 3, it is noticed that the range is twice compared to the LE 1M PHY when LE coded S = 2 and the maximum throughput is 382 kbps. However, when LE coded S = 8, the range shows quadruple compared to the LE 1 M PHY. In this case, the maximum throughput is 112 kbps. When LE 2 M PHY, the maximum throughput is observed 1438 kbps. The PDU length is 0 - 257 that is same for all PHY.

Table 3. The summary of BLE 5 PHYs

| **PHY** | **Error control** | **PDU length** | **Range multiplier** | **Packet duration** | **Max throughput** |
|---|---|---|---|---|---|
| 1M | CRC | 0-257 | 1 x | 80 µs -2.12 ms | 800 kbps |
| 2M | CRC | 0-257 | 0.8 x | 44 µs -1.064 ms | 1438kbps |
| coded S=2 | CRC & FEC | 0-257 | 2 x | 462 µs-4.542 ms | 382 kbps |
| coded S=8 | CRC & FEC | 0-257 | 4 x | 720 µs-17.04 ms | 112 kbps |

### *2.5.1 Advertising*

In Bluetooth 4.0, basically, the whole advertising process was taken place on only three channels. This mechanism is improved using Bluetooth 5 technology by permitting a small header packet sent on the three channels that are used for primary advertising to point to a bigger payload sent at a later time on one among the remaining thirty-seven data channels. It says that there is no need to copy the data payload on all three advertising channels while permitting significantly a lot of advertising data within the area before running into coexistence problems. In order to broadcast data devices use advertisements and also it is used for information for other observer devices to discover and process. For discovering without a connection between the observers and broadcaster, advertisements give permission to the device to broadcast this information for many devices. There is also an additional mode called Periodic Advertisement that allows a scanner or observer to be synchronized with the advertisements sent in a continuous manner by the broadcaster [46]. There are two major categories of advertisements in BLE technology which are Legacy advertisement and Extended advertisements. Legacy advertisement is existed in the earlier versions of Bluetooth Low Energy 4.0, 4.1, 4.2 and also used in BLE 5.0. Extended advertisements have been introduced in recently published BLE 5. For transmitting more data than the legacy advertisements, these are used. They can also be utilized for initiating Periodic advertisements.

Periodic advertisements is another feature of Bluetooth 5. Extended advertisements are used for broadcasting packets to devices at a set period between two unconnected devices which means that more than one device can listen and tune in on these periodic advertisements.

### 2.5.2 *Packet format for uncoded PHYs*

The general packets comprise of a Preamble, Access address, variable length PDU, and a CRC. This packet format is defined for uncoded PHYs which is used for both data channel and advertising channel packets. The preamble is 1 octet when the LE1 M PHY is transmitted or received and 2 octets when the LE 2 M PHY is transmitted or received. Here, the access address and CRC are 4 octets and 3 octets respectively. The PDU range is in between 2 and 257 bytes. Firstly, the preamble is transmitted then it is followed by access address, PDU and CRC. All packets are sent at the same symbol rate (modulation of either 1 Msym/s or 2 Msym/s). The receiver uses the preamble to conduct symbol timing estimation, frequency synchronization, and automatic gain control training. The preamble consists of an alternating sequence of 0 and 1 for the uncoded LE 1 M and 2 M PHYs, where the first bit is similar as the access address LSB. The value of the access address (AA) is set during advertising in the Sync Info field or is set to 0x8E89BED6 [12]. Each LL connection between two devices and individual periodic advertisement has a different access address. Access address is followed by the PDU. The PDU will be the advertising channel PDU if the packet is either the secondary advertising channel or primary advertising channel. If the packet is sent on a data physical channel, the PDU will be a data channel PDU. There is a 3 octets (24 bit) CRC at the end of each packet which is calculated over the PDU [12]. The LL packet format for LE uncoded PHYs is shown in Figure 7 [12].

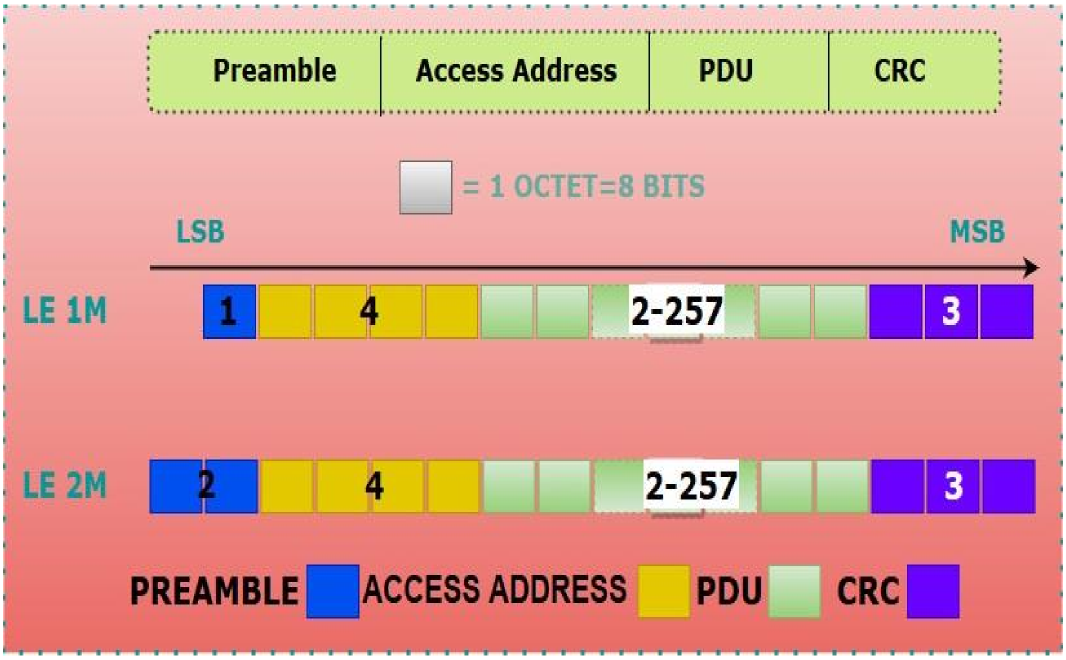


Figure 7. Link layer packet format for LE uncoded PHYs.

### 2.5.3 *Packet format for coded PHYs*

Each packet includes an uncoded preamble, FEC Block 1 and FEC Block 2. LE 1M packets in Bluetooth 5 and Bluetooth 4 packets utilise an 8-bit preamble of alternating 0 s and 1s. But, LE 2 M utilises a 16-bit preamble that takes the same amount of time to reach because the symbol rate is increased. However, LE Coded utilizes an 80 bit preamble composed of ten repetitions of the 8 bit pattern ' 00111100 '. The rest of the packet is split into FEC Block 1 and FEC Block 2. To get maximum redundancy, FEC Block 1 is coded with S = 8, and contains the coding indicator (CI), which is utilised to code FEC Block 2 (i.e., S = 2 or S = 8). Each block finishes with a TERM value that is a bit of a 000 pattern. The TERM value will reset the FEC encoder during bit stream processing [12]. The second FEC block includes the packet's remainder, containing the PDU itself and the CRC. The duration of coded packets is shown in Figure 8 [12]. Here, the preamble, access address and CRC consist of 10 octets, 4 octets and 3 octets, respectively.

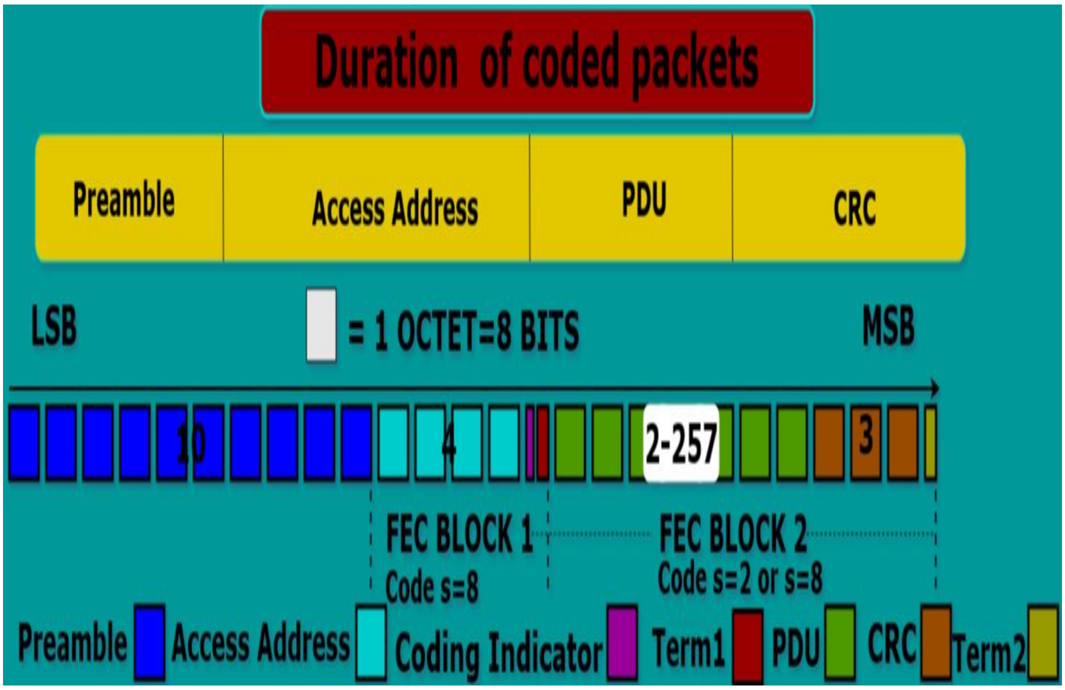


Figure 8. Duration of coded packets.

## 2.6 Bit stream processing

Bluetooth devices use the processing schemes for bit streams as described in the Sections below. The bit stream processing for PDUs on the LE uncoded PHYs and LE coded PHYs are shown in Figure 9 [12] and Figure 10 [12] respectively. Depending on the PHY utilized data accepts one path out of two paths. Here, the data with advanced encryption standard (AES) – counter with CBC MAC are encrypted by both paths. Here, CBC-MAC represents the initialism for Cipher block chaining message authentication code. At the end of the encryption process, data is sent through a process called CRC algorithm, and then a data whitening algorithm for preventing long strings of 0's and 1's. Data whitening algorithm is described in details in Section 2.6.2. CRC generation and data whitening are common steps. In case of LE coded, data is then sent through an encoder called FEC and a pattern mapper. After completing decoding and dewhitening process, CRC checking processed is done. Then, data is broadcast through the air.

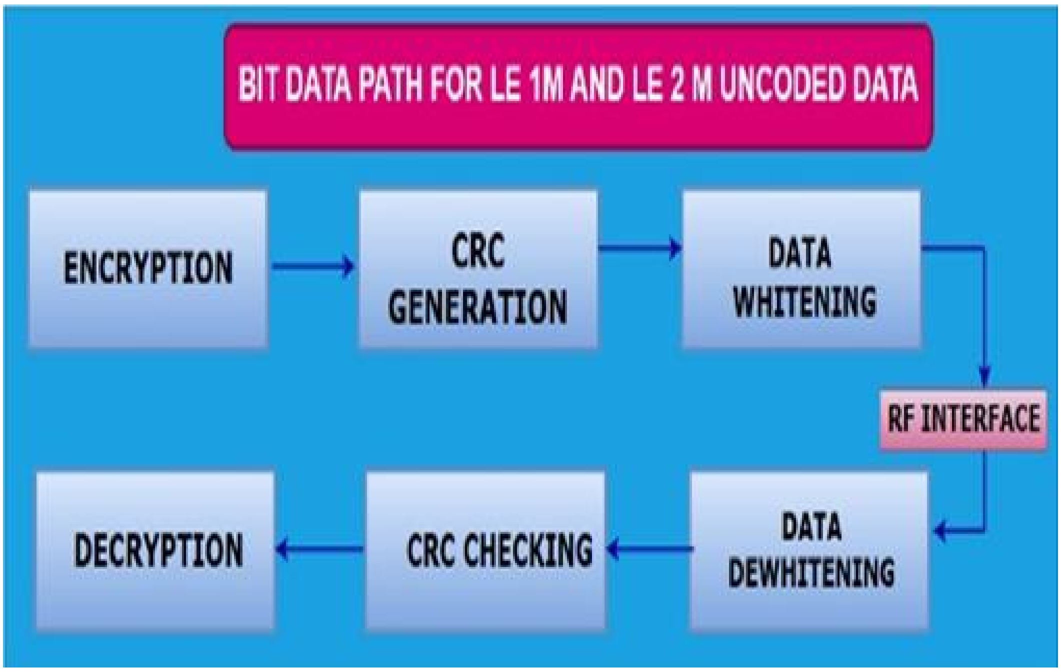


Figure 9. Bit data path for LE 1M and LE 2M uncoded data.

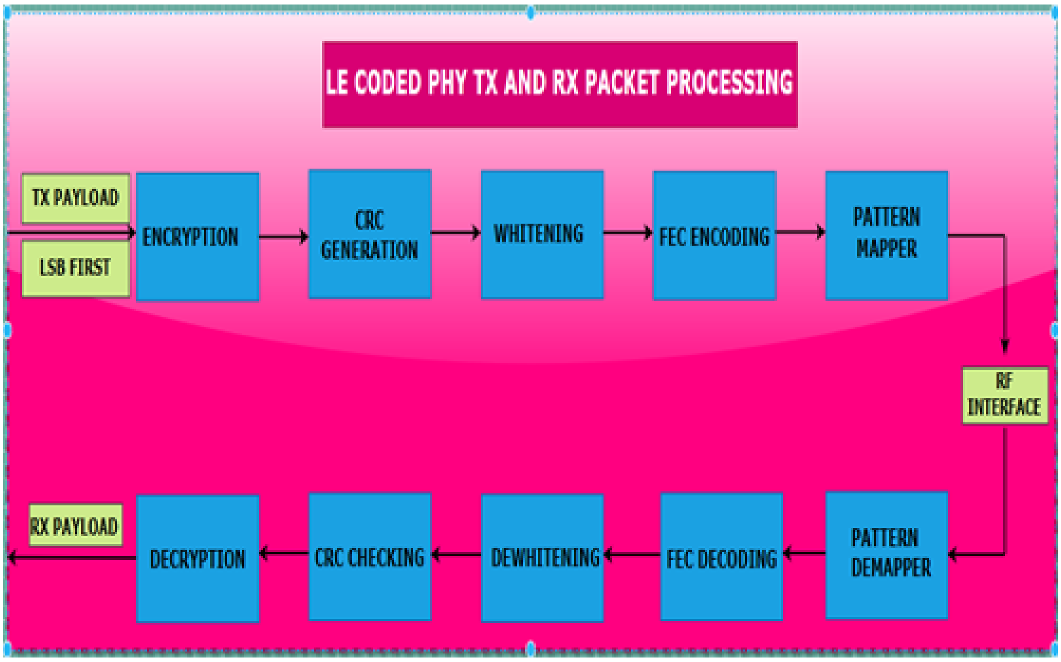


Figure 10. LE coded PHY TX and RX packet processing.

### *2.6.1 Cyclic redundancy check*

A CRC is an error-detecting code commonly utilized in digital networks and storage devices to detect accidental changes to raw data. The sensitivity of the BLE receiver can be improved by up to 3 dB by enabling CRC error correction [47], [48].

The CRC is executed at the PDU field in all link layer packets. It is calculated after encryption, and the calculation is usually done at this condition when the PDU is encrypted. All packets have a CRC value of 24-bit, which is computed by the transmitter, and added to the packet. The receiver computes again the value of CRC, and make a comparison of the computed value with the value that is added to the packet. In the event that they are not similar, an error has happened. When errors are found, systems can respond in one or two other ways. They may consider the error as damning, and discard the communication, or they may request or hint that the transmitter ought to transmit the data once more so that the next endeavor will be successful. After receiving a packet, the Access Address is checked followed by the CRC. If either is not correct, the packet is refused, and it stops processing. When a CRC check has become unsuccessful, Bluetooth, both version 4 and 5, triggers the transmitter for retransmitting data. Inability to get an acknowledgment, makes the transmitter send the data once more [49].

### *2.6.2 Data whitening*

Data whitening is a technique that is used to reduce direct current (DC) bias in data packets. This can be achieved by introducing randomness in additional, data patterns utilizing a data whitening word. Data whitening is applied to packet payload and packet header only and is carried out just before FEC encoding. At the receiving end, payload and packet header after FEC decoding is processed with similar data whitening word to get back original data. The method called De-whitening is carried out before the CRC in the receiver. The whitener and de-whitener each utilize a 7-bit linear feedback shift register (LFSR) with taps at bit 4 and bit 7 [48], [47].

For doing the whitening and "dewhitening" operations, a setting like PKTCTRL0. WHITE_DATA=1 is needed, and it is done in the transmitter and receiver. It whitens all data. However, it cannot whiten the preamble and sync word in the transmitted packet. Before transmitted the data, performance can be developed by whitening [50], [51].

### *2.6.3 FEC and pattern mapper*

Bluetooth 5 utilizes a strong error correction system known as FEC. FEC is also called as Hamming codes, invented by Richard Hamming in the 1950s [52]. FEC (channel coding) is a technique that is used to control data transmission errors through unstable or noisy channels of communication [52], [53].

The core idea is that the sender uses an error-correction code (ECC) to encode message in a redundant way. FEC makes up a word by replacing a single digit '1' or '0' with multiple digits [48], [52], [55], [57], [58]. There are several types of schemes that permits a receiver for detecting errors. Among them, BLE 5 usually utilizes a type of checksum called a CRC. CRC algorithm was described in details in Section 2.6.1. Errors can be detected and corrected at the receiver. The receiver therefore does not need the data to be transmitted again.

Bluetooth 5 presents an error correction capability where the version 4 of Bluetooth low energy is able to detection only error and it cannot correct an error. Advanced error correction techniques can play a vital role in case of correcting errors and it is possible to decode correctly at the lower SNR and also at a larger range from the transmitter.

There is a change in the bit stream processing for Tx and Rx operations. The LE Coded PHYs is responsible for adding two steps into the packet transmissions and reception. Firstly, FEC method is applied to the packet to allow the receiver to correct bit errors when the packet is received, and would be capable to improve the packet error rate. Secondly, a pattern mapper method is applied to the packet. This FEC and pattern mapping results in getting better sensitivity [53].

The FEC encoding utilizes a convolutional encoder. And it uses the following generator polynomials to produces 2 bits for every input data bit [51], [54]

$$\mathrm{G_0(X) = 1 + X + X^3} \tag{1}$$

$$\mathrm{G_1(X) = 1 + X + X^2 + X^3} \tag{2}$$

First, the bit from the generator polynomial $\mathrm{G_0\ (a_0)}$ is sent, and the bit from the generator polynomial $\mathrm{G_1\ (a_1)}$ is sent later. The initial state is set to all 0 for the convolution FEC encoder. The FEC encoder is always returns to its original state with an input sequence of three consecutive 0. This types of sequence is called as the termination sequence. The FEC block converts each input bit to two output bits by convolutional error correction encoder that is shown in Figure 11 [12], where, the square describes the operations for storing bits, while the circles illustrates the addition of binary mod 2. Here, the number of bits transmitted is duplicated by applying FEC to the packet. After getting the bit from the convolutional FEC encoder are converted into P symbols in the pattern mapper, where the value of P depends on the selected coding scheme. Usually, a FEC encoder encode the data, and then the data goes to a pattern mapper [53].

Pattern mapper output option is shown in Table 4. Pattern Mapper output optionsFrom the Table 4Table 4, it is observed that there are two pattern mapper options: P = 1 and P = 4. Pattern mapper P = 1 is used by S = 2 and pattern mapper P = 4 is used by S = 8. The P = 1 mapper generates an output bit that is similar to the input bit. However, when the input bit is 0, the four output bits 0011 are generated by the P = 4 mapper, while the input bit is 1, it produces four output bits 1100 [53].

Table 4. Pattern Mapper output options

| **Input from FEC Encoder** | **Output S = 2** | **Output S = 8** |
|---|---|---|
| 0 | 0 | 0011 |
| 1 | 1 | 1100 |

A convolutional encoder is formed of a fixed number of shift registers. A shift register is entered by an input bit, and the output of the encoder is obtained by combining the bits in the shift register. These codes are frequently applied in concatenation with a hard-decision code, especially Reed-Solomon [55]. Usually, convolution coding is known as a bit-level encoding system. Convolutional codes are utilized in such an application that needs excellent performance with less implementation cost.

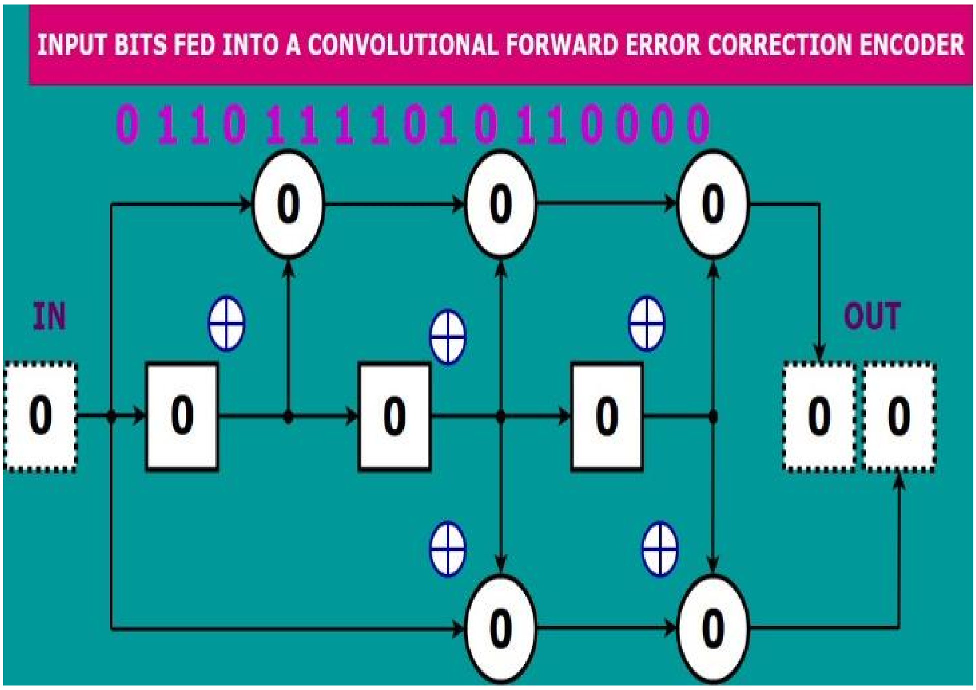


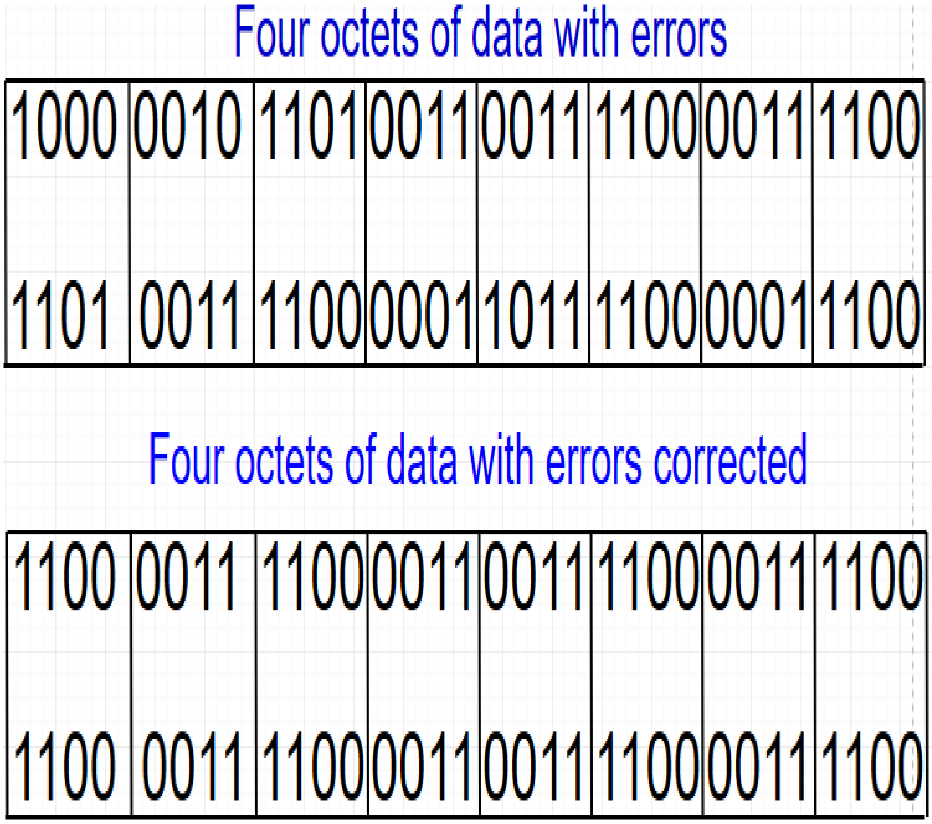
Figure 11. Input bits fed into a convolutional FEC encoder.

The encoder has $n$ modulo – 2 adders and $n$ generator polynomials. The number of output bits relies on the number of modulo 2 – adders utilized with the shift registers. Usually, data is shifted to a non-systematic, non-recursive, 1/2 rate, FEC encoder that has constraint length $k = 4$. Each input bit produces two output bits. For creating output bits, it is repetitively added the input bit and bits earlier is stored in the register with the XOR operator. The encoder is three consecutive zeros in initial state and termination sequence [55]. The data that is fed to the FEC "01101111010110000" produces "0011010111101001101101001001 00". The extra data permits a decoding algorithm for correcting a single incorrect bit, and for detecting two consecutive incorrect bits [55].

### *2.6.4 Data reception*

The operation of FEC decoding is the opposite of the operation of FEC encoding. The process of FEC decoding addresses the linear formula used to recover the lost source packets. Each FEC packet can be used in the range covered by that FEC packet to recover only one origin Packet.

When bits arrive at the receiver, external electromagnetic energy in the receiver's vicinity can trigger bits to be detected incorrectly. For the LE 1 M Coded PHY, the additional bits produced by the pattern encoder and extra data produced by the FEC encoder permits multiple bit errors to be corrected by the decoding algorithm, but the rise in the number of symbols reduces the entire throughput. Since the pattern map (0 = 0011 and 1 = 1100) is known, it is possible to immediately correct a number of incorrect bits [55]. The scenario of four octets of data with errors and corrected errors is shown in Figure 12 [55].



Four octets of data with errors

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1000 | 0010 | 1101 | 0011 | 0011 | 1100 | 0011 | 1100 |
| 1101 | 0011 | 1100 | 0001 | 1011 | 1100 | 0001 | 1100 |

Four octets of data with errors corrected

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1100 | 0011 | 1100 | 0011 | 0011 | 1100 | 0011 | 1100 |
| 1100 | 0011 | 1100 | 0011 | 0011 | 1100 | 0011 | 1100 |

Figure 12. Four octets of data with errors and with errors corrected.

The additional information encoded by the FEC encoder can be used to detect and correct those incorrectly decoded bits, even when the pattern decoder is not able to correct the bits. The shift registers ' internal state is changed by individual bits that are pushed into the FEC encoder. Each current state of the shift register can change to just one (not a whole eight) of two other states [55].

Every circle below indicates the values contained in one shift register state and the path to the next permissible states. The next allowed state is decided by new input bits (0 or 1) moving from left. The state diagram of decoded bits from encoded bits is shown in Figure 13 [55].

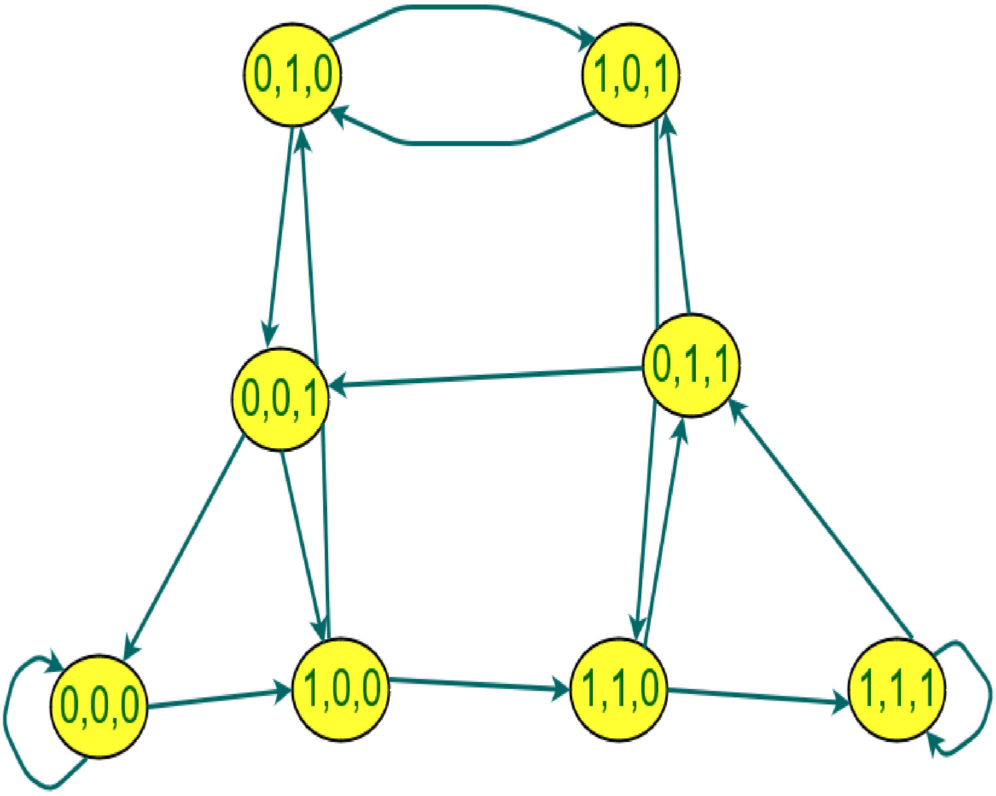


Figure 13. State diagram of decoded bits from encoded bits.

By knowing the output bits and the shift register's permitted state path, the decoder can estimate the shift register's current and past state and then utilise that information to determine the actual input bits.

### *2.6.5 Coding gain*

Coding gain is the measure in coding theory of the difference between the uncoded system SNR, and the coded system SNR to meet the same BER levels when using the error correction code [56]. The asymptotic coding gain for a binary-input additive white Gaussian noise (AWGN) channel is given as [12]

$$\mathrm{G_a} = 10log_{10}(d_{free}r)\ \mathrm{dB}, \tag{3}$$

where $d_{free}$ is the error correction code's free distance, and $r$ is the code rate of a convolutional code. The LE coded PHY with S = 8 is taken into account in this case. The value of $d_{free}$, and $r$ is 6, and 0.5, respectively. The asymptotic coding gain of this code is 4.8 dB, though the achievable gain for binary modulation formats is comparatively less (maybe 2 – 3 dB). The receiver sensitivity in dBm for a provided PHY is given in the Table 5 [12], where the sensitivity of LE uncoded PHY is ≤ – 70. However, the sensitivity of LE coded PHY with S = 2, and S = 8 is ≤ – 75, and ≤ – 82. From the Table 5, it is observed that the sensitivity of LE uncoded PHY is 2 dB less than in the LE coded PHY (S = 2). In BLE 5 coded mode, 4.8 dB gain is from the convolutional code. Additional coding gain is enabled by using the pattern mapper with P=4 while in S=2 mode pattern mapper uses P=2.

Table 5. Sensitivity of receiver for a provided PHY

| **PHY** | **Sensitivity (dBm)** | **Coding gain** |
|---|---|---|
| LE uncoded PHY | ≤ – 70 | |
| LE coded PHY with S = 2 | ≤ – 75 | 5 dB |
| LE coded PHY with S = 8 | ≤ – 82 | 7 dB |

# 3 ANALYTICAL MODEL

An analytical energy consumption model for both BLE 4 and BLE 5 is proposed here to calculate the PER, and SER of BLE at different distances.

For LOS scenarios the path loss equation is usually defined as [59]

$$PL(\mathrm{d}) = PL_0 + 10nlog_{10}\left(\frac{d}{d_{h0}}\right), \tag{4}$$

where the path loss exponent is defined by $n$, $d_{h0}$ is the reference distance of the $PL_0$ reference path loss, and $d$ is the distance.

The reference path loss [60] can be calculated as

$$PL_0 = 20log_{10}\left(\frac{4\pi d_{h0}}{\lambda}\right). \tag{5}$$

The wavelength, λ [61] is

$$\lambda = \left(\frac{C}{f}\right), \tag{6}$$

where $C$ is the speed of light and $f$ is the communication frequency.

The SER (uncoded mode) for non-coherent demodulation, can be calculated as [61], [62], [63]

$$SER = \frac{1}{2}e^{-E_s/2N_0}, \tag{7}$$

where $E_s$ is defined as the energy per symbol, and $N_0$ is the noise power spectral density per hertz.

The noise power spectral density can be calculated as [64], [65], [66]

$$N_0 = KT, \tag{8}$$

where $K$ is the Boltzmann's constant, and $T$ is the receiver system noise temperature.

The energy per symbol, $E_s$ is

$$E_s = t_b \times P_{rx}, \tag{9}$$

where $t_b$ is the transmit bit duration, and $P_{rx}$ is received signal power.

The received power per symbol, $P_{rx}$ is [67], [68]

$$P_{rx} = P_{tx} - PL(d), \tag{10}$$

where $PL(d)$ is the pathloss as a function of distance, and $P_{tx}$ is the transmit power.

$PL(d)$ can be found from Equation (4).

Signal-to-noise ratio (SNR) can be calculated as

$$SNR = \frac{P_{rx}}{N_o}, \tag{11}$$

where $P_{rx}$ is the received signal power. $P_{rx}$ can be calculated using Equation (10) and $N_o$ can be found from Equation (8). In case of BLE 5 mode, coding gain is added to SNR calculated using Equation (11). The value of coding gain is 12 dB [12] as discussed in Section 2.6.5. Using this SNR value in Equation (7), SER for coded mode can be calculated, and from the Equation (12), PER for coded mode can be calculated.

The PER for the affected BLE link can be computed as [59]

$$PER = 1 - (1 - \alpha)^x, \tag{12}$$

where the length of the packet of the desired signal is $x$ is and the SER is denoted by $\alpha$. SER can be calculated Equation (7).

Total energy consumption for uncoded mode and coded mode can be written as

$$E_u(d) = E_{T_u}(d) + E_{R_u}(d), \tag{13}$$

$$E_c(d) = E_{T_c}(d) + E_{R_c}(d), \tag{14}$$

where $E_u$ and $E_c$ are the total energy of uncoded mode and coded mode, $E_{T_u}$ and $E_{T_c}$are the transmitted energy consumption of encoded mode and coded mode, $E_{R_u}$and $E_{R_c}$ are the received energy consumption of encoded mode and coded mode.

Energy consumption model for uncoded mode, and coded mode can be written as

$$E_{Tu} = P_T t_b N_{tx}(d), \tag{15}$$

$$E_{Ru} = P_R t_b \, N_{tx}(d), \tag{16}$$

where $E_{Tu}$ is the transmission energy consumption, and $E_R$ is the received energy, $P_T$ and $P_R$ are the power consumption of transmitter, and receiver, $t_b$ is the transmit bit time, and $N_{tx}(d)$ is the number of required transmission for success in different distance.

The expected number of transmission can be calculated as

$$N_{tx}(d) = \frac{1}{(1 - PER)}, \tag{17}$$

where PER can be calculated using Equation (12).

Energy consumption can be calculated as

$$E_{cdp} = E_{Tu} + E_{Ru}, \tag{18}$$

where $E_{cdp}$ is the measured energy consumption in different distance, which is based on analytical model.

Energy consumption per number of information bits can be calculated as

$$E_{cd} = \frac{E_{cdp}}{B_n}, \tag{19}$$

where $B_n$ is the number of information bits.

# 4 EXPERIMENTAL PERFORMANCE EVALUATION

In this chapter, the details of the hardware and software used in this thesis measurements will be described. The procedure of the measurement setup and the scenario of outdoor measurement will also be explained here.

## 4.1 Hardware and software

In this experimental work, the nRF52840 – one of the first BLE 5 chipsets [69] introduced by Nordic Semiconductor have been utilized. The nRF52840 is a system on chip (SoC) that integrates a 2.4 GHz multiprotocol transceiver.

In the experiments two nRF52840 Preview DK development kits were used that are shown in Figure 14 [69], [70] and the hardware platform layout and important components are shown in Figure 15 [69]. These two boards are built with a BLE 5 protocol stack and a 32-bit, 64 MHz ARM cortex – M4F based microcontroller CPU with 1 Mb flash and 256 kb RAM on chip. The nRF52840 SoC with features of the comprehensive system of adaptive and automated power management is the ideal solutions for the homes that are smartly connected.

The nRF52840 DK board PCA10056 can be utilized as a developed platform for the nRF52840 SoC. It also has features of on-board programming and debugging solution. Moreover, for radio communication, the nRF52840 SoC has the ability for communicating with a computer through a virtual COM port and USB. Furthermore, the kit has access to all I/O (48) and interfaces via connectors, and for direct RF test measurements, the integrated printed colour board (PCB) trace antenna and radio frequency (RF) connectors are used [69]. The nRF52840 DK includes hardware, access to software components, reference design files, and documentation. It also includes a near field communication (NFC) antenna and the developed kit board PCA10056.

In the experimental work, among the used two boards one was selected as an advertiser and other was selected as a scanner. In the boards controls buttons are available to select BLE physical layer as LE 1M, LE2M or LE coded. For example, mode 3 and mode 1 button support BLE 5 coded and BLE 4 respectively. In this case, programming was done so that the mode buttons work for both BLE 4 and BLE 5 version. At 0 dBm, the current of transmitter (Tx) and receiver (Rx) is 4.8 mA peak and 4.6 mA. The voltage supply range is from + 1.7 V to 5.5 V The nRF52840 has a wide range of operating temperature from − 40°C to 85°C and the maximum RF input level is 10 dBm [69], [70].

The nRF52840 developed kit are used in the followings ares: industrial IoT sensors and controllers, connected home sensors and controllers, connected health, advanced personal fitness devices, advanced remote controls, virtual or augmented reality applications, gaming controllers and so forth. It also gives access to all I/O and interfaces via edge connectors, and has buttons and four user-programmable LEDs. To enable NFC tag functionality, designers can connect an NFC antenna.

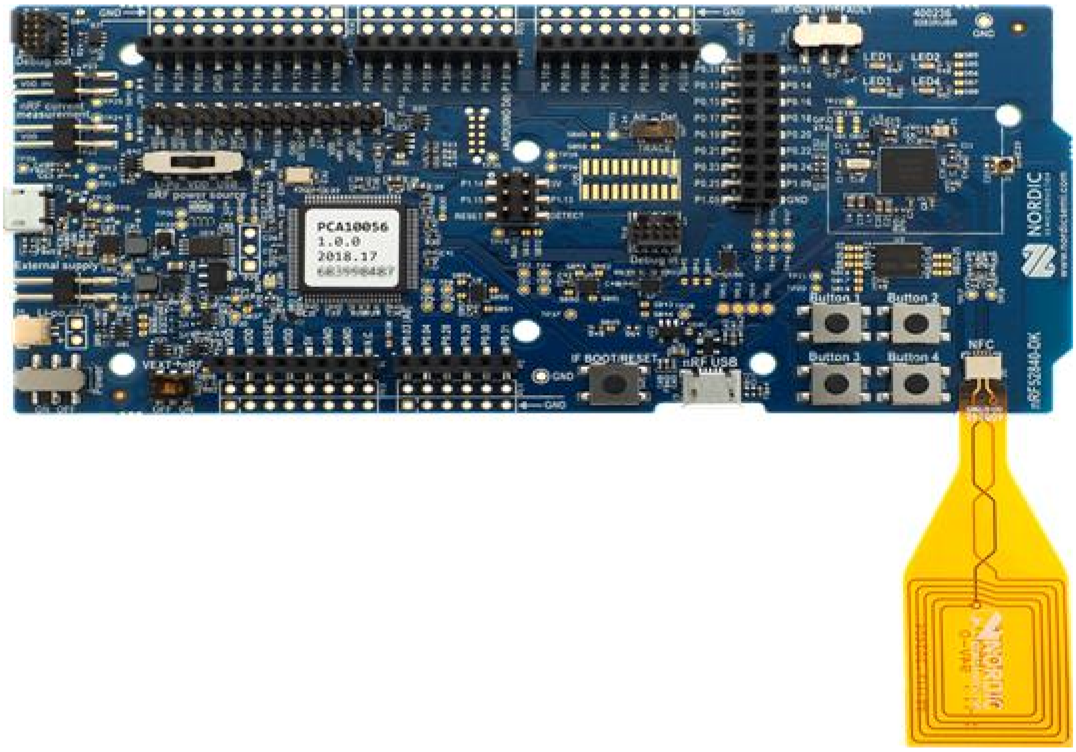


Figure 14. nRF52840 DK board (PCA10056) and NFC antenna.

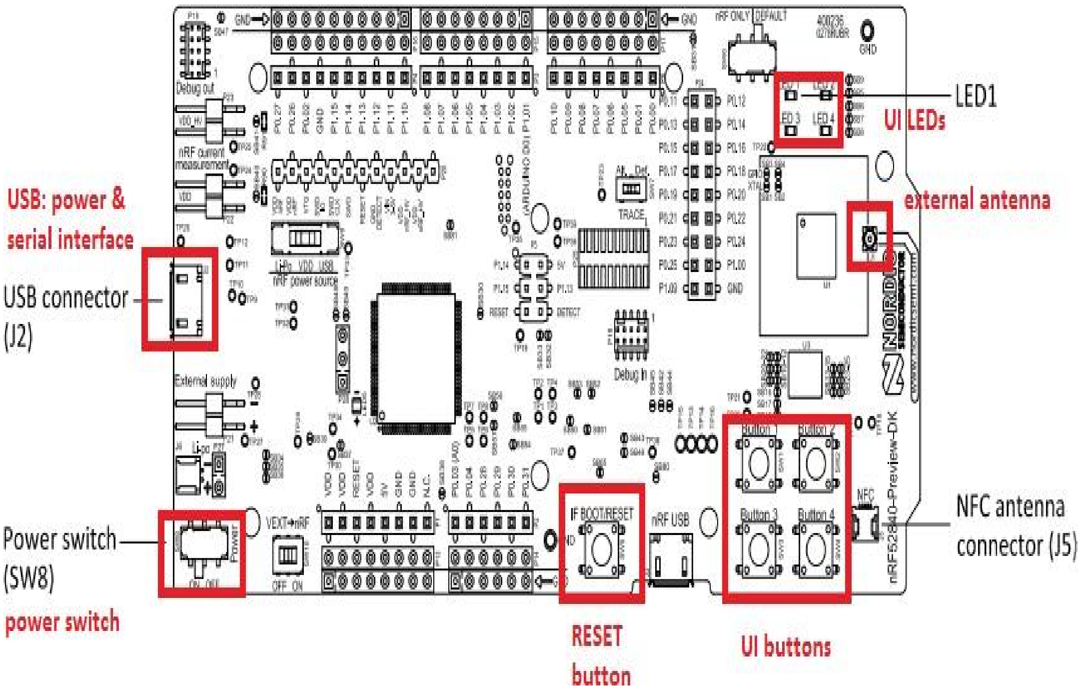


Figure 15. The hardware platform layout and important components.

The chipset – nRF52840 supported by over-the-air device firmware upgrade (OTA-DFU) was programmed with S140 v 5.0. (alpha) soft device, which is a precompiled, and linked binary software implementing BLE protocol introduced by Nordic Semiconductor and it also allows in the field updates of application or protocol stacks. Usually, they stay in a separate memory location to one's application and ensures reliable, easier, and more secure application development. The S140 soft device is the qualified stack of BLE 5 that supports 20 BLE links in concurrent operation for all 4 roles: central, peripheral, broadcaster, and observer. The on-chip ARM trust zone crypto Cell provides best-in-class security. The chip also has a full-speed (12 Mbs) USB 2.0 controller. In case of this thesis experiments S140 was the only soft device supporting for some of the BLE 5 features. The nRF52840 can be considered as the ideal solutions for smartly connected home applications that is able to support Bluetooth 5`s long-range features and also for IEEE std. 802.15.4 – one of the popular technology for home networking protocols [69].

## 4.2 Advertiser and scanner application

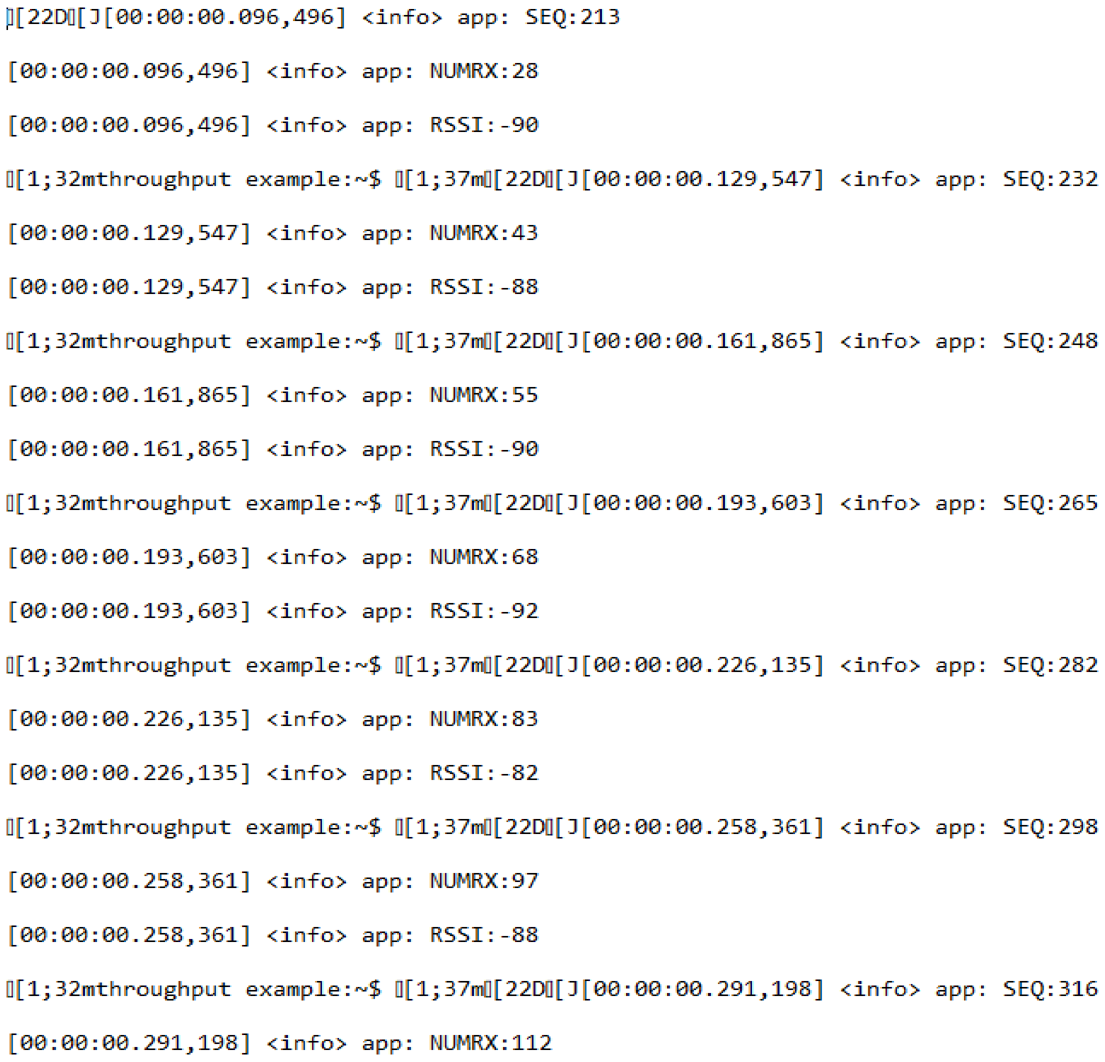
The experiment parameters and configurations for advertiser are shown in Table 6 [69]. Bluetooth device sends advertising packets (PDUs) to broadcast data, and to allow other device called scanner to find and connect to them.

Table 6. Experiment parameters and configurations for advertiser

| **Parameter** | **Operation mode 1** | **Operation mode 3** |
|---|---|---|
| Advertising event | Non connectable<br>Nonscannable<br>Undirected | Extended<br>Nonconnectable<br>Nonscannable<br>Undirected |
| Primary adv. channels IDs | 39 | |
| Tx power, dBm | 0 | |
| Primary adv. channel PHY | 1 Mbps | coded (S=8) |
| Secondary adv. channel IDs | 0..36 | |
| Advertisement payload | 12 bytes | |
| Secondary adv. channel PHY | NOT SET | coded (S=8) |
| Advertising delay, ms | 50 ms | |
| Serial interface report period | 1 second | |
| Serial interface configurations | Universal asynchronous receiver/transmitter (UART), data rate 115200 bps, 8 bits data, 1 stop bit, no parity | |

The above Table 6 shows that in case of mode 1 advertising event happens in three condition: nonconnectable, nonscannable and undirected, while it happens in four condition (extended, nonconnectable, nonscannable and undirected) for mode 3. From the Table 5, it is noticed that both mode 1, and mode 3 use 12 bytes advertisement payload and primary advertising channels IDs is 39 for both modes. There is an advertising delay for 50 ms during advertising process for mode 1 and mode 3, and serial interface report period is 1s. When the amount of data sent are periodically reported by the serial interface, the serial interface takes 1 second.

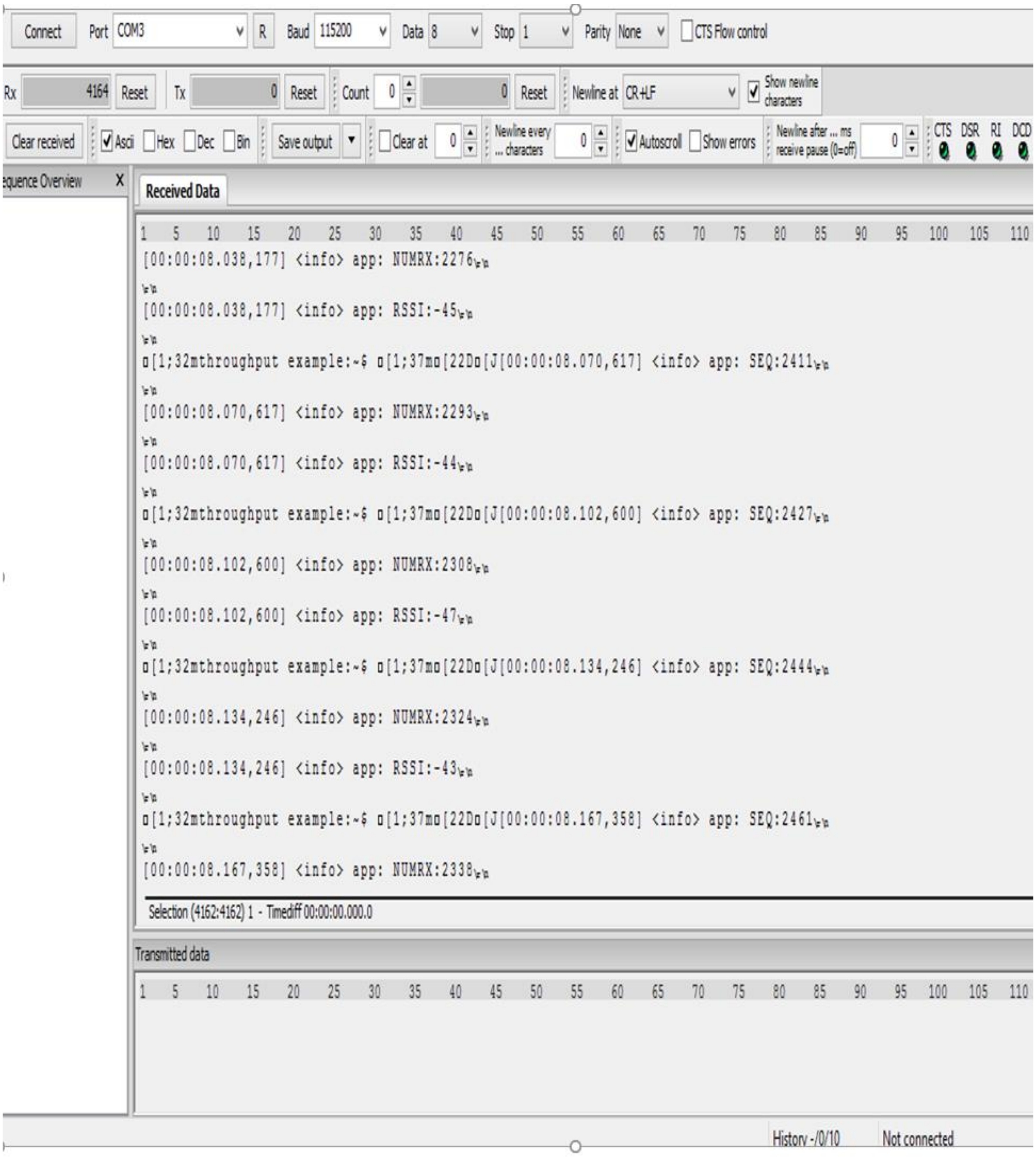
The illustration of periodic serial reports by advertiser is described in Figure 16 [69] where the number of transmitted packets from Tx node, and RSSI are shown. Here, 213 is the number of transmitted packets, and – 90 is RSSI.



```
▯[22D▯[J[00:00:00.096,496] <info> app: SEQ:213

[00:00:00.096,496] <info> app: NUMRX:28

[00:00:00.096,496] <info> app: RSSI:-90

▯[1;32mthroughput example:~$ ▯[1;37m▯[22D▯[J[00:00:00.129,547] <info> app: SEQ:232

[00:00:00.129,547] <info> app: NUMRX:43

[00:00:00.129,547] <info> app: RSSI:-88

▯[1;32mthroughput example:~$ ▯[1;37m▯[22D▯[J[00:00:00.161,865] <info> app: SEQ:248

[00:00:00.161,865] <info> app: NUMRX:55

[00:00:00.161,865] <info> app: RSSI:-90

▯[1;32mthroughput example:~$ ▯[1;37m▯[22D▯[J[00:00:00.193,603] <info> app: SEQ:265

[00:00:00.193,603] <info> app: NUMRX:68

[00:00:00.193,603] <info> app: RSSI:-92

▯[1;32mthroughput example:~$ ▯[1;37m▯[22D▯[J[00:00:00.226,135] <info> app: SEQ:282

[00:00:00.226,135] <info> app: NUMRX:83

[00:00:00.226,135] <info> app: RSSI:-82

▯[1;32mthroughput example:~$ ▯[1;37m▯[22D▯[J[00:00:00.258,361] <info> app: SEQ:298

[00:00:00.258,361] <info> app: NUMRX:97

[00:00:00.258,361] <info> app: RSSI:-88

▯[1;32mthroughput example:~$ ▯[1;37m▯[22D▯[J[00:00:00.291,198] <info> app: SEQ:316

[00:00:00.291,198] <info> app: NUMRX:112
```

Figure 16. Illustration of periodic serial reports by advertiser.

The illustration of periodic serial reports by scanner is described in Figure 17 [69] where the number of received packets in receiver node (Rx) from the transmitted packets, and RSSI are shown. Here, 2293 represents the number of received packets, and – 44 represents RSSI.



Port COM3
Baud 115200
Data 8
Stop 1
Parity None
☐ CTS Flow control
Rx 4164
Tx 0
Count 0
0
Newline at CR+LF
☑ Show newline characters
☑ Ascii ☐ Hex ☐ Dec ☐ Bin
☐ Clear at 0
Newline every ... characters 0
☑ Autoscroll ☐ Show errors
Newline after ... ms receive pause (0=off) 0

```
1   5    10   15   20   25   30   35   40   45   50   55   60   65   70   75   80   85   90   95   100  105  110
[00:00:08.038,177] <info> app: NUMRX:2276␍␊
␍␊
[00:00:08.038,177] <info> app: RSSI:-45␍␊
␍␊
□[1;32mthroughput example:~$ □[1;37m□[22D□[J[00:00:08.070,617] <info> app: SEQ:2411␍␊
␍␊
[00:00:08.070,617] <info> app: NUMRX:2293␍␊
␍␊
[00:00:08.070,617] <info> app: RSSI:-44␍␊
␍␊
□[1;32mthroughput example:~$ □[1;37m□[22D□[J[00:00:08.102,600] <info> app: SEQ:2427␍␊
␍␊
[00:00:08.102,600] <info> app: NUMRX:2308␍␊
␍␊
[00:00:08.102,600] <info> app: RSSI:-47␍␊
␍␊
□[1;32mthroughput example:~$ □[1;37m□[22D□[J[00:00:08.134,246] <info> app: SEQ:2444␍␊
␍␊
[00:00:08.134,246] <info> app: NUMRX:2324␍␊
␍␊
[00:00:08.134,246] <info> app: RSSI:-43␍␊
␍␊
□[1;32mthroughput example:~$ □[1;37m□[22D□[J[00:00:08.167,358] <info> app: SEQ:2461␍␊
␍␊
[00:00:08.167,358] <info> app: NUMRX:2338␍␊
```

Selection (4162:4162) 1 - Timediff 00:00:00.000.0

History -/0/10
Not connected

Figure 17. Illustration of periodic serial reports by scanner.

## 4.3 Block diagram

The connections between the different blocks are shown by the nRF52840 DK block diagram [69] that is noticed in Figure 18 [69]. This block diagram describes about the entire system. The arrows indicate signals that share physical pins with other signals. The buttons and LEDS are connected with nRF52840 DK. RF connector is connected through a matching network and antenna is connected with an RF connector. To measure the current, there is a current measurement device that is connected with nRF52840 DK. The nRF52840 DK takes power from a power supply circuit through nRF USB. Battery and external supply are connected with the power supply circuit.

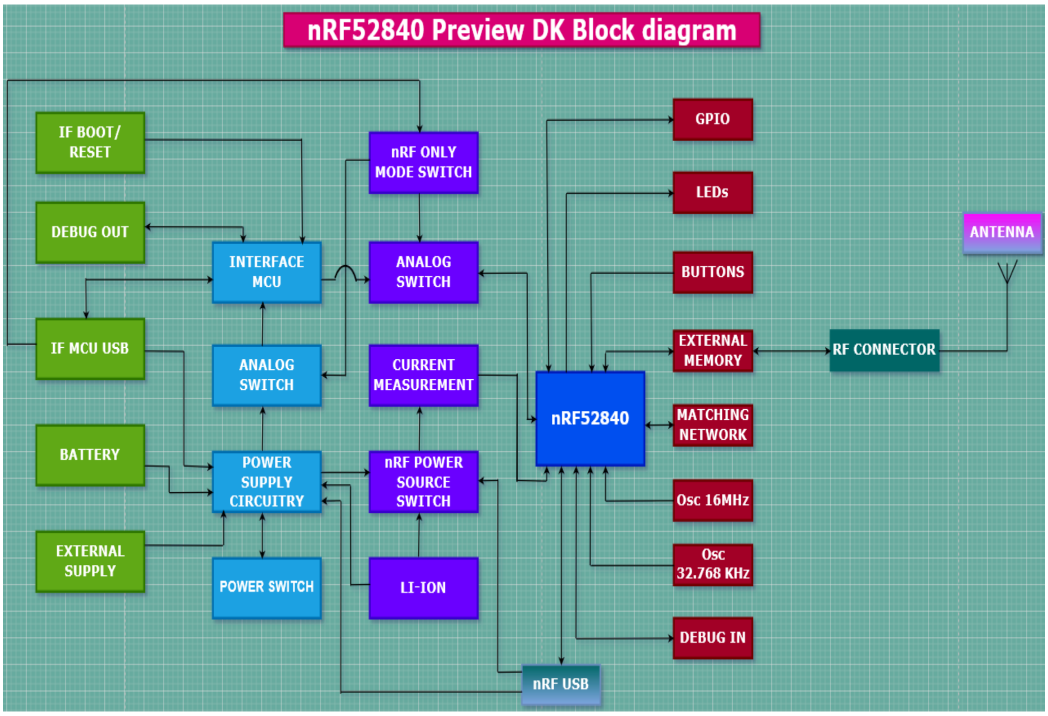


Figure 18. The block diagram of nRF52840 DK.

## 4.4 Different modes of nRF52840 DK

The nRF52840 DK has four PHY buttons named as mode 1, mode 2, mode 3, and mode 4. Four different BLE operations can be performed enabling these modes. In this case programming was done by Dr. Konstantin Mikhaylov to enable these modes. Among them, mode 1 and mode 2 are for BLE 4 nonextended version and BLE 4 extended version whereas, mode 3 and mode 4 are for BLE 5 coded (S = 8) and BLE 5 extended version respectively. In this experiment, mode 1 and mode 3 were used for BLE 4, and BLE 5 coded version, respectively.

## 4.5 Measurement setup

In the experiments, two nRF52840 preview DK development kits were used [69] with the laptop running a measurement software that is noticed in Figure 19. In order to carry out research, the proposed software was developed in CWC lab by Dr. Konstantin Mikhaylov – researcher at University of Oulu. The proposed software was based on the ATT_MTU throughput example of the nRF5 software development kit (SDK) v 15.0.

Figure 19. Devices used for measurements.

The methodology of this thesis experiments is as follows. Basically, in order to conduct measurements, firstly, the firmware was modified. Then the BLE boards were placed in the specified locations, the scanner board was connected to a computer via a universal serial bus (USB) interface, configured to operate with the required PHY layer option and forced to scan a single advertising channel continuously. After activation of the scanner board, the advertiser was powered by power bank and its PHY layer was configured. The advertiser began to send the advertisements periodically, each with a unique sequence number. Then after the received signal strength indicator by the board with the serial interface was measured. After that, the board's transmission power with the serial interface enabled was controlled. The scanner recorded the advertisement’s number received from the board of an advertiser, as well as sequence identifier and RSSI for the final advertisement it obtained, about every second through serial interface. The number of data received is reported periodically via the serial interface. Once the predefined quantity of bytes is sent, the experiment is finished, and the PER is calculated at the end of the experiment from the total number of packets received by the scanner, and the sequence number of the packet that is received at the end. In this measurement the height of BLE boards was considered 1m for both cases. At a time of this measurement, the number of transmitted and received packets were recorded for at least 15 minutes for both cases (which results getting at least 12 000 BLE packets being sent).

Initially, the two devices were kept close enough to each other to allow the connection to be established utilizing the desired parameters like maximum unit size, PHY data channel, connection interval, transmission power and also for getting ensure that the device is working properly. After that, one device named Receiver (Rx) was placed in the fixed condition, and the position of other device called Transmitter (Tx) was changed gradually until the connection was broken. This allowed to detect the "maximum communications range" for specific parameters. In this range, few points were selected, and were measured PER, and RSSI to examine how the propagation environment impacts BLE communications performance.

Figure 20 Illustrates the flow diagram used in this thesis measurements working approach. At the initial stage, the power switch of Tx and Rx is kept on. It was found that when the power button is pressed 4 LEDs starts blinking. Then both Tx and Rx are configured, and all the parameters are checked for the measurements. After the configuration of Tx, data are transmitted that is based on the PHY option to the configured Rx. After that, Rx starts receiving transmitted data from Tx at a different distance, and then both the devices are prepared for taking accurate measurements at a different distance. If the desired measurement is not achieved, the button of Tx and Rx is reset and the devices are prepared ready for taking measurements again. If the desired measurement is found, the devices are prepared ready for taking measurements for different distance. The data is observed and logged that is reported by the scanner until the desired number of advertisements has been seen or received. During taking measurements, if two LEDs blink is noticed it is needed to keep the device power off and on using the power switch. Finally, the performance of PER and RSSI at a different distance is observed.

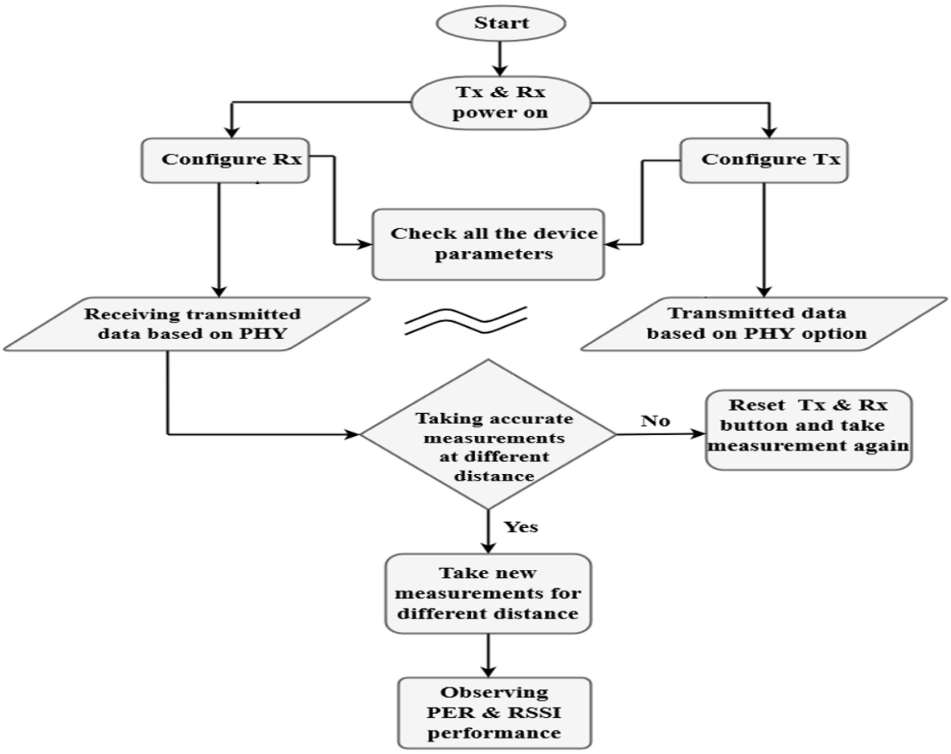


Figure 20. Measurements working diagram of the master's thesis work.

## 4.6 Outdoor measurements

In the case of this experiment, outdoor measurement was conducted for only Line-of-sight (LOS) case which will be described in this section.

The LOS measurements were performed outside on a bike track in Kaitoväylä, Oulu, with a straight line of 500 meters. This measurement aimed to determine the “maximum communications range”, and also the number of correctly received packets to determine *PER* and RSSI for both BLE 4, and BLE 5 with coded PHY when using the maximum transmit power of 0 dBm, since the communication range growth is demanded to be one of the major design goals of BLE 5.The results of this measurements are shown on the map in Figure 21 and Figure 22 shows the straight bicycle road used for LOS measurements.

Figure 21. Results of the outdoors LOS measurements (Map in different distances).

Figure 22. Outdoors LOS measurements (straight bicycle road).

The blue circle is the Rx point, and the yellow circle is the point where BLE 4 connection was lost. The red circle is the point where BLE 5 mode with transmit power 0 dBm stopped working. From the results in Figure 21, it is noticed that for BLE 4 with 0 dBm, the maximum range was 230 m, whereas it was found to be 490 m for BLE 5 coded mode. It is seen from the Figure 21 that the communications range for BLE 5 coded (S=8) mode with transmit power of 0 dBm is very impressive, being 490 meters, compared to BLE 4 mode that goes up to 230 m.

The PER is calculated using

$$PER = \frac{NT_x}{NR_x}, \tag{20}$$

where, $NT_x$ is the number of transmitted packets, and $NR_x$ is the number of received packets.

### *4.6.1 Line-of-sight measurements with Tx, and Rx at height 1.7 m*

Figure 23 shows the PER, and RSSI measurement results in case of BLE the PER, and RSSI measurement results in case of BLE 4 keeping both Tx and Rx at height 1.7 m. From the Figure 23, it is seen that the PER is zero until 150 m. After 150 m, the PER goes up sharply until 240 m. At point 240 m, PER is almost 100 %. It is noticed that the PER at 200 m, 210 m, and 220 m is 42 percent, 64 percent and 80 percent, respectively.

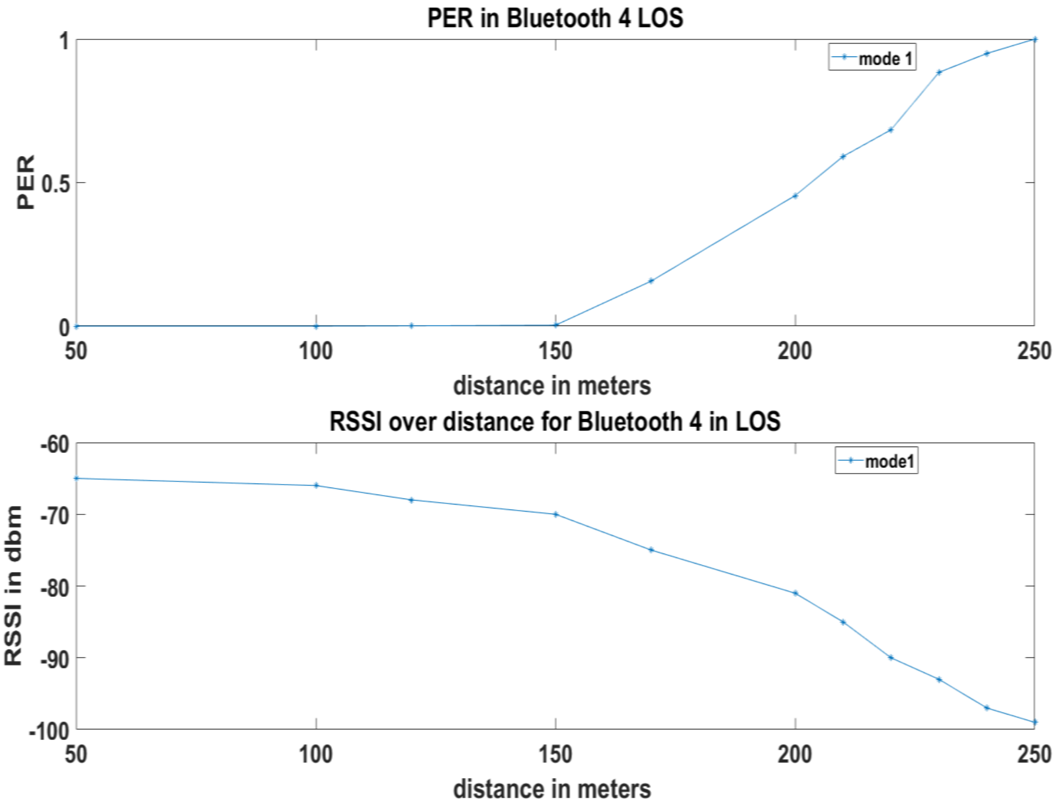


Figure 23. PER & RSSI measurement results in case of BLE 4

In case of BLE 4, almost similar signal strength is found until 100 m that is noticed from the Figure 23. For example, at 50 m distance from Tx point, the signal strength is – 65 dBm and the signal strength is – 66 dBm at 100 m distance. After that point (100 m), the signal strength becomes weak rapidly and at 240 m distance, the connection was found to be disconnected.

Figure 24 shows the PER, and RSSI measurement results in case of BLE 5 coded mode having both Tx and Rx at height 1.7 m. From the Figure 24, it is seen that the PER is zero until almost 300 m. After 250 m, the PER goes up gradually until 490 m. BLE 5 coded case measurement results from Figure 24 show that the error correction makes it possible to maintain low PER, i.e., the PER is only 20 %, until the link distance rises to more than 350 m. After that point, the coding is unable to correct the errors which results in breaking connection. At point 450 m, the PER is 70 %. Therefore, for the next 150 m link distance, almost (60 – 65) % packet loss is found.

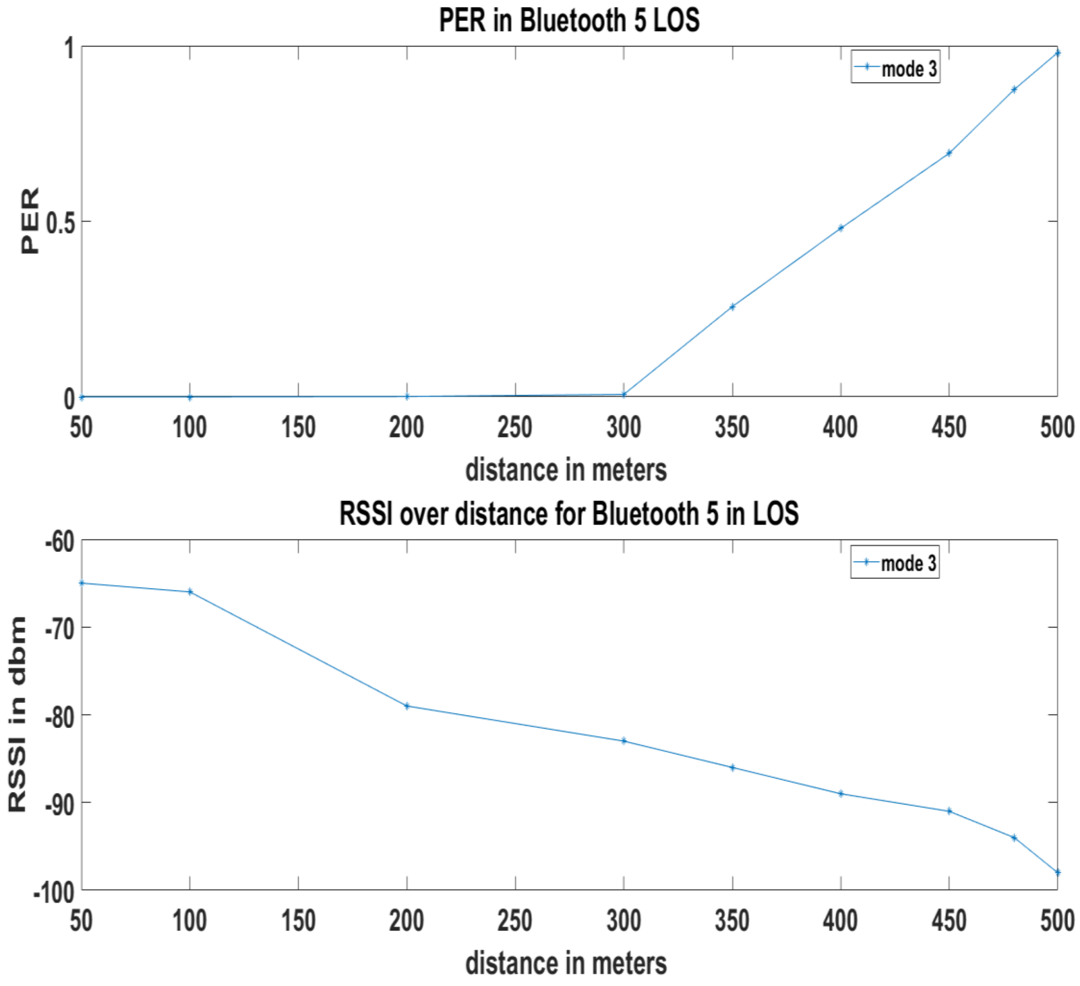


Figure 24. PER & RSSI measurement results in case of BLE 5

From the Figure 23, and Figure 24, it is clearly seen that at 200 m, the PER is almost 45 % in the case of BLE 4 where it is almost 0 % in terms of BLE 5. From the Figure 23 and Figure 24, between 50 m and 300 m, in case of BLE 5 the strongest signal strength is found that is – 65 dBm. After 300 m, it begins to be weak with the increasing of distance and at 490 m the

RSSI value is approximately – 98 dBm. At this point the signal strength is too much poor. Figure 23 and Figure 24 show that the interference effect, i.e., there were trees along the road side and people walking was noticed during taking measurements, is noticeable when the length of the BLE 4 and BLE 5 link distance is longer than 150 m and 300 m, respectively. From the Figure 23, and Figure 24, in BLE 4 case, it can be noticed that 160 m of BLE link distance can be obtained with PER less than 10 %, and in case of BLE 5, almost 280 m of BLE link distance can be obtained with PER less than 10 %. It is also noticed that the RSSI value, at 200 m distance, is different for BLE 4, and BLE 5. The RSSI values are affected by the antenna radiation and interference (dense vegetation besides the road) those were found during taking measurements.

### *4.6.2 Line-of-sight measurements with Tx, and Rx at height 1 m*

Figure 25 shows the PER, and RSSI measurement results in case of BLE 4 having at height 1m. From the Figure 25, it is seen that the PER is zero until 120 m. After 120 m, the PER goes up sharply until 210 m. At point 210 m, the PER is 92 %. It is noticed that the PER at 140 m, 160 m,180 m, 200 m, 210 m, and 220 m is 12 percent, almost 50 percent, 70 percent, 85 percent, and almost 100 percent, respectively.

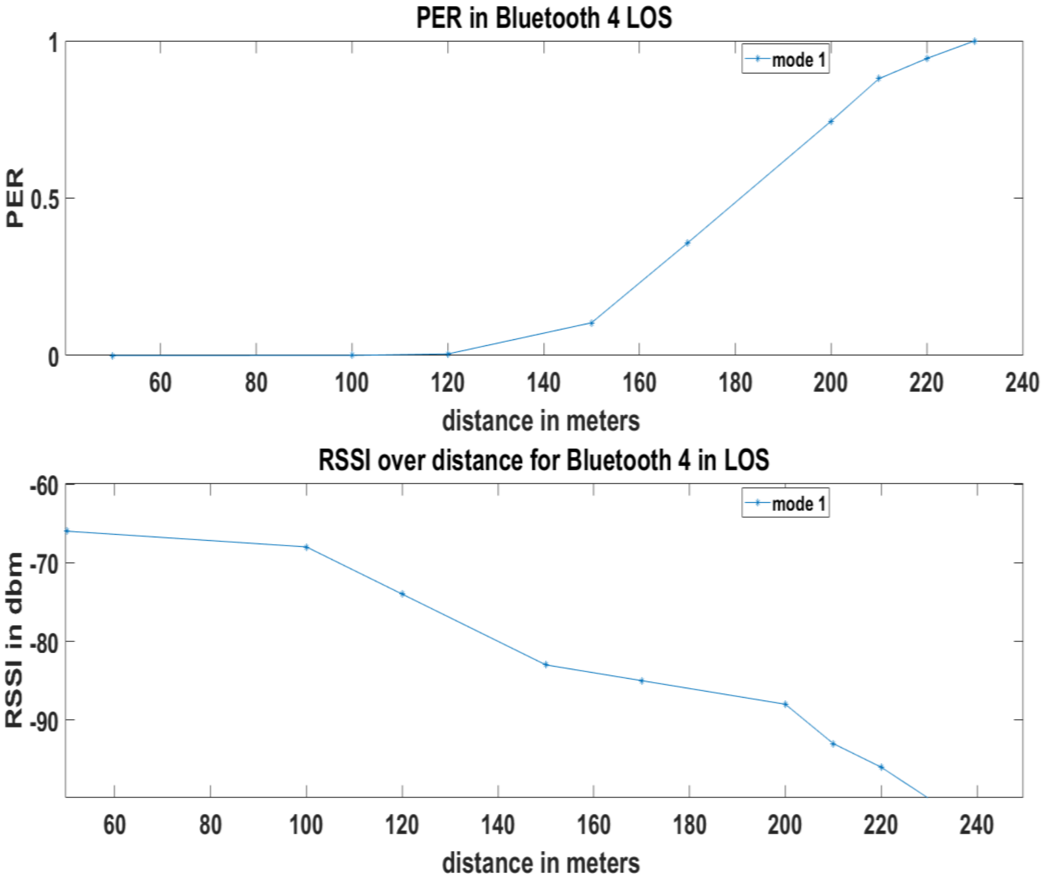


Figure 25. PER & RSSI measurement results in case of BLE 4.

From the above Figure 25, between 50 m and 160 m, the similar behaviour of signal strength (– 66 dBm) is found. At 230 m, the signal strength is – 100 dBm. From the Figure 25, it is noticed, BLE 4 stops working at 230 m.

Figure 26 shows the PER, and RSSI measurements in case of BLE 5 coded mode having Tx and Rx at height 1 m. From the Figure 26, it is seen that the PER until 200 m is zero. After 200 m, the PER goes up gradually until 490 m. At point 450 m, the PER is 85 %. It is noticed that the PER at 250 m, 300 m, 350 m, 400 m, 450 m, and 480 m is 5 percent, 8 percent, 40 percent, 50 percent, 80 percent, and 93 percent, respectively.

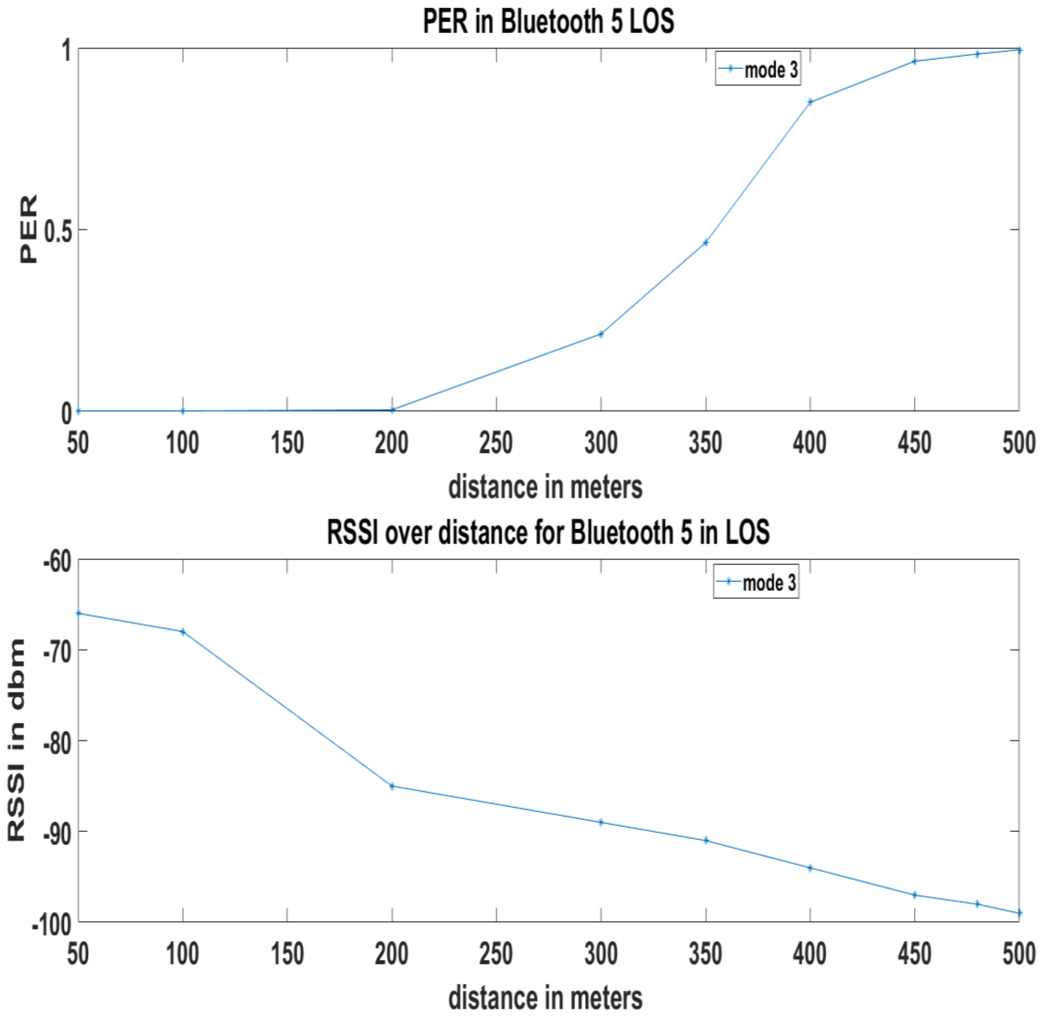


Figure 26. PER & RSSI measurement result in case of BLE 5

From the Figure 25, and Figure 26, it is observed that the error correction can maintain low PER until 200 m link distance for BLE 5 and there is zero PER until 120 m for BLE 4. After 200 m, the PER goes up significantly even in the coded mode, i.e., the coding is unable to correct the errors. So, there is 80 m link distance improvements in case of BLE 5. At 220 m link distance, the PER is almost 98 % in the case of BLE 4, while it is only 0.5 % in terms of BLE 5. From the above Figure 25 and 26, it is seen that, between 50 m and 300 m, the signal strength is strong, being between – 66 dBm and – 68 dBm. After 300 m, it begins to be weak with the increasing of distance and at 490 m the RSSI value is approximately – 99 dBm, and at this point BLE 5 coded mode stopped working. Because of coding, the performance of PER in case of BLE 5 is sometimes better than BLE 4 that is clearly seen from the above Figure 25 and Figure 26. For example, at 200 m link distance, the signal strength (– 85 dBm) of BLE 5 is better compared to the signal strength (– 88 dBm) of BLE 4. At 200 m link distance, the RSSI values are affected by the antenna radiation and interference those were found during taking measurements, which results in getting not the same RSSI value in the case of BLE 4, and BLE 5. The RSSI value of BLE 5 decreases slowly because of effect of antenna position. Also, at 200 m link distance, the PER is almost 0 % in case of BLE 5, whereas it shows approximately 70 % in BLE 4 case.

From the above Figure 25, and Figure 26, in BLE 4 case, it can be noticed that 150 m link distance can be obtained with PER less than 10 %, and in case of BLE 5, 250 m link distance can be obtained with PER less than 10 %.

# 5 ANALYTICAL RESULTS AND COMPARISON

The analytical model of this thesis work has been implemented in Matlab, and for evaluating of BLE PER and RSSI measurements were performed at a different distance as introduced in Chapter 4. This Section shows the results calculated using the models. The parameters that have been used in analytical, and experimental performance evaluation of BLE 4, and BLE 5 are shown in Table 7.

Table 7. Parameters for analytical and experiment evaluation

| **Parameters** | **BLE 4** | **BLE 5** |
|---|---|---|
| Frequency | 2.480 GHz | 2.480 GHz |
| BLE communication Channel | CH # 39 | CH # 39 |
| Communication frequency, *f* | 2.4 GHz | 2.4 GHz |
| Transmit power, BLE | 0 dBm | 0 dBm |
| BLE link length | 0 – 230 m | 0 – 490 m |
| Path loss exponent, *n* | 2.1, 2.4 | 2.1, 2.4 |
| Implementation loss | 12 dB | 12 dB |
| Reference distance, $d_{h0}$ | 1 m | 1m |
| Payload length, BLE | 12 bytes | 12 bytes |
| Transmitter power consumption, Tx | 8.16 mw – 26.4 mW | 8.16 mw – 26.4 mW |
| Receiver power consumption, Rx | 7.82 mw – 25.3 mw | 7.82 mw – 25.3 mw |
| Thermal noise power | $N_0$ = – 114 dBm at 1 MHz | $N_0$ = – 114 dBm at 1 MHz |

## 5.1 Path loss

Figure 27 shows the path loss versus distance curve in the case of BLE 5 (mode 3), and BLE 4 (mode 1) for different path loss exponent value. Path loss can be calculated using Equation (4) of Chapter 3. From the Figure 27, it is noticed that BLE 4 and BLE 5 path loss plot show similar behaviour, as the path loss component (2.1, and 2.4) is the same for both cases. For example, when the path loss component is 2.1, at 50 m, and 100 m link distance, similar path loss (87.72 dB, and 94.046 dB) is found for both BLE 4, and BLE 5 cases.

The path loss increases with increasing the path loss exponent, *n* that is observed from the Figure 27. When the path loss exponent is 2.1, the path loss at 200 m is 100.36 dB for BLE 4, and BLE 5 cases. However, when the path loss exponent is 2.4, the path loss at 200 m goes up by 7 dB in the case of BLE 4, and BLE 5. Moreover, when the path loss exponent is 2.1, path loss increases by 6.32 dB between 50 m and 100 m link distance, while it goes up by 7.22 dB in case of path loss exponent (2.4). From 200 m to 490 m link distance, in BLE 5 case, path loss increase by 8.36 dB, and 9.55 dB, respectively for the path loss exponent (2.1, and 2.4).

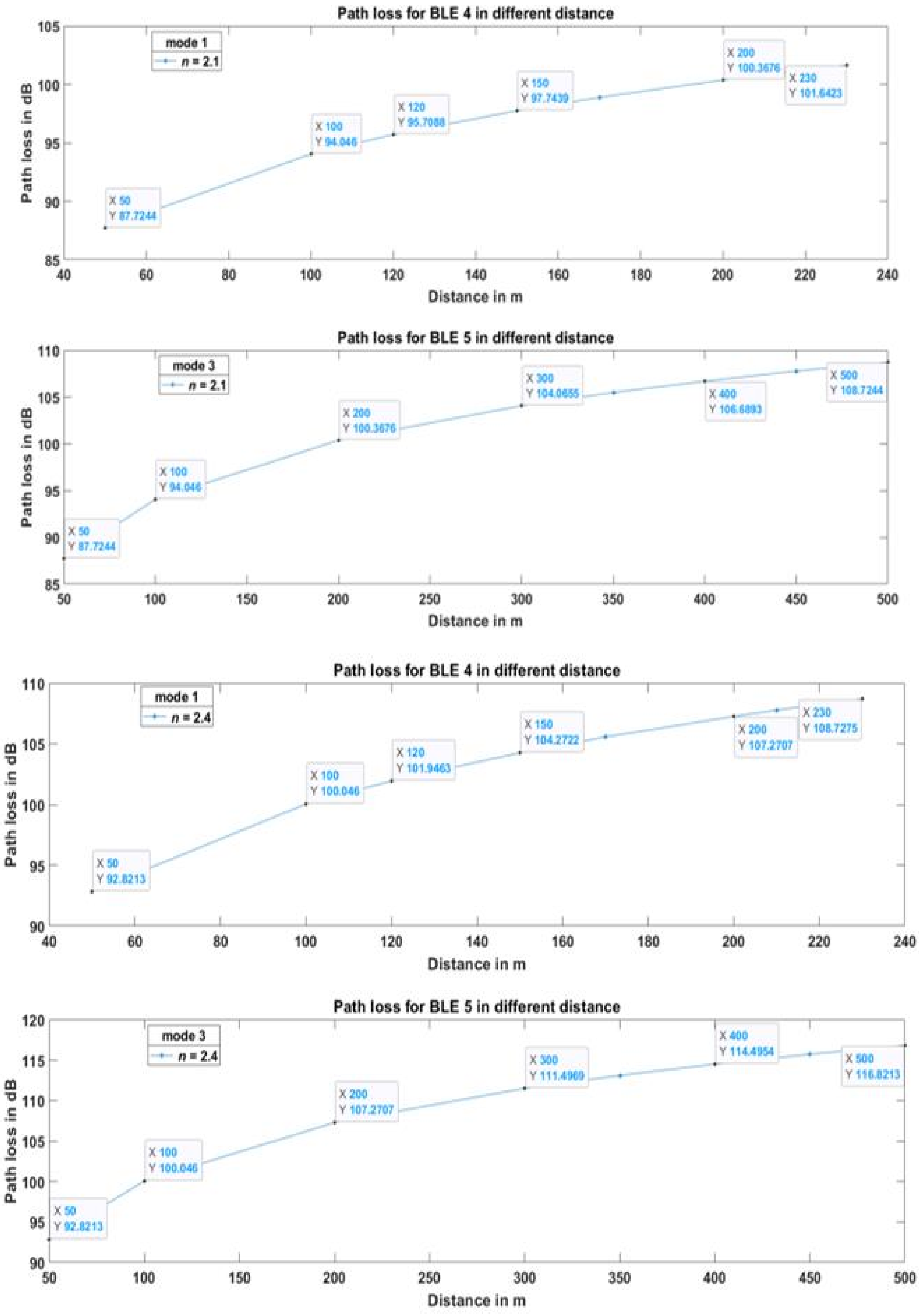


Figure 27. Path loss at different distance when *n* is 2.1, and 2.4.

## 5.2 Signal-to-noise ratio

Figure 28 shows SNR versus distance curve in case of BLE 4, and BLE 5. SNR can be calculated using Equation (11) of Chapter 3.

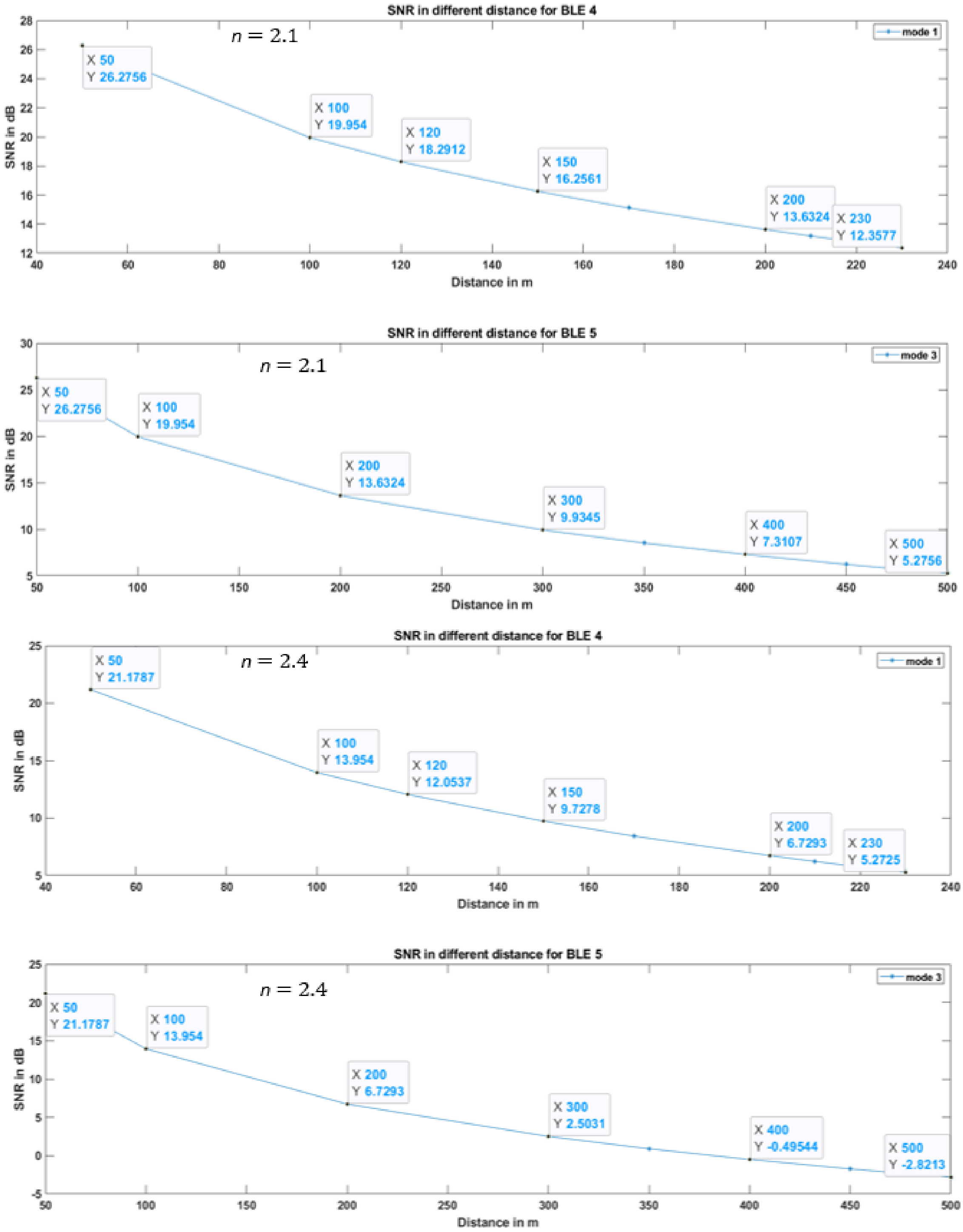


Figure 28. SNR versus distance curve for BLE 4, and BLE 5.

From the Figure 28, it is observed that SNR reduces with increasing the path loss exponent. For example, in case of the BLE 4, when the path loss exponent is 2.1, SNR at 50 m link distance is 26.27 dB, while it shows 21.17 dB for path loss exponent (2.4). Moreover, when the path loss exponent is 2.1, SNR goes down by 7.6 dB between 100 m and 230 m link distance, while it decreases by 8.68 dBm in case of path loss exponent (2.4). However, for BLE 5 coded mode, at 100 m link distance, SNR is 19.95 dB for path loss exponent (2.1), while it shows 13.95 dB for path loss exponent (2.4). Moreover, from 200 m to 490 m link distance, SNR decreases by 8.36 dB and 9.54 dB, respectively for the path loss exponent (2.1 and 2.4).

From the Figure 28, it is found that BLE 4 does not perform well at 200 m link distance with SNR 6.73 dB, and stops working at 230 m link distance due to low SNR (5.28 dB), while BLE 5 with same SNR (6.73 dB), at 200 m, performs better as compared to BLE 4. At, 400 m, the SNR of BLE 5 is much lower though at that distance (400 m), it works. BLE 5 has error correction capability, which results in going to longer distance with lower SNR value.

## 5.3 Symbol error rate as a function of distance

Figure 29 shows SER versus distance curve in case of BLE 4, and BLE 5. SER can be calculated using Equation (8) of Chapter 3.

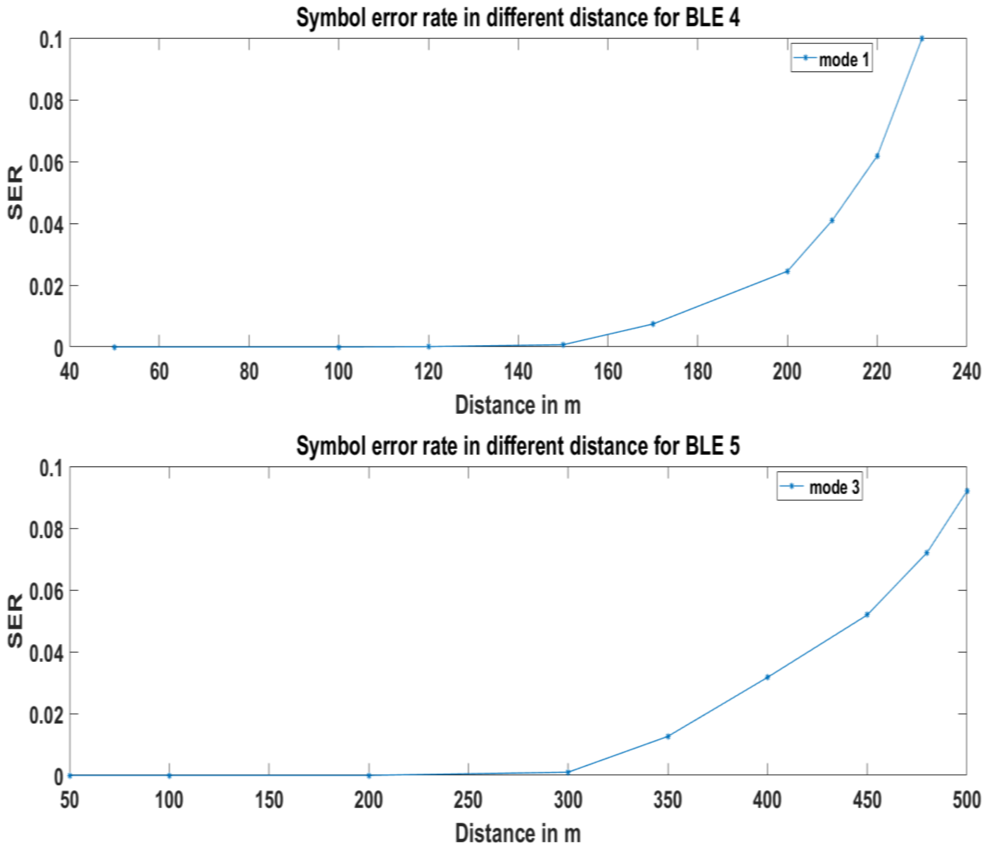


Figure 29. SER versus distance curve for BLE 4, and BLE 5.

It can be observed from the Figure 29 that for the same transmitting power (0 dBm), in case of BLE 4 until 140 m link distance there is zero SER, and in case of BLE 5 zero SER is experienced until 240 m link distance. So, there is 80 m link distance improvements in case of BLE 5 that is due to coding gain. Also, at 200 m link distance, in case of BLE 4 the SER is found as 0.03 percent, while it shows zero percent SER for BLE 5. In case of BLE 4, almost 98 percent SER is found within 80 m (between 150 m and 230 m) link distance, while, between 150 m and 230 m link distance, it is still 0 % in case of BLE 5. Because of coding behaviour of BLE 5, better SER performance is always observed in the case of BLE 5 compared to BLE 4. In BLE 5 case, coding gain affects in correcting errors which results in getting link distance improvements.

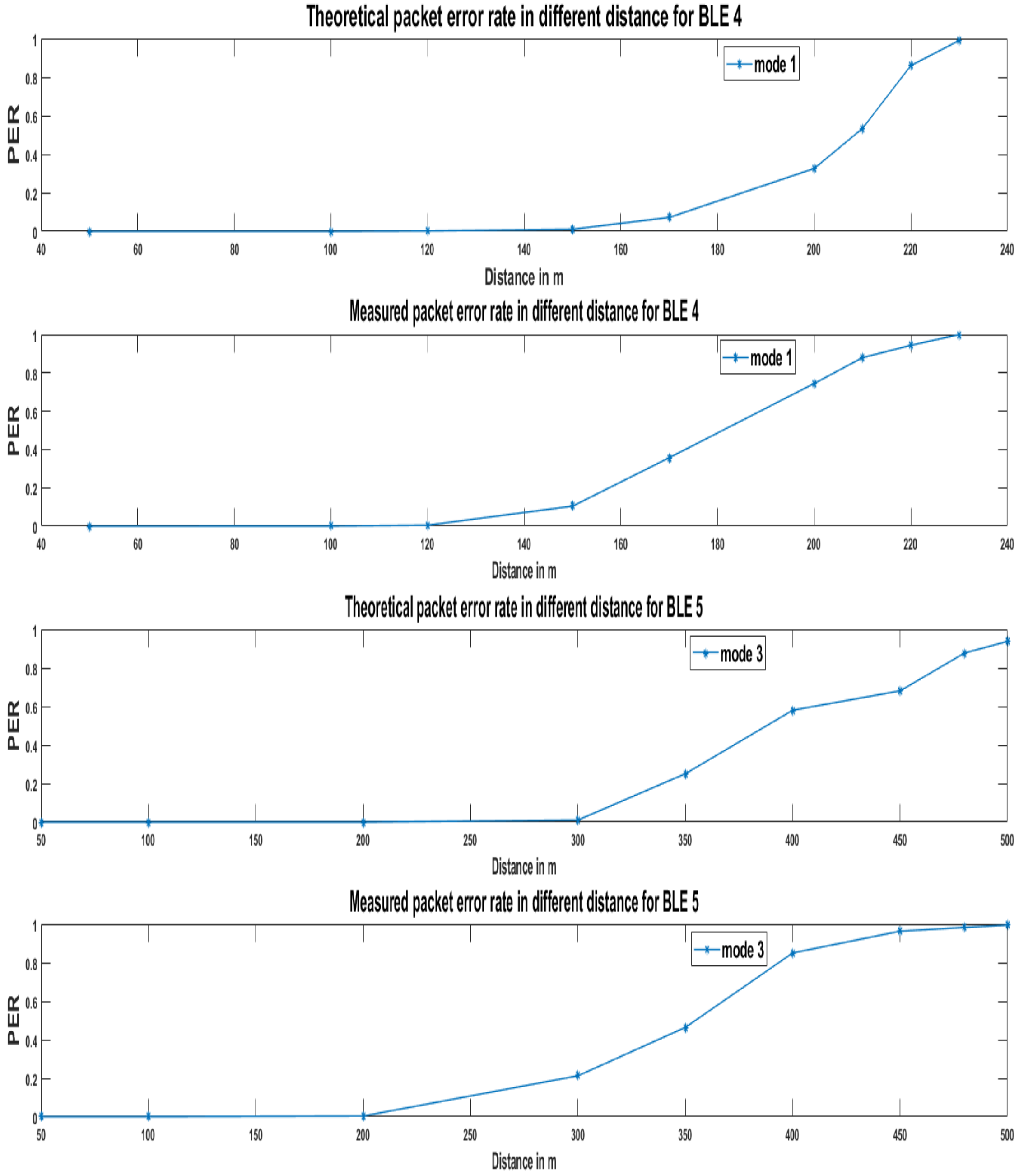
## 5.4 Packet error rate

Figure 30 shows theoretical, and measurements PER versus distance curve for BLE 4, and BLE 5. PER is calculated using Equation (12) of Chapter 3. For BLE 4, the PER is almost zero until 160 m in case of theoretical analysis, while it is noticed as zero until 120 m for real measurement. In terms of BLE 4 measurements, there is 40 m less link distance is experienced than theoretical analysis (BLE 4) due to interference, i.e., there was a different type of obstructions created by vegetation and people walking was noticed. Moreover, after 160 m link distance, in case of theoretical analysis (BLE 4), the PER goes up sharply until 230 m. At point 230 m, the PER is 96 %, while it is almost 100 % in the case of real measurements. So, because of interference, in BLE 4 experimental analysis case, there is 4 % more PER is experienced compared to theoretical analysis (BLE 4).

However, for BLE 5 coded mode, the packet loss is almost zero until 300 m link distance in case of theoretical analysis, while it shows zero percent until 200 m link distance in terms of real measurement. Here, in case of theoretical analysis (BLE 5) there is 100 m more link distance is experienced than real measurement (BLE 5). At point 490 m link distance, the PER is 93 %. So, because of interference, in BLE 5 experimental analysis case, there is 7 % more PER is experienced compared to theoretical analysis (BLE 5).

From the Figure 30, it is observed that the performance of PER is always less in case of measurement analysis for both BLE 4, and BLE 5 coded mode compared to theoretical analysis for BLE 4, and BLE 5 coded mode. To exemplify, at 200 m link distance, the PER is 40 percent for BLE 4 theoretical analysis, whereas almost 70 percent PER is found in case of BLE 4 measurements analysis. Here, the PER is 30 percent more in case of BLE 4 measurements analysis than BLE 4 theoretical analysis. At 400 m link distance, approximately 40 percent PER is experienced in case of BLE 5 coded mode theoretical analysis, while it shows almost 85 percent in case of BLE 5 coded mode measurements analysis. Here, the PER is 45 percent less in case of BLE 5 coded mode theoretical analysis than BLE 5 coded mode measurements analysis. Because of coding gain, BLE 5 coded mode is able to correct the errors, which results in achieving longer distance.

The amount of successfully received packet depends on the value of the SER, path loss exponent, and the length of the packet. From the above discussion, it can be observed that the experimental result matches well with the analytical results.


Theoretical packet error rate in different distance for BLE 4

Measured packet error rate in different distance for BLE 4

Theoretical packet error rate in different distance for BLE 5

Measured packet error rate in different distance for BLE 5

Figure 30. Theoretical and measurements PER analysis for BLE 4, and BLE 5.

### 5.5 Energy consumption

Figure 31 shows energy consumption versus distance curve for BLE 4, and BLE 5. Energy consumption can be calculated using Equation (18) of Chapter 3. From the Figure 31, it is observed that until 170 m for BLE 4 theoretical analysis, the amount of energy consumption is less that is 0.0945 J where it is 0.19468 J for BLE 4 real measurements. The energy consumption is calculated based on the PER results which have been derived from the measurement results. At 230 m link distance, for BLE 4 theoretical analysis, the most significant consumed energy is 2.0189 J, whereas it shows 5.9276 J for BLE 4 measurements analysis, i.e., it was calculated during analysing in Matlab. However, for BLE 5 coded mode theoretical analysis, the amount of consumed energy is less until 300 m that is 0.0003 J, whereas it is 0.001 J for BLE 5 measurements analysis. At 480 m link distance, for BLE 5 coded mode theoretical analysis, the amount of consumed energy is 8.147 J, while it shows 14.285 J for BLE 5 coded mode measurements analysis. Considering the distance up to 200 m for both cases, it is noticed that the amount of successfully received packet is less in case of BLE 4 than BLE 5 which results in consuming more energy in case of BLE 4 because to get more successful packet, it takes more energy. With the same transmit power, the energy consumption by BLE 5 technology is less than BLE 4 for an achievable range. For example, at 100 m link distance, BLE 4 (measurements analysis) consumes 0.098 J, while it shows approximately 0.0001 J for BLE 5 coded mode (measurements analysis). For the same link distance, it is found that, BLE 5 consumes 27.89 % less energy as compared to BLE 4. For example, at 200 m link distance, the energy consumption of BLE 4, and BLE 5 are 0.27987 J and 0.0009 J, respectively.

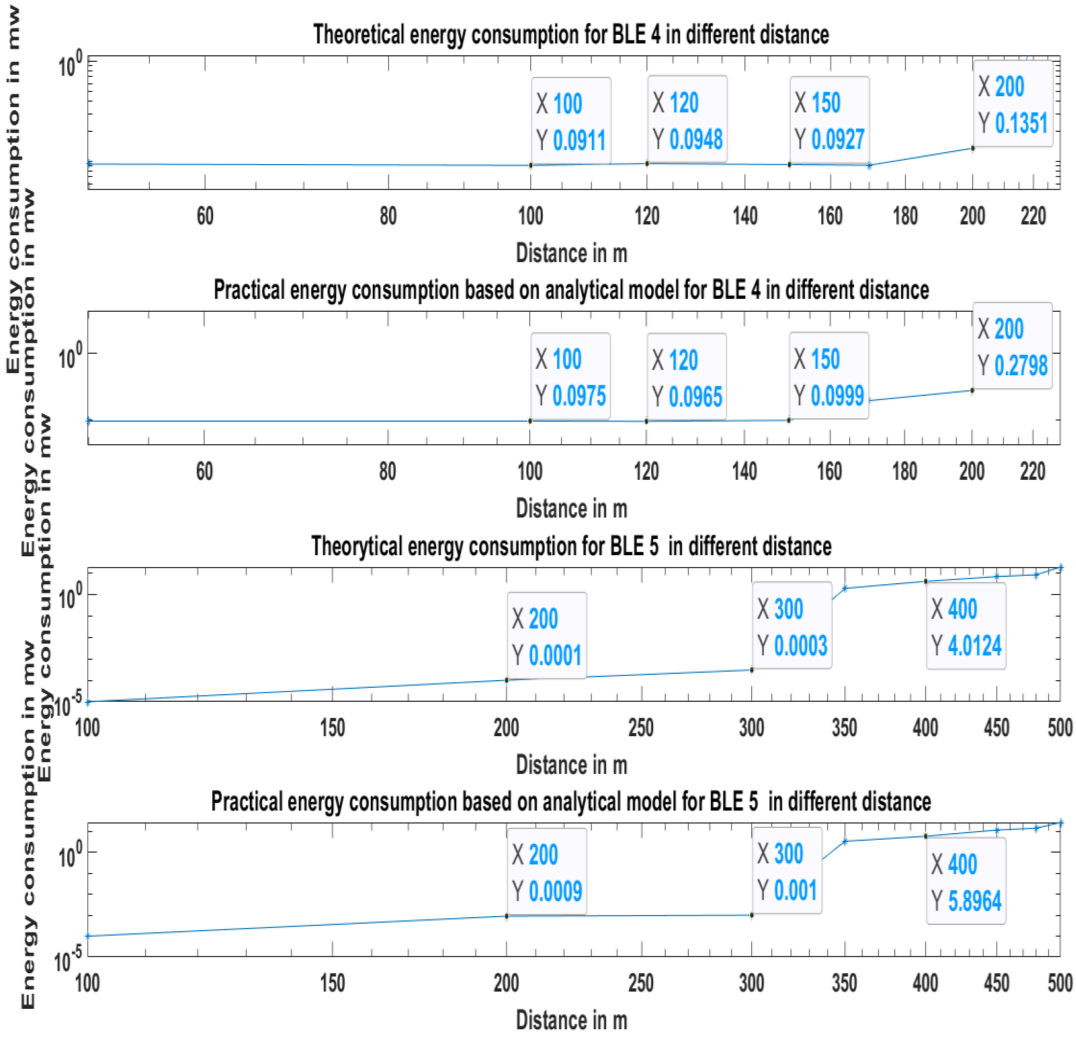


Figure 31. Energy consumption analysis for BLE 4, and BLE 5.

### 5.6 Energy consumption per information bit

Figure 32 shows theoretical energy consumption per information bit versus distance curve for BLE 4, and BLE 5. Energy consumption per information bit is calculated based on measurements PER, and it can be found using Equation (19) of Chapter 3. From the Figure 32, it is seen that the consumed energy per information bit is almost same until 120 m for BLE 4 being $0.0098 \times 10^{-5}$ J and then after 120 m, it goes up gradually up to 200 m. The most energy consumed per information bit is noticed for BLE 4 at 230 m which is $0.9662 \times 10^{-5}$ J. However, the consumed energy per information bit remains same up to 200 m in case of BLE 5 coded mode being $0.0008 \times 10^{-5}$ J and then after it starts increasing slowly up to 300 m. In this case, the highest energy is consumed at 490 m which is $0.1424 \times 10^{-4}$ J. For the same link distance it is noticed that, BLE 5 consumes $0.303 \times 10^{-6}$ J less energy per information bit as compared to BLE 4. For example, at 200 m link distance, the energy consumption per information bit is $0.383 \times 10^{-6}$J in case of BLE 4, whereas it shows $0.8 \times 10^{-7}$ J in case of BLE 5 coded mode. Therefore, BLE 5 coded mode performs better than BLE 4 in case of energy consumption.

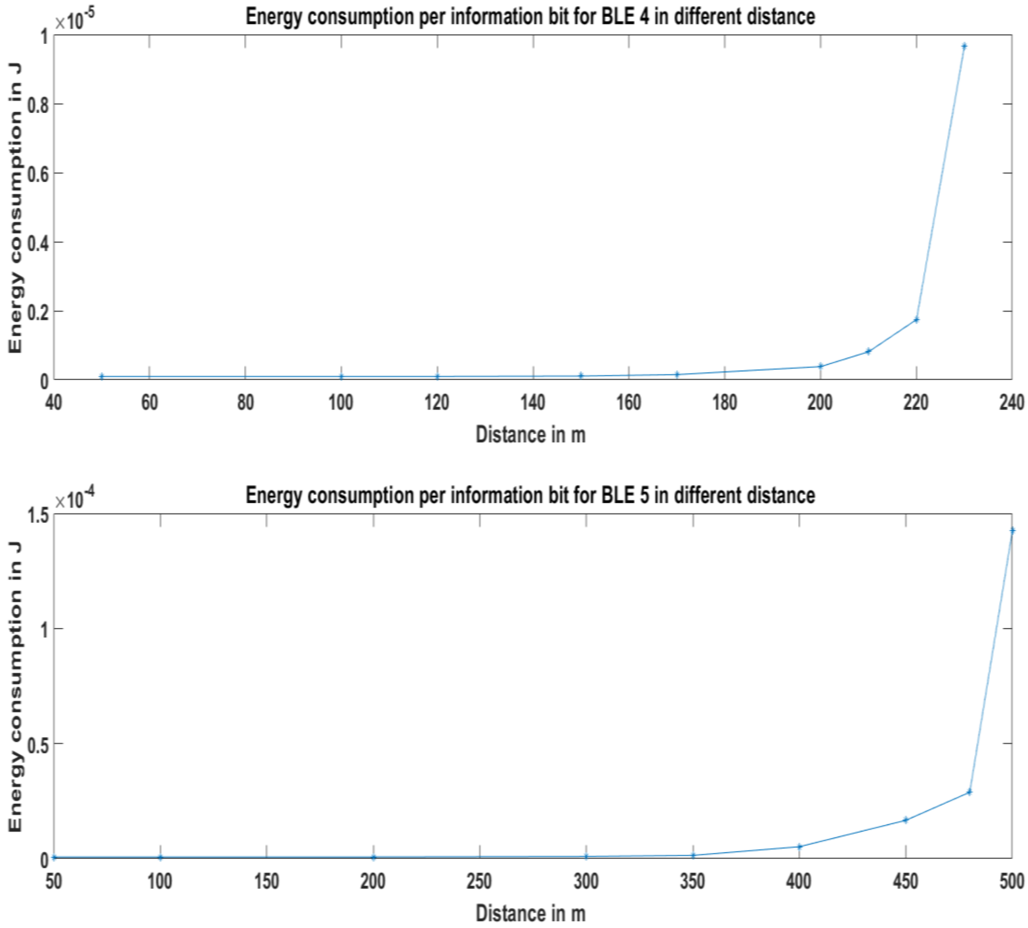


Figure 32. Energy consumption per information bit analysis for BLE 4, and BLE 5.

### 5.7 Discussion of results

Based on the discussed outdoor line-of-sight results, it can be compared the communications range performance of BLE 4 versus BLE 5 coded version. It is experienced that the BLE 5 coded version can improve remarkably communications range compared to the version of BLE 4.

A summary of measurements results is shown in Table 8. From the Table 8, it is noticed that, in case of BLE 5, there is 80 % packet loss occurred by 190 m link distance (300 m – 490 m), while it is observed 90 % by 80 m link distance (150 m – 230 m), in case of BLE 4. From the Table 7 it is noticed that ,in case of BLE 5, there is 80 % packet loss occurred by 190 m link distance (300 m – 490 m), while it is observed 90 % by 80 m link distance (150 m – 230 m), in case of BLE 4.

Table 8. Summary of measurements results

| **BLE 4** | | **BLE 5** | |
|---|---|---|---|
| **Range (m)** | **PER (%)** | **Range (m)** | **PER (%)** |
| 50 | 0 | 50 | 0 |
| 100 | 0 | 100 | 0 |
| 120 | 0 | 200 | 0 |
| 150 | 10 | 300 | 20 |
| 200 | 80 | 400 | 90 |
| 220 | 96 | 450 | 95 |
| 230 | 100 | 490 | 99 |

From the measurements analysis during keeping the height 1m (the height of Tx and Rx from the ground), at 200 m, it is noticed that BLE 4 stops working at 230 m link distance, whereas BLE 5 coded mode goes up to 490 m. In addition, at 150 m link distance, there is 10 % less PER in case of BLE 5 coded mode in comparison to BLE 4 version.

From the theoretical analysis, it is noticed that there is zero PER until 160 m link distance for BLE 4 and approximately 300 m link distance for BLE 5. So, there is around 140 m link distance improvements in case of BLE 5. However, the measurement result shows that there is around 80 m link distance improvements in case of BLE 5. Because of coding, there is almost two times link distance improvements in case of BLE 5. After 480 m, the PER is started increasing remarkably even in the coded mode, i.e., the coding does not correct the errors. Moreover, from the theoretical analysis, it is experienced that BLE 5 consumes much less energy compared to BLE 4. For instance, until 300 m link distance, BLE 5 consumes almost (10 – 28) % less energy than BLE 4, and after 350 m link distance, in case of BLE 5, the amount of energy consumption goes up significantly. Furthermore, due to having some losses like environmental loss (wind effect), antenna position loss and interference (people walking, different type of obstructions created by dense vegetation) the PER performance in case of measurements analysis is worse compared to analytical analysis for both BLE 4, and BLE 5. The performance of BLE 5 coded mode is better than BLE 4 in case of path loss analysis, SER that are observed during theoretical analysis. It is also noticed that the height of Tx and Rx plays a vital role in performing better PER performance. For example, the communication performance is found better during conducting measurements at height 1.7 m than the measurements at height 1 m.

## 5.8 Future work possibilities

Since the internet landscape is burgeoning and BLE technology is a well-known energy efficient technology, this BLE 5 technology can be fruitful solution for us. For instance, it can be used smartly in advance label applications like in smart home, in sending data during performing measurements around the human body, industrial sectors and so forth.

In this project, the payload length is considered as 12 bytes. So, therefore, using different payload length measurements might be conducted to evaluate the performance of PER, RSSI, and communication range. In the future, a study using some different coding methods that could improve communication range and energy efficiency might be carried out. In the future experiments, energy consumption might be measured in practical to compare the theoretical results with the measurements results. A research work on BLE 5 technology might be carried out to improve the model in order to get better performance in case of energy efficient than the present time.

# 6 SUMMARY

Energy-efficient communication has become a major concern as the demand for various types of new technologies used in wireless communication has increased. In this case, the BLE 5 coded technique aims to improve communication range, and costs compared to the previous BLE technology version (BLE 4.2), while keeping up the same communication range. BLE 5 provides remarkable improvements with reduced radio communication time for energy efficiency and wireless coexistence. With the feature of faster transmit speed, BLE 5 spent less time with the radioactive, which potentially results in decreasing battery consumption. The applications of BLE in various areas are significantly increasing, which makes BLE one of the preeminent short-range communication technologies during the following generation of networks.

The objective of this thesis work was to evaluate the performance of PER at different distances, and to measure the communication ranges. This thesis also illustrates the BLE protocol stack, provides this technology with a performance evaluation, and describes its potential application. In this work, energy efficiency analysis of recently published BLE 5 coded technique, which new functions are in particular focused on the emerging IoT scenarios, was presented. This thesis has provided analytical model and comprehensive experimental measurements at different distance. Analytical result shows the performance evaluation of PER, SER and energy consumption for BLE 4, and BLE 5, whereas measurements results show the performance evaluation of PER, communication range, and RSSI for both cases: BLE 4, and BLE 5. Measurements results are used to verify the analytical model results, and a comparison between the two models has been described.

From the theoretical analysis, it is seen that there is 140 m link distance improvements in case of BLE 5, while the measurement result shows that there is around 80 m link distance improvements in case of BLE 5. After 350 m, the PER goes up significantly even in the coded mode, i.e., the coding is unable to correct the errors. Results also show that the amount of erroneous packet reception cause reducing the energy efficiency that is immensely significant in case of IoT applications.

Moreover, from the theoretical analysis, it is experienced that until 200 m link distance, BLE 5 consumes almost (10 – 28) % less energy than BLE 4, and after 350 m link distance, in case of BLE 5, the amount of energy consumption increases remarkably. The antenna radiation and interference (dense vegetation next to road), which were observed during the measurements, affect the RSSI values that was noticed at 200 m link distance.

Furthermore, there were some losses like environmental loss, antenna position loss and interference, which resulted to make worse PER performance in case of measurements analysis than analytical analysis. The performance of BLE 5 coded mode is better than BLE 4 in case of path loss analysis, and SER that are observed during theoretical analysis. During performing measurements, it is also experienced that the height of Tx, and Rx plays an important role in performing better PER performance.

From the above discussion, it is observed that the experimental results match well with the analytical results. Therefore, it can be generalized from the above discussion that BLE 5 is an efficient technology that is used immensely in commercial application, and it is expected that it would be a strong reliable candidate in the future of providing smart solutions for meeting communications demand in the field of the IoT.

# 7 REFERENCES

[1] Flockett, A. (2018).*Using Bluetooth 5 to connect the IoT*. [online] Wireless. electronic specifier.com. Available : https://wireless.electronicspecifier.com/iot-1/using-bluetooth-5-to-connect-the-iot. [Accessed 5 Sep. 2018].

[2] Bluetooth SIG,"Bluetooth core specification version: 5.0", *Uni-obuda.hu*, 2016. [Online]. Available: http://www.uni-obuda.hu/users/wuhrlt/MSc_Adatatvitel/Core_v5.0.pdf. [Accessed: 05- Sep- 2018].

[3] Nordic Semiconductor,"nRF52840 DK", *Nordic Semiconductor*. [Online]. Available: https://www.nordicsemi.com/Software-and-Tools/Development-Kits/nRF52840-DK. [Accessed 7 Sep. 2018].

[4] L. Xu, W. He and S. Li, "Internet of Things in Industries: A Survey", *IEEE Transactions on Industrial Informatics*, vol. 10, no. 4, pp. 2233-2243, 2014. Available: 10.1109/tii.2014.2300753. [Accessed: 07- Sep- 2018].

[5] K. Chang, "Bluetooth: a viable solution for IoT? [Industry Perspectives]", *IEEE Wireless Communications*, vol. 21, no. 6, pp. 6-7, 2014. Available: 10.1109/mwc.2014.7000963 [Accessed: 08- Sep- 2018].

[6] H. B. Pandya and T.A Champaneria, "Internet of Things: Survey and case studies", in 2015 International Conference on Electrical, Electronics, Signals, Communication and Optimization (EESCO), Jan 2015. pp 1-6.

[7] C.J Mathias, “Bluetooth is dead,” EE Times, October, 2003. [Accessed: 09- Sep- 2018].

[8] V. Gaziz, “A survey of standards for machine to machine (m2m) and the internet of things (IoT),”IEEE Communications surveys Tutorials, vol. pp, no.99, p.1-4, 2016.

[9] S. Raza, P. Misra, Z. He, and T. Voigt, “Bluetooth smart: An enabling technology for the internet of things, “In Wireless and Mobile Computing, Networking and Communications (Wi Mob), 2015 IEEE 11th International Conference, on October 2015, pp.155-164.

[10] S. Jaycon. (2017)."Bluetooth Technology: What Has Changed Over The Years" [Online]. Available:https://medium.com/jaycon-systems/bluetooth-technology-what-has-changed-over-the-years-385da7ec7154. [Accessed: 13- Sep- 2018].

[11] J. R. Lin, T. Talty and O. K. Tonguz, "On the potential of Bluetooth low energy technology for vehicular applications," in IEEE Communications Magazine vol. 53, no.1, pp. 267-275, January 2015.

[12] Bluetooth SIG, "Bluetooth Core Specification v 5.1 Feature Overview | Bluetooth Technology Website", *Bluetooth Technology Website*, 2019. [Online]. Available: https://www. bluetooth.com/bluetooth-resources/bluetooth-core-specification-v5-1-feature-overview/. [Accessed: 13- Sep- 2018].

[13] Bluetooth SIG, "Bluetooth core specification version 4,”Specification of the Bluetooth system, 2010. [Online]. Available : https://www.bluetooth. /archived-specifications [Accessed: 13- Sep- 2018].

[14] W. Warne, "Exploring Bluetooth 5 -What’s New in Advertising? | Bluetooth Technology Website", *Bluetooth Technology Website*, 2017. [Online]. Available: https:// www.com/blog/exploring-bluetooth5-whats-new-in-advertising/. [Accessed: 13-Sep- 2018].

[15] Heydon, K. The Physical Layer. In Bluetooth Low Energy-The Developer’s Handbook; Goodwin, B., Ed.; Prantice Hall-Pearson Education, Inc: Upper Saddle River, NJ, USA, 2012; p. 52-75.

[16] M. Tailor, "What’s New with Bluetooth 5.0?", *Wireless Connectivity Blog*, 2017. [Online]. Available: http://www.summitdata.com/blog/whats-new-with-bluetooth-5-0/. [Accessed: 15- Sep- 2018].

[17] H. Karvonen, K. Mikhylov, M. Hämälainen, J. Iinatti, “Experimental Performance Evaluation of BLE 4 Vs BLE 5 in indoor and outdoor scenarios”. [Online]. Available: https://www. researchgate.net/publication/320196487_Experimental/. [Accessed: 15- Sep- 2018].

[18] J. Sponås, "Things You Should Know About Bluetooth Range", *Blog.nordicsemi.com*, 2018. [Online]. Available: https://blog.nordicsemi.com/getconnected/things-you-should-know-about-bluetooth-range. [Accessed: 16- Sep- 2018].

[19] D. Ray, "Understanding Bluetooth 5". [online] Mouser.com. Available at: https: // www. mouser.com/pdfdocs/Methods%20Bluetooth%205%20%20Volume%201%20Issue%201.pdf. [Accessed: 18- Sep- 2018].

[20] B. Wire, "Bluetooth Technology to Gain Longer Range, Faster Speed, and Mesh Networking in 2016", *Businesswire.com*, 2016. [Online]. Available: https://www. businesswire.com/news/home/20151111005390/en/Bluetooth%C2%AE-Technology-Gain-Longer-Range-Faster-Speed. [Accessed: 20- Sep- 2018].

[21] I. Texas, "Bluetooth 5, High speed mode". [Online]. Available: http://www.ti.com/ wireless-connectivity/simplelink-solutions/bluetooth-low-energy/overview/bluetooth-5.html. [Accessed: 21- Sep- 2018].

[22] E. Akpinar, "Beacons: Everything you need to know", *Blog.pointr.tech*, 2015. [Online]. Available:https://blog.pointr.tech/beacons-everything-you-need-to-know. [Accessed: 21- Sep- 2018].

[23] D. Girish, "Bluetooth 5: How it will impact IoT, Beacons and more", *Blog.beaconstac.com*, 2016. [Online]. Available: https://blog.beaconstac.com/2016/06/bluetooth-5-how-it-will-impact-iot-beacons-and-more/. [Accessed: 22- Sep- 2018].

[24] K. Raval, "How will Bluetooth 5 impact IoT and Beacons". [Online]. Available: https:// www.letsnurture.com/blog/will-bluetooth-5-impact-iot-beacons.html. [Accessed: 25- Sep- 2018].

[25] E. Esteve, "4 Reasons for Bluetooth 5 Adoption in IoT", 2016. [Online]. Available: https://semiwiki.com/semiwiki.com/semiconductor-ip/ceva/6113-4-reasons-for-bluetooth -5-adoption-in-iot. [Accessed: 28- Sep- 2018].

[26] N. Allurwar, "Bluetooth vs. Bluetooth Low Energy", *IoT Dunia-Helping you to succeed with the Internet of Things*, 2017. [Online]. Available: https://iotdunia.com/bluetooth-vs-bluetooth-low-energy/. [Accessed: 28- Sep- 2018].

[27] Cloud and Mobile network traffic forecast-Visual networking index (VNI).” Cisco, 2015.URL". [Online]. Available: http://cisco.com/c/en/us/solutions/service-provider/visual-networking-index-vni/index.html. [Accessed: 30- Sep- 2018].

[28] Danova, Tony. “Morgan Stanley: 75 Billion Devices Will Be Connected To The Internet Of Things By 2020.” Business Insider, October", 2013. [Online]. Available: http://www.businessinsider.com/75-billion-devices-will-be-connected-to-the-internet-by-2020-2013-10. [Accessed: 03- Oct- 2018].

[29] Global Connectivity Index." Huawei technologies Co. Ltd", 2015. [Online]. Available: http://www.huawei.com/minisite/gci/en/index. [Accessed: 03- Oct- 2018].

[30] K. Marianne, "*GAO assesses IoT vulnerabilities*", 2017. [Online]. Available:https:// www.bankinfosecurity.com/gao-assesses-iot-cybersecurity-other-risks-a-9926. [Accessed: 03- Oct- 2018].

[31] A. Bharathi, B. Balamurugan, R.Sathiyaraj, "Internet of things technologies". [Online]. Available: https://doi.org/10.1016/B978-0-12-817356-5.00015-2. [Accessed: 04- Oct- 2018].

[32] A. Bhishek Singh, "Internet of things – overview", *Tutorials point*.[Online]. Available: https://www. tutorialspoint.com/internet_of _things_ overview [Accessed: 04- Oct- 2018].

[33] J. Nielsen, "Bluetooth low-energy technology for IoT applications", *Power electronics*. [Online].Available:https://www.powerelectronicsnews.com/news/bluetooth-low-energy-technology-for-iot-applications. [Accessed: 05- Oct- 2018].

[34] S. Lyengar, "Impact of Internet of Things (IOT) on IT, Business and our lives", *theinnovationenterprise.com*.[Online].Available:theinnovationenterprise.com/articles/8745-impact-of-internet-of-things-iot-on-it-business-and-our-lives. [Accessed: 07- Oct- 2018].

[35] C. Gomez, J. Oller and J. Paradells, "Overview and Evaluation of Bluetooth Low Energy: An Emerging Low-Power Wireless Technology", *Sensors*, vol. 12, no. 9, pp. 11734-11753, 2012. Available: 10.3390/s12091173 [Accessed: 09- Oct- 2018].

[36] Townsend, K. Cufi, C. Wang, C. Davidson, R. Introduction. In Getting Started with Bluetooth Low Energy: Tools and Techniques for Low-Power Networking; Sawyer, B., Loukides, M., Eds.; O'Reilly Media, Inc.: Sebastopol, CA, USA, 2014; pp.1-18.

[37] S. Direct, "Bluetooth Protocol Stack - an overview | Science Direct Topics", *Sciencedirect.com*. [Online]. Available: https://www.sciencedirect.com/topics/computer-science/bluetooth-protocol-stack. [Accessed: 08- Nov- 2018].

[38] Heydon, K. The Physical Layer. In Bluetooth Low Energy-The Developer's Handbook; Goodwin, B., Ed.; Prentice Hall-Pearson Education, In: Upper Saddle River, NJ, USA, 2012; pp. 52-73.

[39] Rf wireless world, "Bluetooth physical layer". [Online]. Available: https: //www. rfwireless -world.com /Tutorials /Bluetooth-physical-layer. [Accessed: 27- Oct- 2018].

[40] Bluetooth SIG, Bluetooth SIG. Vol 3: core system package, Generic attribute profile", 2016. [Online]. Available: https://www.bluetooth.org/. [Accessed: 28- Oct- 2018].

[41] Bluetooth SIG, "Bluetooth Network Encapsulation Specification, version 0.95a, 2001", *Grouper.ieee.org*. [Online]. Available: http://grouper.ieee.org/groups/802/15/Bluetooth/BNEP.pdf. [Accessed: 30- Oct- 2018].

[42] Bluetooth SIG, "Bluetooth SIG. Vol 1: Architecture & terminology overview, Architecture. in specification of the Bluetooth system",2019. [Online]. Available: https://www.bluetooth.org/. [Accessed: 01- Nov- 2018].

[43] Bluetooth SIG, "Bluetooth Low Energy Channels - Developer Help", *Microchipdeveloper.com*.[Online].Available:http://microchipdeveloper.com/wireless:ble-link-layer-channels. [Accessed: 06- Nov- 2018].

[44] Bluetooth SIG, Bluetooth SIG. Vol 6: Core system package , Physical layer specification", 2016. [Online]. Available: https://www.bluetooth.org. [Accessed: 10-Nov- 2019].

[45] Heydon, K. The Host/Controller interface. In Bluetooth Low Energy–The Developer's Handbook; Goodwin, B., Ed.; Prantice Hall- Pearson Education, In.: Upper Saddle River, NJ, USA, 2012; pp.131-167.

[46] M. Afaneh, "Bluetooth 5 Advertisements: Everything you need to know - Novel Bits", *Novel Bits*, 2017. [Online]. Available: https://www.novelbits.io/ bluetooth-5-advertisements/. [Accessed: 12- Nov- 2018].

[47] W. Peterson, D. Brown, "Cyclic codes for error detection", *Proc. IRE*, vol. 49, no. 1, pp. 228-235, Jan. 1961.

[48] S. Babaie, A. K Zadeh, S. H. Es-hagi, and N.J Navimipour, "*Double bits error correction using CRC method"* in pro. 2009 IEEE 5th Int. conf. on semantics knowl. Grid, 2009.

[49] W. Kowalk, "Cyclic redundancy check analyzing and correcting errors", *Einstein informatik.uni-oldenburg.de*, 2006. [Online]. Available: http:// einstein. informatik.uni-oldenburg.de/papers/CRC-BitfilterEng.pdf. [Accessed: 15- Nov- 2018].

[50] I.Sakai, "Bluetooth Technology and its Expected Application.", *The Journal of the Institute of Electrical Engineers of Japan*, vol. 121, no. 6, pp. 387-390, 2001. Available: 10.1541/ieejjournal.121.387. [Accessed: 20- Nov- 2018].

[51] G. Christiansen, "Data Whitening and Random TX Mode". [Online]. Available: http://www.ti.com/lit/an/swra322/swra322.pdf. [Accessed: 28- Nov- 2018].

[52] J. Fiedler. (2004). "Hamming code". [Online]. Available: http://orion.math.iastate.edu/linglong/Math690F04/HammingCodes [Accessed: 30-Nov- 2018].

[53] A. Stummer, "Use forward error correction to improve data communications", *Electronic design*. [Online]. Available: https://www.electronicdesign.com/communications/use-forward-error-correction-improve-data-communications. [Accessed: 03- Dec- 2018].

[54] F. Mohamed, "Cyclic Codes for Error" Available: https://pdfs. semanticscholar detection "[Online].org/44c1/4780d58015f8411fb85efa58a4aa3747a6ad.pdf. [Accessed: 07- Dec- 2018].

[55] J. Modestino and S. Mui, "Convolutional code performance in the Rician fading channel." *University of Miami's Research Profiles*. [Online]. Available:https:// pure. elsevier.com/en/publications/convolutional-code-performance-in-the-rician-fading-channel. [Accessed: 10- Dec- 2018].

[56] D. Forney, "opencourseware - Synonyms for opencourseware | Synonyms Of opencourseware",*Synonymsbot.com*.[Online].Available:https://synonymsbot.com/opencourseware. [Accessed: 15- Dec- 2018]. [Accessed: 15- Dec- 2018].

[57] E. Tsimbalo, (2015) CRC error correction for energy-constrained transmission. In: IEEE 26th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC).

[58] E. Tsimbalo, "CRC error correction in IoT applications". [Online]. Available: https://research-information.bristol.ac.uk/en/publications/crc-error-correction-in-iot. [Accessed: 20- Dec- 2018].

[59] H. Karvonen, K. Mikhaylov, D. Acharya, M. Rahman,"Performance Evaluation of Bluetooth Low Energy Technology under Interference". [Online]. Available: https://www.researchgate..net/publication/328065789_Performance_Evaluation_of_Bluetooth_Low_Energy_Technology_under_Interference.

[60] S. K amrul and M. Rafiqul, "Sensors and low power signal processing", *Amazon.com*, 2010. [Online]. Available:https://www.amazon.com/Sensors-Low-Power-Signal-Processing/dp/0387793917. [Accessed: 22- Dec- 2018]. p. 49. ISBN 978-0387793917.

[61] H, Eugene (1987). Optics (2nd ed.). Addison Wesley. pp. 15–16. ISBN 0-201-11609-X.

[62] R. Natarajan, P. Zand and M. Nabi, “Analysis of Coexistence between IEEE 802.15.4, BLE and IEEE 802.11 in the 2.4 GHz ISM band,” 42th Conference of the IEEE Industrial Electronics Society (IECON 2016), Florence, Italy, 2016, pp. 6025-6032.

[63] H. Karvonen, K. Mikhaylov, M. Hämäläinen, J. Iinatti and C. Pomalaza-Ráez, "Interference of wireless technologies on BLE based WBANs in hospital scenarios," *International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, Montreal, QC, 2017.

[64] D. Forney, "MIT open course Ware, 6.451. Principles of digital communication II, lecture notes section 4.2", *Ocw.mit.edu*, 2019. [Online]. Available:https://ocw.mit.edu/Available: https://ocw.mit.edu/index.htm. [Accessed: 30-Dec- 2018].

[65] Pearce. J, "Eb/N0 Explained". [Online].
Available: https://eletrica.ufpr.br/evelio/TE111/Eb_N0. [Accessed: 10- Jan- 2019].

[66] W. D. Reeve, "Additional Noise Concepts", *Reeve.com*. [Online]. Available: https://www.reeve.com/Documents/Noise/Reeve_Noise_2_AddlNoiseConcepts.pdf,pp. 9. [Accessed: 30- Jan- 2019].

[67] Jerry C. Whitaker (2005). The Electronics handbook, second edition. CRC press.pp.636. ISBN 978-1-4200-3666-4.

[68] C. Hero, "Large scale fading and network deployment". [Online]. Available: https://www.sis.pitt.edu/prashk/info 1072/Fall16/lec5.pdf. [Accessed: 18- Feb- 2019].

[69] Nordic Semiconductor, "nRF52840-preview-DK.", *Infocenter.nordicsemi.com*. infocenter. nordicsemi.com/pdf/nRF52840_PDK_User_Guide_v1.2.pdf. [Accessed: 26-Feb- 2019].

[70] Nordic Semiconductor, "nRF52840 Objective Product Specification v 0.5". [Online]. Available:https://static6.arrow.com/aropdfconversion/24041f730963d441b8c447118a14df49cd4f00a3/nrf52840_ops_v0.5.pdf. [Accessed: 27- Feb- 2019].