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An Experimental Investigation of the Bluetooth Smart for Use in Wearable Home-Care Monitoring Systems

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Abstract: As the demand for continuous online remote monitoring of patients grows, the energy consumption of wearable home-care monitoring systems (WHMSs) requires careful evaluation. Selecting the right communication protocol therefore is crucial to minimize energy usage and extend device lifecycles. Recent versions of Bluetooth Smart (IEEE 802.15.1 are promising for WHMSs, offering low energy consumption and extended coverage range. However, their energy consumption in WHMSs remains underexplored. This paper investigates the energy consumption and maximum coverage range of Bluetooth V4.2, V5/1MB and V5/2MB in various home-care environments. We propose a software and hardware-based energy monitoring framework to practically measure the energy consumption of the protocols, conducting extensive experiments in typical home scenarios with obstacles like kitchen cabinets, brick walls, and the human body. Our results show similar power consumption for BLE v4.2 and BLE v5 modules, but the BLE v5/2MB has lower energy usage than BLE v5/1MB due to faster transmission. Additionally, obstacles significantly impact energy consumption and range, with BLE v5/1MB achieving a maximum range of 108m in line-of-sight conditions, which drops to 45m and 29m with brick walls and human bodies, respectively. Finally, the BLE v5/2MB effective range in all experimental scenarios is about 80% of BLE v5/1MB.

Keywords: Bluetooth Low Energy, Energy Consumption Analysis, Wearable Sensors, Internet of Things, Remote Health Monitoring.

1 Introduction

THE aging of the population is one of the main concerns of many countries worldwide. It is estimated that by 2050 approximately 20% of the world's population will be 60 years or older, posing severe challenges to existing healthcare systems and highlighting the need for a new generation of health monitoring systems. The Internet of Things (IoT) and the wearable sensor devices have recently paved the way for developing powerful home-care monitoring frameworks [1], [2], [3], [4]. Wearable home-care monitoring systems (WHMSs) monitor users' activities and vital signs, including body temperature and heartbeat, and send the processed environmental and physiological data to a gateway. In many implementations, collected data are sent to the cloud, which can be stored, evaluated, and used to eliminate the potential health hazards of the tracked people [7], [8], [9], [10].

Rault et al. [5] have shown that the communication unit is the most energy-consuming component of the WHMSs. Hence, low-power wireless communication protocols should be used in WHMSs where possible. RFID, WiFi, ZigBee, NFC, Z-wave, and Bluetooth are examples of low-power, short-range wireless communication protocols that can be theoretically used for remote monitoring by WHMSs.

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Among the above-mentioned wireless communication technologies, the latest versions of the IEEE 802.15.1 protocol, known as Bluetooth low energy (BLE) or Bluetooth Smart, including BLE v4.2, BLE v5, and BLE v5.1, are well suited to be utilized in WHMSs. These versions of the Bluetooth protocol were announced respectively at the beginning of 2014, 2016, and 2019 by the Bluetooth Special Interest Group (Bluetooth SIG). The lower power consumption, extended packet size, higher level of security, small size and cheaper chipset are the main characteristics of BLE that make it appropriate for any wearable monitoring device [11], [12].

The Bluetooth's hardware consists of low-power minimal circuits designed for low-power, low-interference, and long-range wireless communications. BLE v4.2 and v5 packet capacity are ten times greater than BLE v4.1. The data segment capacity of the data link layer in BLE packets has been increased from 27 bytes to 251 bytes compared to the previous versions, making it possible to communicate with IPv6 and improve communication security [10], [11]. An elliptical curve encryption protocol is used for key management in BLE v4.2 and above that make it a secure communication protocol for WHMSs along with a symmetrical encryption in message authentication and message encryption [20], [21]. BLE v5 has surpassed BLE v4.2 in terms of data transfer rate. Its physical data transfer rate reaches 2Mbps, meaning that it can transfer the same amount of data in half-time and half-energy consumption compared to BLE v4.2 [13], [14]. BLE v5 has extended the maximum operating range to four times higher than its ancestors [13], [14].

Although the BLE v4.2 and v5 are suitable candidates and widely used technologies for WHMSs, their energy consumption and full coverage range in such applications have not been experimentally studied. In WHMSs, the wireless signal often passes through typical home obstacles such as concretes, metals, brick walls, and other common barriers, which undoubtedly affect the device's operating range and energy consumption. In [6] we have conducted a primarily investigation on the effective coverage and energy consumption of BLE v4.2 in indoor environments but the latest versions of Bluetooth such as v5 has not been investigated. In this paper, the maximum coverage range and also power consumption BLE v4.2 and BLE v5 in various home-care scenarios have been experimentally examined and compared using a proposed software and hardware-based energy monitoring platform. To the best of our knowledge, there is no such comprehensive empirical study on this area. Our contributions are summarized as follows:

- We propose the design and implementation of a highly precise hybrid software and hardware energy monitoring platform to monitor the energy consumption of the mobile phone and the BLE module. The hardware of our platform consists of four components: a BLE v4.2 and BLE v5 modules, which transfer a sort of agreed data in response to a received request, a smartphone with BLE v4.2 and BLE v5 support to communicate with the module, and two super-precise National Instrument (NI) energy monitoring systems, connecting to the BLE module and the mobile phone to monitor and sample their energy consumptions. The software of our proposed energy monitoring system consists of three programs, including an Android-based application, an energy consumption logger, and modules' firmware. Sending and receiving data from/to the BLE modules is managed by the Android-based application that is installed on the mobile phone which can also record the necessary metadata of each communication. In addition, the energy consumption logger is installed on two laptops, independently linked to the BLE module and the mobile phone.
- Four most probable obstacles between the BLE-enabled devices in a typical home are selected including wooden and metal kitchen cabinets, brick walls, and human bodies to conduct our experiments. The Line of Sight (LOS) condition is reported as a benchmark.

Our results indicate that the BLE v5/2 MB's energy consumption and its effective coverage range are less than the BLE v5/1MB due to the higher transmission speed of BLE v5/2 MB. We found that the thickness and the composition of the obstacles highly affect the energy consumption of both the mobile phone and the BLE module. The most energy-consuming obstacles are the human body and brick walls. Our experiments results also reveals that the maximum effective range (MER) of the BLE v5/1MB module while sending and receiving data with 99.9% reliability in the LOS situations is 108 meters and declines to about 45 and 29 meters, respectively, in the presence of a brick wall and human body. These numbers reduce by 20% when using the BLE v5/2MB and can be reported as 82, 39, and 27 meters, respectively, for the LOS, the brick wall, and the human body.

The rest of the paper is organized as follows. Section 2 reviews the related works. Section 3 presents the design of our energy measurement system and its hardware and software implementation details. In section 4, we describe our recommended home-care scenarios. Section 5 discusses the experimental results and findings as well as an in-depth analysis of the observations. The conclusion and future works are discussed in Section 6.

2 Related Works

Many systems have been developed in recent decades to track patients' conditions using WHMS [1], [3], [4], [15]. Mshali et al. [16] have proposed a classification for home-based health monitoring systems. According to their survey, ambient assisted living (AAL), movement tracking and fall detection (MTFD), and physiological health monitoring (PHM) are three main categories of WHMs. Although WHMSs are supposed to be widely used in human daily live, their energy consumption is challenging since a tiny and limited rechargeable battery typically powers them.

Appropriate energy reduction strategies are selected according to the requirements and applications of these systems. Choosing a proper communication protocol is one of the primary methods to reduce energy consumption considered by researchers and practitioners [17]. Each communication protocol has advantages and disadvantages [18], [19], [20]. The Bluetooth protocol is cheaper, easier to use, and consumes less energy than other wireless communication protocols, particularly WiFi protocols. The best option for personal applications is therefore the Bluetooth protocol when high-speed communication is not required.

The latest versions of the Bluetooth protocol are well adapted for the IoT-based home care monitoring applications because of their low energy consumption and more coverage range than other short-range wireless communication protocols [13], [21], [22]. Table 1 summarizes recent studies discussing the BLE's power consumption [21], [22], [23]. Similarly, Table 2 summarizes important studies on the operating range and received signal strength indicator (RSSI) of the Bluetooth protocols.While many studies have investigated the different aspects of the Bluetooth protocol, none of them have examined the mobile phone and BLE v4.2 and v5 module energy consumption and their MERs simultaneously in the WHMSs. Similarly, the existing studies have not considered the impact of various obstacles and the importance of time in different home care scenarios. Our study uses an extensive set of controlled experiments to expose the first empirical evidence on the energy consumption and operating range of the BLE modules in healthcare systems. In the next section, we explain our energy monitoring and measuring platform to analyze the performance of the BLE v4.2 and v5 in the WHMSs.

3 Experiments Design

This section discusses the proposed software and hardware energy monitoring platform and experimental design.

3.1 Proposed architecture

Figure 1 displays a typical WHMS architecture with three layers of sensor, gateway, and server. In the sensor layer, a wearable sensor such as a thermometer, blood pressure, heart, or respiratory rate halter is connected to the human body to monitor and record medical and vital parameters. The sensor transfers the obtained health data via the BLE module to a BLE-supported gateway, e.g., a mobile phone. The gateway receives sensors' data, accomplishes protocol conversion, and provides defined services such as data compression and storage in offline mode. Suppose the mobile gateway has an internet or cellular network connectivity.

Table 1. Related works on the Bluetooth energy consumption.

Scenario	Approach	Results
Connection-less communications: evaluating the performance and energy consumption of the scanning and advertising intervals	Investigation of the latency and power consumption of the BLE v4.2 on an Android-based mobile phone [24].	Considerable energy consumption of the scanning phase of the BLE.
	Analyzing the impact of different internal transmitter parameters of the BLE v4 on efficiency and energy consumption [7].	The key role of the correct settings for the scanning and advertising parameters on the BLE's performance.
	A multi-channel model for finding adjacent devices that use an automatic scanning interval adaptation[25].	Improvement in the speed and efficiency of the scanning and connecting phases.
Connection-oriented communications: measuring the energy consumption after GATT connection	Four simple point-to-point wireless sensor networks (WSN) power measurement methods constructed by Arduino and Bluetooth modules[27].	The transmitting state consumes the highest power regardless of the data rate.
	Investigation of the current consumption and battery lifetime of the peripheral device running version 1.2 of the BLE stack with an oscilloscope [26].	Enables users to estimate their battery life based on their custom usage scenario.

Table 2. Related works on the Bluetooth maximum coverage range and RSSI.

Scenario	Approach	Results
Connection-less communications: Evaluating Bluetooth's protocol maximum coverage range and RSSI.	Conducting some technical investigation to determine the MER of the BLE v4.2 and v5 protocols in indoor and outdoor environments [21].	BLE 5 outperforms BLE4 in terms of signal to noise ratio, communication range and energy consumption.
	Investigation of the effect of beams and concretes on the Bluetooth signals in an indoor positioning system.	The higher speed and lower cost of the proposed method.

In that case, it transmits non-pre-processed real-time signals to the cloud server for further review by clinicians to provide an appropriate diagnosis for the patients, particularly in emergency and stressful circumstances.

In cases where the internet and cellular network connectivity are not available, the gateway stores the compressed raw data and local pre-processed results in its local database. The gateway transmits data packets to the cloud server as soon as the gateway is reconnected.

The back-end server has two components: a cloud server for data analysis and decision-making and a user interface for clinicians that work as a dashboard to control users. In this article, we intend to characterize the energy consumption of both the BLE sensor and the gateway, which is a mobile phone, in our experiment design.

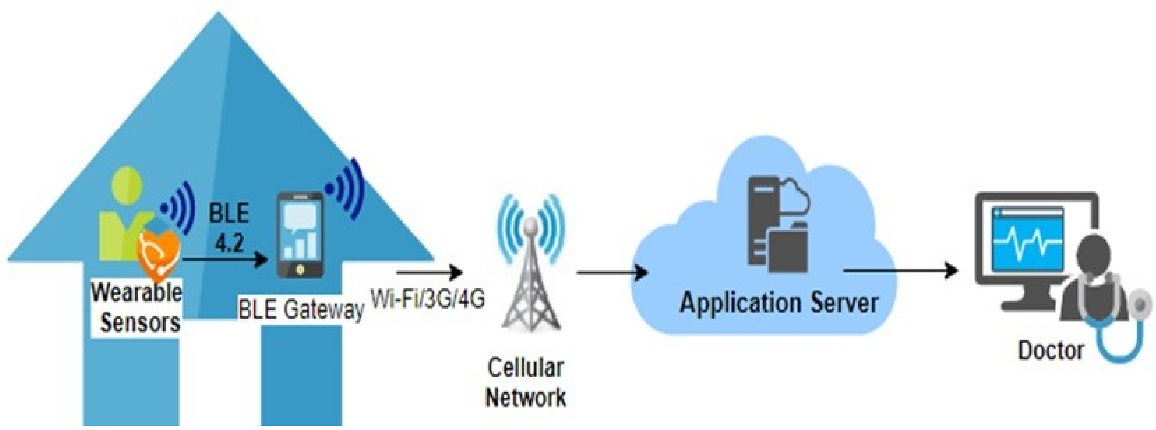


Fig 1. The high level architecture of a remote health monitoring system.

3.2 Energy measurement platform

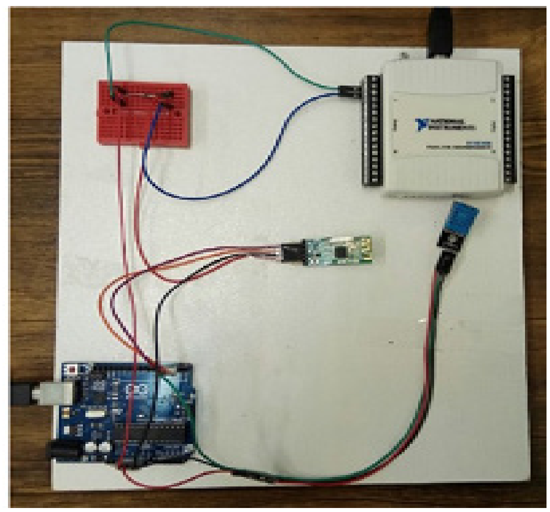
Many Android-based tools are available in the literature for measuring mobile phone power consumption. Battery Manager and Current Widget are two examples of these applications [7]. The main limitation of these measurement tools is that they can only measure the energy consumption at fixed time intervals. For instance, the battery manager only shows the voltage when the battery level changes. Another problem of these applications is the inability to measure the module's power consumption. Hence, these measurement techniques are not appropriate for the purposes of our paper, which needs tiny variations to be calculated over short periods for both the mobile phone and the module simultaneously. Therefore, we need a customized hardware setup to fulfill our requirements and precise energy measurement.

Our proposed hardware setup consists of a mobile phone with BLE v4.2 or v5 support, a BLE v4.2 or v5 modules, and two National Instrument (NI) NI-USB6008 devices which are able to capture the voltage and current variations in a very short period of 100 micro seconds, resulting in 10K samples per second. The data acquisition (DAQ) devices use the LabVIEW software, installed on a laptop, and send samples to the laptop via a USB port. The two mobile phones we use to perform our experiments are 'Nokia 1', which supports BLE v4.2, and 'Samsung A30' with BLE v5 support. We also use Nordic's nRF52832 (HC-42) BLE v4.2 and v5 modules on the Texas Instrument CC2640r2 Launchpad Board with the BLE v5 1MB and 2MB and coded support in the wearable device. The modules are connected to an Arduino Uno board as their power supplier and local processor.

Figure 2a shows the mobile phone energy measurement hardware. The phone battery is like an open battery in the proposed circuit, hijacked at one of its terminals and then serially connected to a 15mΩ shunt resistor. We have connected the National Instrument (NI) NI-USB6008 device to the shunt resistor in parallel. In this way, we can measure the voltage drop through the shunt resistor via LabVIEW at a rate of 1kHz. The voltage drops measurements, along with the start and end timestamps of each scenario, are recorded by LabVIEW at the connected laptops to the DAQ and saved in a comma-separated value (CSV) file. Afterward, using the Ohm law, we measure the current through the shunt resistor, which is the same as the mobile phone's current. To calculate the power consumption, we used the standard power formula, $P = V_b \times I_r$, where V_b is the phone battery voltage, and I_r is the shunt resistor current or phone current computed in the previous step. Finally, the phone's or module's energy consumption in each scenario is computed using equation E = P × t.

Figure 2b illustrates our proposed hardware setup to calculate the module energy consumption, which is similar to the mobile side. However, since the module's voltage and power fluctuations are much smaller than the mobile phone, we had to use a different resistor, a 100Ω military resistor with a 0.1 percent error rate and 0.25W power, to distinguish these slight changes. We conduct the same remaining steps implementation and energy measurement similar to the mobile side. Figure 3 displays the circuit diagram of our energy measurement hardware.

(a) Mobile energy measurement hardware.



(b) Module energy measurement hardware.

Fig 2. Energy measurement hardware setup.

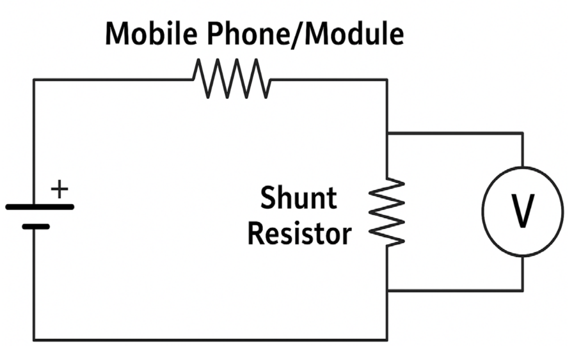


Fig 3. Circuit diagram of energy measurement hardware.

3.3 Software

We have developed an Android application called *BLE Scenarios* to conduct our experiments. Our BLE Scenarios application provides features, including easy and fast connectivity to the BLE modules or other Bluetooth devices, modifying and storing the internal BLE module parameters, and the channel environmental parameters. The internal BLE module parameters in the proposed scenarios include advertising interval, connection interval, and connection slave latency. The channel environmental parameters include the type of obstacles between the mobile phone and the module, ambient, temperature, and humidity. Both categories of parameters influence Bluetooth performance.

Figure 4 shows a screenshot of our BLE Scenarios Android application. After scanning adjacent devices and pairing the mobile phone with the BLE module, the mobile phone starts sending a specific predefined character to the module by pressing the Start Scenario button, shown in Figure 4. When the BLE module receives the start character, the scenario starts, and the module begins to send its predefined data. The data which is sent ten times continuously consists of 100 different five-letter strings. About six seconds later the data transmission is completed and the error rate is reported in a normal situation. The data transmission stops by transmitting another accepted character from the module to the mobile phone. The start and the end timestamps of each scenario are stored in the application at the end of the data transmission process.

To ensure that the two devices are synchronized, we coordinated the two laptops' time and the mobile phone's time via ntp.pool.org, a big virtual cluster of time servers providing a reliable and easy-to-use NTP service for millions of clients. The BLE Scenarios application also holds each five-letter string as criteria in its buffer. Therefore, when the data transmission process is completed, the application compares all the newly received strings with the previously stored strings. Then counts the number of incorrect strings to calculate the error percentage and report it along with the received signal strength indicator (RSSI) and other internal and environmental parameters that we have stored for each scenario. All reported data can be inserted into a database and exported to an excel file for further analysis.

All energy measurement experiments were conducted indoors at the Iran University of Science and Technology (IUST) incubator building. These tests were performed under normal room temperature and humidity conditions. During these tests, WiFi signals were present and a few other electronic devices were present in separate rooms, with obstacles in between, causing some collisions. The maximum effective range (MEF) tests were conducted both indoors and outdoors in the IUST's football stadium. For outdoor tests, only the Bluetooth module, mobile phone, and two laptops used for measurements were present, with no other electronic devices nearby.

In all scenarios, the energy consumption of the Bluetooth module and mobile phone was measured during the transmission and reception of a 1,000-character string. The sending time intervals were varied for each scenario to reach an error rate of less than 0.1% in all cases. Error rates can influence both energy consumption and coverage in BLE systems. Higher error rates require more retransmissions, which use more energy, especially at longer distances or with obstacles. Therefore, there is a tradeoff between reliability and energy consumption, so optimizing error thresholds is essential for achieving a balance between reliability and efficiency in WHMS.

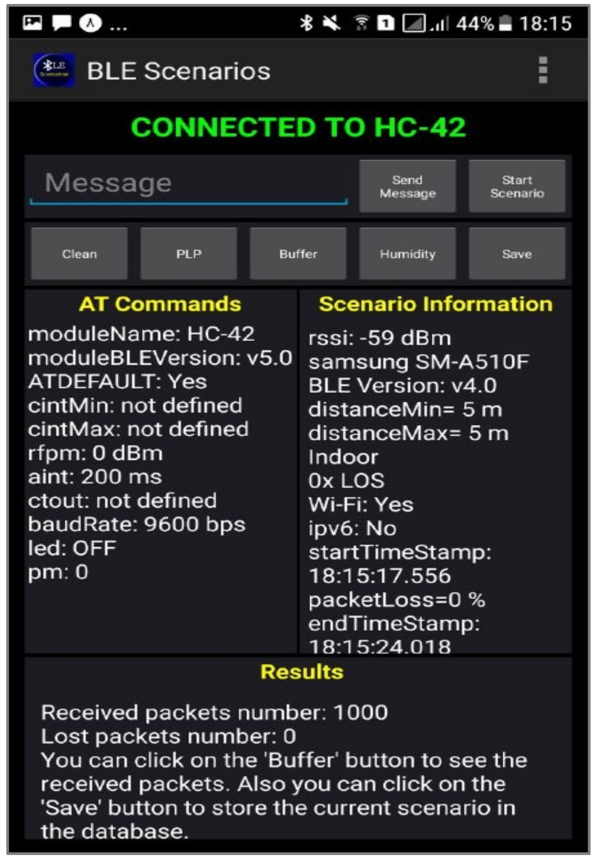


Fig 4. A snapshot of our developed Android application.

Each scenario was checked between 1 to 10 meters and repeated at least five times under the same conditions to ensure the accuracy of results and reach a reliability of 99.9%. Finally, the average energy consumption of all repetitions is recorded as the outcome.

On the module side, the Bluetooth module's LED light was ON, and its internal settings were all in the default mode., All the background processes were turned off to measure the mobile phone energy consumption. Therefore, only the Bluetooth protocol affected the power consumption. In addition, to eliminate mobile battery voltage fluctuations and consider 3.7V in our calculations, the mobile battery charge was held at the level of 95% or above in all cases. The mobile phone screen light was set to 75% brightness in all experiments to prevent any adjustment during our trials. As a consequence, the testing conditions were the same, and our comparisons were fair.

Experimental scenarios are classified into two groups: LOS and Non-LOS. In LOS scenarios, there is no obstacle between the sender and receiver. However, in non-LOS experiments, the impact of four various barriers made of the metal, wood, brick wall, and the human body, on the energy consumption, maximum coverage range, and RSSI was measured and compared with LOS scenarios.

4 Results

In this section, we first measure and illustrate the base power consumption diagram of the mobile phone and the BLE v4.2 module. Then we report their energy consumption after the connection establishment phase and during sending and receiving data from the module to the mobile phone, in LOS or non-LOS scenarios. In the former scenario, Bluetooth signals pass through one of the metal, wood, brick wall, or human body obstacles. After performing each experiment, we report the power consumption diagram of the BLE v5 module and compare its energy consumption with the BLE v4.2.

4.1 Mobile phone and Bluetooth module energy consummation

Figure 5a shows the Bluetooth module's energy consumption when the module is ON and does not connect with other Bluetooth devices. The average power consumption in this state is 3.8mW. While as shown in Figure 5b, in the paired and transmitting mode, the power consumption increased to 5mW on average in 10s. The peak points of the power values in Figure 5b show the triggering of each connection event.

Figure 6a indicates the mobile phone's power consumption over 10 seconds with 10,000 power samples. We keep the phone screen with 75% brightness and intentionally disabled all background processes and communication interfaces (Cellular, Wi-Fi, Bluetooth, etc.). It is observed that the mobile phone's average power consumption is 885mW, while it increases and reaches about 927mW by enabling the Bluetooth interface, shown in Figure 6b.

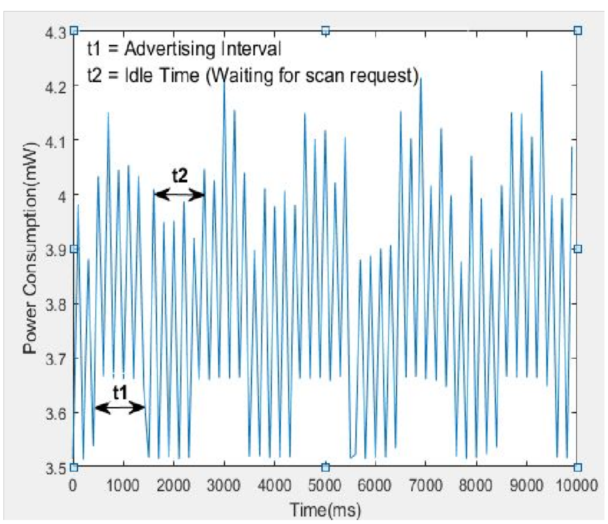
The power consumption rises considerably and gets to 1,350mW after turning the Bluetooth module on and during the scanning intervals. As shown in Fig6c, the mobile phone and the module go into the connected mode after 200ms. An increase in power consumption is noticeable at this phase.

Figure 7 illustrates the energy consumption of both the mobile phone and the BLE module when separated by a distance of 2 meters with the presence of different obstacles. As the figure demonstrated, the human body and brick walls significantly increase energy consumption compared to other obstacles like wood and metal. The human body causes the highest energy usage, consuming 9.3J for the mobile phone and 36.5mJ for the module.

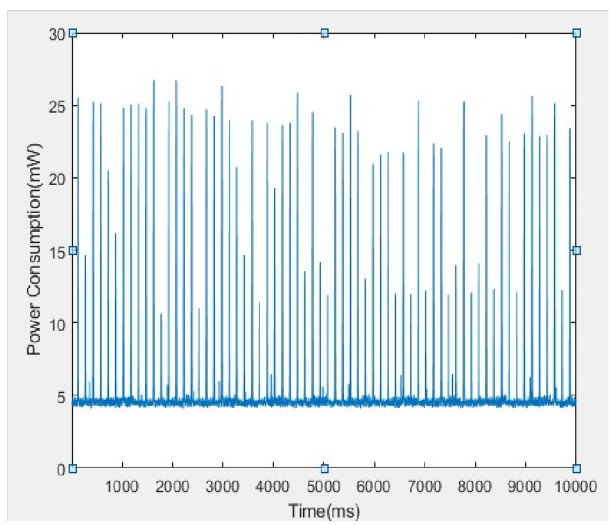
To check the generality of the above findings, we changed the distance between the mobile phone and the module from 1 to 10m, increasing by 1m steps, computed the energy consumption of the mobile phone and the BLE v4.2 module, and repeated the scenarios as long as reaching to reliability more than 99.9%. We keep the distances as short as possible since, in distances longer than 10 meters, energy consumption is mainly affected by the Bluetooth maximum range, not necessarily by the obstacles.

The results of this experiment have been depicted in Figure 8a and Figure 8b.

The figures show the mobile phone and the wearable module energy consumption, respectively. Both figures reveal a similar pattern and confirm our former results.

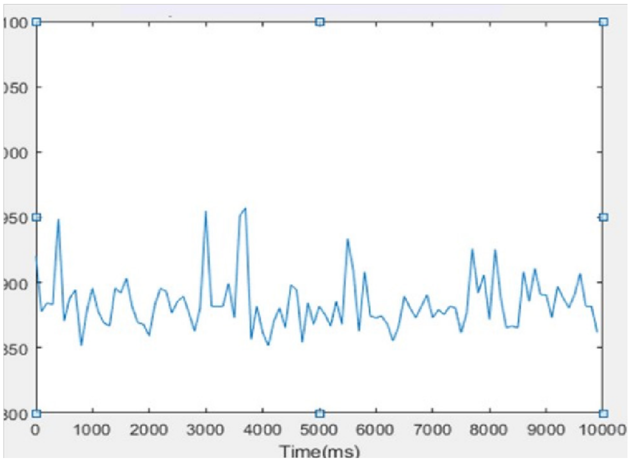


(a) Not connected to another device.

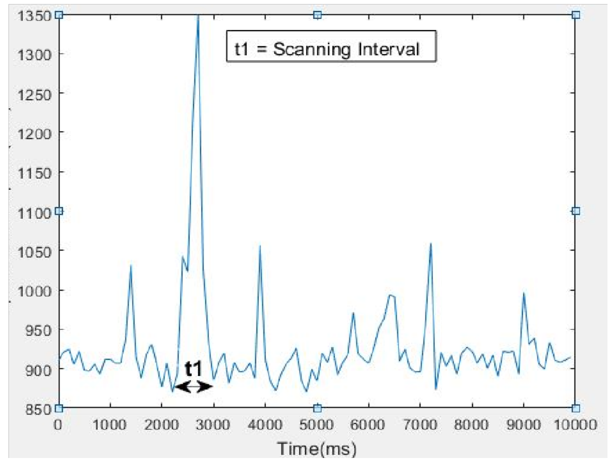


(b) connected and sending data.

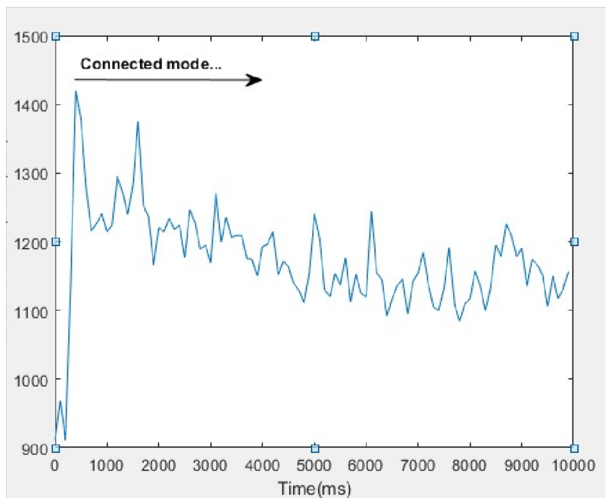
Fig 5. Power consumption of the Bluetooth module



(a) Base power consumption of the mobile phone.



(b) Power consumption of the phone when its Bluetooth is enable.



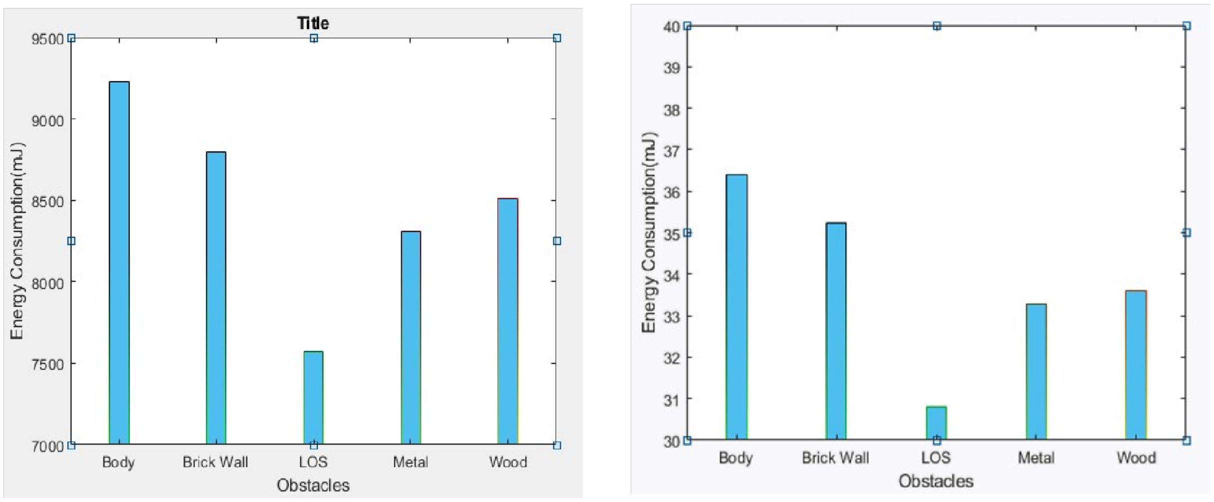
(c) Power consumption of the mobile phone, before and after connecting to the BLE module.

Fig 6. Power Consumption of the mobile phone.

Both the mobile phone and the BLE module show higher energy consumption as the distance increases, with the most significant increase occurring when a human body or brick wall is in the way. The mobile phone uses less energy in line-of-sight (LOS), while the human body leads to the highest energy consumption, highlighting the challenge of dense or absorptive obstacles.

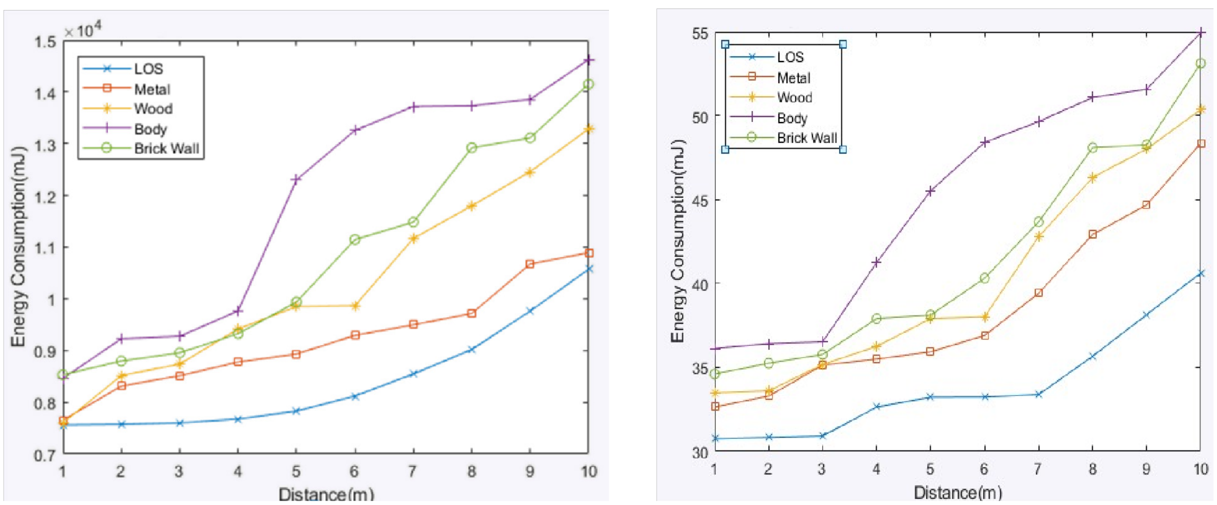
We presented the energy consumption instead of reporting the power consumption because sending and receiving data with an error rate lower than 1% takes more time for the module and the mobile phone, enhancing their energy consumption. Based on the plots in Figure 8, the human body, followed by a brick wall, wood, and metal, has the most negative impact on the mobile phone and BLE module energy consumption in Bluetooth communication.

The thickness of the obstacles is an influential parameter that can acknowledge the energy consumption variations between barriers. Therefore, considering that the thickness of the metal and the wood boxes in our experiments was different is essential when interpreting the results. The metal box was made of a 2mm galvanized sheet, while the MDF wood box was 1.6 mm thick. Moreover, the brick wall's thickness was 35cm. In the human body scenarios, the Bluetooth module was absolutely put between two hands to test certain WHMS medical applications, in which the transmitter antenna is influenced, and the BLE signal absorption and energy consumption enhanced subsequently. Therefore, it shows that if the thickness and the number of obstacles increase then it lead to raising the absorption of the BLE signals which leverages the energy consumption.



(a) Mobile phone. **(b)** Bluetooth module.

Fig 7. The energy consumption in the distance of 2 meters and 0% error.



(a) Mobile phone **(b)** Wearable module

Fig 8. The energy consumption over various distances from 1m to 10m and different obstacles.

Due to our results, other critical factors in determining the energy consumption and maximum coverage range of the Bluetooth protocol are the density and the conductivity of different obstacles.

All energy consumption measurement scenarios for the BLE v5 were performed on two modules: HC-42 and cc2640r2. First, we report the power consumption results of the HC-42 module when it is connected to the Nokia 1 mobile phone, which supports the BLE v4.2. Then we report the results of the Samsung A30 mobile phone with the BLE v5/1MB and 2MB support while sending the default 1,000 letters string. Figure 9 compares the power consumption of BLE v4.2 and BLE v5/1MB during data transmission.

As the plots demonstrate, there is no noticeable change in the transmission speed or power consumption in the BLE v4.2 and BLE v5/1 MB mode, and since their physical data rate is 1MB, their energy consumptions are similar. To compare the power consumption of the BLE v5/1MB and 2Mb, we use the CC2640r2 module. Since the selected module was different, we first measured its power consumption during the advertising phase. We then measured the BLE v5 power consumption in the 1MB and 2MB modes in the connected phase.

The results are shown in Figures 10 and 11. As shown in Figure 10, the average advertising power consumption of the BLE v5/1MB and 2MB are almost the same and are about 10.37mW. Figure 11 shows that the BLE module's power consumption in the BLE v4.2, BLE v5/1MB, and BLE v5/2MB are approximately the same. However, the important thing is that the transmission speed in the BLE v5/2MB is twice the BLE v5/1MB, and such an increase in the transmission speed reduces the time required to send a certain amount of data in half. Therefore, the energy consumption in this case, compared to the BLE v5/1MB, is reduced by about half. We conclude that the BLE v5/2MB is faster than BLE v5/1MB and consumes less energy than BLE v5/1MB. Based on this result, we can decide that BLE v5/1MB is more efficient for applications where fast data transfer is crucial. Overall, the findings highlight the advantages of using BLE v5/2MB for WHMS applications where frequent data communication is required. Considering that battery life is crucial for real-world healthcare monitoring systems, BLE v5/2MB protocol's energy efficiency can help extend the battery life, making it a better choice for these applications.

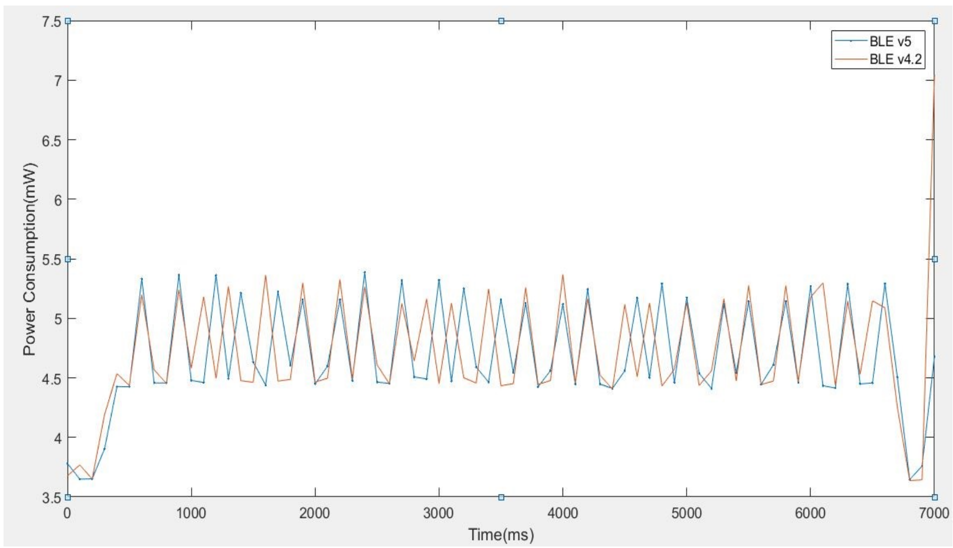


Fig 9. BLE v4.2 and BLE v5/1MB power consumption comparison diagram.

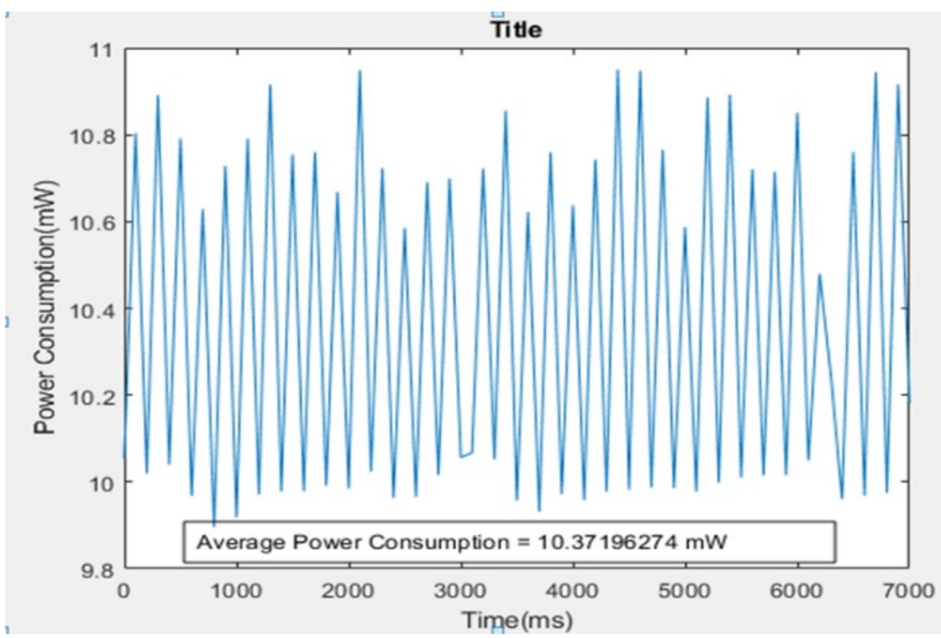


Fig 10. Power consumption diagram of the BLE CC2640r2 module in advertising mode.

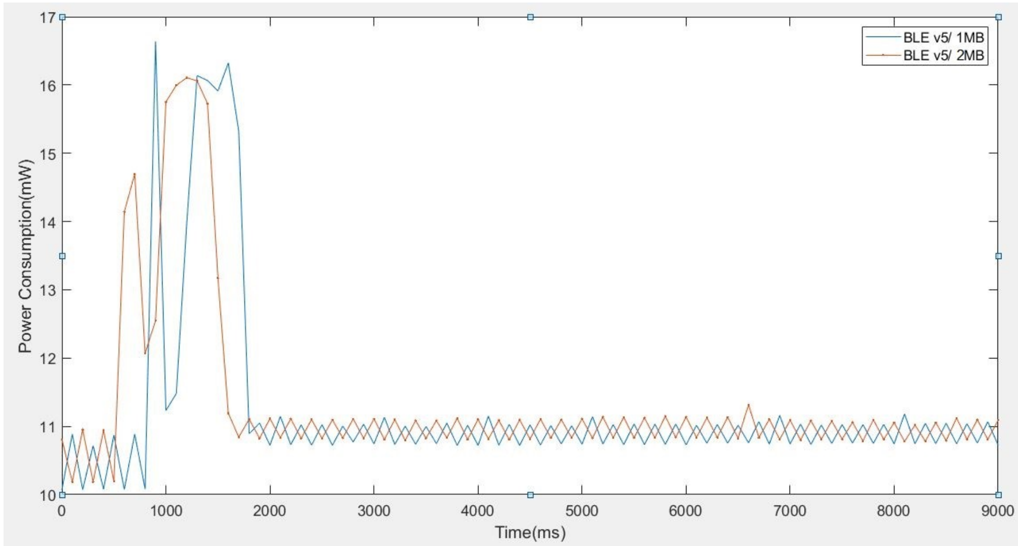


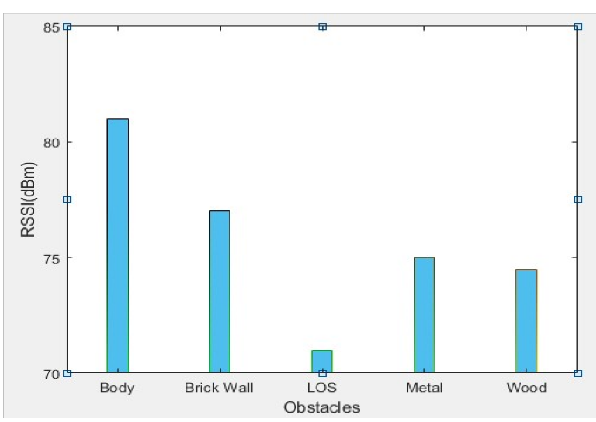
Fig 11. BLE v5/1MB and BLE v5/2MB power consumption comparison diagram.

4.2 Received signal strength indicator

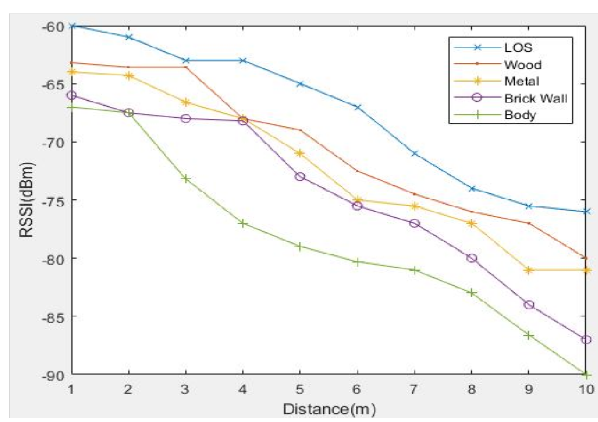
This section examines the relationship between the received signal strength indicator (RSSI), distance, and the number and material of obstacles. All experiments in this section have been performed by Samsung A30 mobile phone and CC2640r2 BLE module. When the mobile phone scans for Bluetooth devices, the Bluetooth radio inside the device measures the RSSI for each visible device. It is the strength of the beacon's signal observed on the mobile phone.

Figure 12 illustrates the RSSI of the wearable module observed by the mobile phone. Figure 12a represents the RSSI for a given distance of 7m, and Figure 12b illustrates the extension of this relationship measurement for distances of 1 to 10 meters. As indicated in Figure 12b, the downward trend of the charts proves that increasing the distance between the sender and the receiver and the presence of obstacles between them reduce RSSI considerably. In the LOS circumstances, the strength of the signal becomes influenced by reflection and the multi-path phenomenon. In contrast, in non-LOS scenarios, signal absorption by obstacles can affect reflection and multi-path phenomenon, and only direct and powerful signals can exist.

It is concluded that dense obstacles with more thickness, such as brick walls and human organs, or obstacles like metal that propagate electromagnetic signals on their surface, have a greater impact on signal absorption. In general, the strength of the signal decreases further if size and number of obstacles between the transceiver and the receiver increase.



(a) At a distance of 7 meters.



(b) At a distance of 1 to 10 meters.

Fig 12. The effect of different obstacles on the received signal strength indicator (RSSI) in different distances.

4.3 Maximum coverage range

This section compares the maximum coverage range of the BLE v4.2, BLE v5/1MB, and BLE v5/2MB protocols tested by HC-42 and CC2640r2 modules. We consider both the LOS and non-LOS situations in indoor and outdoor scenarios in three different states. Tables 3 to 6 summarize the maximum coverage range of BLE v4.2 and BLE v5 protocols under various conditions, including both indoor and outdoor environments. All distances in these tables are reported in meters. We will further explain the meaning of each row in the table, that is, the explanation of the different states.

Table 3 shows the indoor performance of BLE v4.2, where the LOS range is 36 meters in State 3, but obstacles like human bodies reduce it to 18.5 meters. Table 4 presents BLE v4.2's outdoor results, with an LOS range of 42 meters in State 3 that decreases to 23 meters in the presence of a human body. Table 5 highlights BLE v5/1MB's superior outdoor performance, achieving a maximum LOS range of 108 meters but dropping to 29 meters with a human body. Finally, Table 6 focuses on BLE v5/2MB, which has a slightly lower LOS range of 82 meters but offers better energy efficiency due to its faster data transmission.

The rows of each table show different states. For State 1, the maximum distance is reported where just the SSID of the BLE module is visible at the mobile site, but the connection cannot be established. For instance, the maximum and minimum ranges for this state, shown in the first row of Table 5, are around 120m and 41m, respectively, for the LOS and human body.

In State 2, the maximum ranges are reported for connecting to the GATT server and discovering its services. GATT is an acronym for the generic attribute profile, which describes how two BLE devices can be connected and start communicating and transferring data using the predefined services and characteristics. After the advertisement phase, the mobile phone will send a "start request" to the sender which would be accepted by the sender device and finally it lead to pairing two devices which finally cause igniting the service discovery phase. If the connection is robust, the characteristic discovery process and data transmission procedure begin in this stage, otherwise the GATT connection and service discovery phase may be completed successfully but the transmitter and the receiver cannot start sending data due to the poor quality of the established connection. Indeed, if they start a communication over an unstable connection, the connection is probably destroyed soon because of the high error rate. In this state, as expected, the maximum and minimum coverage range of the BLE modules occurs in the LOS and human body scenarios, respectively, with 118m and 37m, shown in the second row of Table 5.

Finally, in State 3, the maximum range we could reliably send/receive data to/from the module was measured and recorded. According to the values in the third row of Table 5, 108m and 29m are the maximum and minimum ranges reported in this stage, respectively, for LOS and human body scenarios. However, according to the RSSI findings in Section 5.2, it has been proven that the maximum coverage range reduces, and the connection establishment becomes difficult at longer distances. In conclusion, these results show the impact of obstacles like human bodies and walls on Bluetooth performance and highlight the benefits of BLE v5 over v4.2 for WHMS applications.

Table 3. Maximum Coverage Range of BLE v4.2 Protocol, tested by HC-42 module, considering different types of barriers in indoor situations in three different states

Scenario	LOS	Metal	Wood	Human	Brick wall
State1	40	36	37	33	35
State2	38	35.5	35	25	28
State3	36	29	29.5	18.5	25

Table 4. Maximum Coverage Range of BLE v4.2 Protocol, tested by HC-42 module, considering different obstacles in outdoor situations in three different states.

Scenario	LOS	Metal	Wood	Body	Brick wall
State1	59	41.5	43	37	40
State2	56	40	38.5	29	35
State3	42	37	36	23	33

Table 5. Maximum Coverage Range of BLE v5/1MB Protocol, tested by CC2640r2 module, considering different obstacles in outdoor situations in three different states.

Scenario	LOS	Metal	Wood	Body	Brick wall
State1	120	72	73	41	60
State2	118	66	65	37	48
State3	108	58	63	29	45

Table 6. Maximum Coverage Range of BLE v5/2MB Protocol, tested by CC2640r2 module, considering different obstacles in outdoor situations in three different states.

Scenario	LOS	Metal	Wood	Body	Brick wall
State1	92	57	56.5	36	48
State2	85	53	51	30	45
State3	82	45	49	27	39

5 Discussion

The results of this study align with existing research on Bluetooth energy consumption and maximum effective range. For instance, prior studies have demonstrated that Bluetooth Low Energy (BLE) v5/2MB, despite its higher transmission speed, consumes less energy than BLE v5/1MB due to reduced transmission time for the same amount of data [12]. Moreover, our findings that BLE v5/1MB has a maximum effective range of 108 meters in line-of-sight (LOS) conditions, decreasing to 45 meters and 29 meters with brick walls and human body obstacles, respectively, are consistent with studies highlighting the significant impact of dense materials on Bluetooth signal strength and range [20]. Additionally, our results corroborate with the Bluetooth Special Interest Group's guidelines indicating an effective range varying from under a meter to over a kilometer, depending on environmental factors such as obstacles, transmit power, and antenna gain. This comparison underscores the reliability and generalizability of the reported findings within the broader context of BLE research.

6 Conclusion and Future Work

Continuous monitoring and communication tasks can deplete sensors' batteries quickly. Hence, energy consumption is one of the most significant issues in wearable home-care monitoring systems (WHMSs). New versions of the IEEE 802.15.1 protocol, known as Bluetooth low energy, significantly reduce the energy consumption and increase the MER of the WHMSs. However, the researcher has not performed an extensive experimental study on energy consumption and the MER of the IEEE 802.15.1 protocol in the presence of various home obstacles. In this paper, a novel hybrid tool has been implemented i.e., both software and hardware tools are employed, which can measure and compare the exact energy consumption, error rate, and received signal strength indicator of the BLE v4.2 and BLE v5/1MB and 2MB modes. We consider different home-care situations, in LOS and non-LOS situations, with the presence of wood, concrete, brick wall, human body, and other common obstacles.

We show that the BLE v5/2 MB's energy consumption and MER are less than the BLE v5/1MB due to its higher transmission speed. We also illustrate that the BLE protocol's highest energy consumption and lowest coverage range happens when there is a human body or brick wall obstacle between the sender and receiver. Our detailed measurements demonstrate that the MER of the BLE v5/1MB is 108m in the LOS scenarios, which decreases to around 45 and 29m in the presence of the brick wall and the human body.

Furthermore, the effective range of the BLE v5/2MB is about 80% of the BLE v5/1MB in all cases due to its higher transmission rate. Finally, considering the energy consumption and maximum range results, it concludes that the BLE v4.2 and v5 protocols are highly appropriate for use in WHMS applications. Future works can be focused on repeating our experiments with different mobile phones and Bluetooth modules to check the correctness of our results. Investigating the impact of the Bluetooth module antenna and other obstacles on the coverage range and energy consumption of the WHMS modules are also recommended as future work in this direction.

Conflict of Interest

All of the authors declares that they have no conflict of interest.

Authors' contributions

Nasibeh Heshmati Moulaei: Methodology, Formal analysis, Visualization, Data Curation, Writing - Original Draft.

Seyed Ali Seyedalian and **Alireza Sinaee Oskouie:** Developing the energy measurement platform and data collection.

Eisa Zarepour: Leading the research

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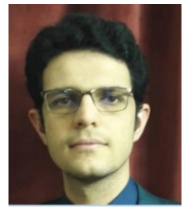

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