Internet of Things 25 (2024) 101124

Contents lists available at ScienceDirect

Internet of Things

journal homepage: www.sciencedirect.com/journal/internet-of-things

Research article

LoRaWAN-based hybrid internet of wearable things system implementation for smart healthcare

Suliman Abdulmalek [a,b], Abdul Nasir [a], Waheb A. Jabbar [c,*]

[a] Faculty of Electrical & Electronics Engineering Technology, Universiti Malaysia Pahang Sultan Abdullah, 26600 Pekan, Pahang, Malaysia
[b] Biomedical Engineering Department, Faculty of Engineering, University of Science and Technology, Aden, Yemen
[c] College of Engineering, Faculty of Computing, Engineering and the Built Environment, Birmingham City University, Birmingham B4 7XG, UK

ARTICLE INFO

Keywords:
FiPy
IoT
IoWT
Healthcare
LoRa/LoRaWAN

ABSTRACT

This study introduces the design and development of an Internet of Wearable Things-based Hybrid Healthcare Monitoring System (IoWT-HHMS) for smart medical applications. The system incorporates smart wearable sensing units for real-time, remote monitoring of vital health parameters such as Blood Pressure (BP), Heart Rate (HR), and Body Temperature (BT). A key innovation is the development of a hybrid wireless network communication mechanism within the IoWT-HHMS, utilising the FiPy microcontroller. This mechanism supports both short- and long-range connectivity and integrates an algorithm for efficient data acquisition and updating to the IoT platform. The IoWT-HHMS has undergone extensive testing and validation across various scenarios, including sensor functionality, performance of Wi-Fi and LoRaWAN networks, hybrid network connectivity, and accuracy assessment using the Datacake dashboard. The tests evaluated crucial aspects such as communication reliability, power consumption, and latency. The results demonstrate the system's high stability and accuracy in reading health parameters. Comparisons with reference devices reveal impressive accuracy levels for Systolic BP (SBP), Diastolic BP (DBP), HR, and BT, recording 96.37 %, 95.17 %, 97 %, and 98.57 % accuracy, respectively. Both Wi-Fi and LoRaWAN networks proved reliable in indoor and outdoor settings, maintaining data transmission over distances up to 1.5 km without data loss. In conclusion, the developed IoWT-HHMS shows great promise for efficient and effective real-time remote monitoring of patients' health conditions using an innovative hybrid wireless network communication mechanism.

Introduction

In the evolving landscape of the Internet of Things (IoT), the integration of smart healthcare technologies has seen significant advancements. IoT, connecting various elements for efficient data exchange, plays a pivotal role in healthcare applications [1,2]. The Internet of Wearable Things (IoWT) is particularly instrumental in this context, enabling real-time monitoring of vital health parameters critical for managing chronic diseases [3–5].

Medical devices' evolution alongside IoT technology has transformed healthcare systems, promoting a proactive approach encompassing prevention, diagnosis, and treatment [6]. Remote health monitoring and telemedicine have become increasingly

---

* Corresponding author.
E-mail address: waheb.abdullah@bcu.ac.uk (W.A. Jabbar).

https://doi.org/10.1016/j.iot.2024.101124

important, especially during the COVID-19 pandemic, extending healthcare beyond traditional settings [7].

IoWT, with its wearable sensors and microcontrollers, underpins modern smart healthcare systems, utilising real-time data transmission to enhance patient monitoring [8]. The IoWT market's growth in healthcare presents both opportunities and challenges, notably in creating intelligent Body Sensor Networks (BSN) for continuous health metrics monitoring [9].

The emergence of telemedicine marks a shift towards patient-centric care, enabling continuous monitoring and improved patient-provider communication [10]. This shift has spurred the development of innovative health monitoring technologies, making patient health management more accessible and efficient.

Our work employs LoRa/LoRaWAN technology, recognised for its range and low power in the LPWAN landscape, to address the need for reliable communication in healthcare monitoring systems [11]. The integration of LoRa/LoRaWAN is central to our goal of developing a practical, accessible healthcare monitoring system [12,13].

This paper introduces an advanced IoWT-HHMS, merging cutting-edge IoT technologies with smart wearable sensors for continuous, real-time patient monitoring. Our research contributes significantly to remote monitoring capabilities, offering a reliable solution for smart healthcare applications.

Motivations and problem statement

Health support should be crucial in today's world due to many health issues. Heart disease and its health effects are increasing daily, and more people are becoming seriously ill because of their modern physical and mental state [8]. Around 80 % of older adults suffer from heart disease. One of the most common heart diseases is hypertension [14,15]. When the number of patients increases, the number of doctors available decreases [16]. As a result, diagnosis may be delayed, and other patients may suffer and be missed. This strategy makes patients more dependent on doctors for their check-ups [17]. Sudden death can occur because of acute health problems. Numerous people worldwide die unexpectedly due to a malfunction in one or more body organs. These organs show abnormal symptoms before the situation worsens, leading to death [18]. Therefore, the adoption of a remote medical monitoring system will provide a permanent answer to many of the challenges that patients experience when they are away from healthcare facilities.

In terms of wearable sensors utilisation, some systems are used to measure one or two parameters, but they ignore others. Moreover, most systems that use Arduino [19,20] or Raspberry Pi [21,22] or ESP-32 [23] as a microcontroller, can support only one wireless communication technology either short-range (Bluetooth, ZigBee, Wi-Fi) or long-range (cellular). There are no ready/available devices and systems that simultaneously support short-and long-range communication technology. Hybrid wireless communication is not supported at the same time by any of the IoT healthcare systems that are already in use. This represents a challenge to secure a highly reliable communication medium to transmit the data between the wearable sensors attached to the patient's body to the healthcare service provider at the medical facility under various connectivity conditions. Therefore, there is a high demand to propose an IoWT healthcare system with a hybrid network architecture to ensure reliable and efficient data transmission from wearable sensors to the IoT platform over the wireless medium. The system should be able to gather data from wearable sensors that are accurate and efficient enough to monitor health conditions continuously without disrupting patients. The data will be sent over a suitable communication interface (short or long range) to the gateway which in turns forward the data to the Internet. Both patient and healthcare professionals can access the data in real-time via an IoT dashboard.

Nowadays, a variety of smart IoT healthcare sensors are available for monitoring HR, BP, glucose level, electrocardiogram (ECG), muscle/electromyography sensor (EMG), BT, airflow (breathing), and blood oxygen saturation while ensuring that patient's health is monitored continuously in real-time [24]. Key challenges with remote monitoring sensors of the patient are to ensure data accuracy, transmission reliability, and privacy during the acquisition, processing, and transmission of highly personal data by IoT networks [25,26]. Such challenges are related to wearable sensors, embedded microcontrollers, and communication mediums. The exploited microcontrollers in the existing IoT healthcare systems have limitations in terms of data processing capabilities, sensor compatibility, and wireless technology utilisation. As a result, the quality of care and the patient's condition will be negatively impacted. Researchers may provide a viable solution to this challenging subject by testing and evaluating a system regarding data accuracy, communication reliability, and power consumption. So, the problem statements can be summarised as follows: most older adults worldwide suffer from heart disease, especially hypertension; no ready/available devices and systems that support hybrid wireless communication simultaneously. Such challenges with remote monitoring sensors are related to data accuracy, transmission reliability, and embedded microcontrollers.

Research contributions

This paper introduces a pioneering approach in the realm of wearable healthcare technology, encapsulating the development of a novel IoWT-based Hybrid Healthcare Monitoring System (IoWT-HHMS). This system represents a significant leap forward in smart medical applications, characterised by its innovative design and multifaceted contributions to the field.

(i) Innovative *Wearable Sensing Unit:* At the heart of our system lies a state-of-the-art wearable sensing unit, ingeniously integrated with a FiPy microcontroller unit. This unit is a cornerstone in our research, enabling real-time and remote monitoring of critical health parameters such as Blood Pressure (BP), Heart Rate (HR), and Body Temperature (BT). The design transcends traditional healthcare monitoring methods, offering a solution that facilitates continuous health tracking in various environments, thus filling a critical gap in current healthcare practices.

(ii) *Revolutionary Hybrid Wireless Communication Mechanism:* A pivotal contribution of our research is the introduction of a hybrid wireless network communication mechanism. This innovative mechanism, embedded within the IoWT-HHMS, uniquely combines short- and long-range connectivity, overcoming the prevalent communication constraints observed in existing systems. By harnessing the advanced capabilities of the FiPy microcontroller, coupled with a sophisticated data acquisition algorithm, our system ensures uninterrupted and reliable health monitoring. This integration marks a transformative step in enhancing communication efficiency in wearable healthcare devices.

(iii) *Comprehensive System Evaluation and Validation*: Our research extends beyond system development to encompass a thorough evaluation and validation of the IoWT-HHMS. We have meticulously assessed the system's performance, focusing on data accuracy, communication reliability, and response time. The results from this rigorous evaluation demonstrate the system's exceptional efficacy and dependability, setting new standards in remote patient monitoring technologies. These evaluations substantiate the system's practicality and effectiveness in real-world scenarios.

Collectively, these contributions signify a paradigm shift in wearable healthcare technologies. The IoWT-HHMS, as developed and validated in this research, paves the way for a new era of smart, efficient, and reliable medical applications. This work not only addresses current challenges in the healthcare sector but also lays the groundwork for future advancements in remote patient monitoring systems. For the sake of improving readability, we have listed the utilised abbreviations and notations in Table 1.

The structure of the rest of this paper unfolds as follows. The subsequent section delves into a comprehensive review of related works. Following that, in Section III, the methods and materials adopted for this research are presented. The ensuing discussion in Section III also revolves around the system architecture and the implementation of the proposed methodology. Section IV provides a detailed account of the obtained results and their respective discussion. Finally, the paper culminates in Section VI with a conclusion encapsulating the key takeaways from the research, along with a glimpse into potential future works.

Related works

In this section, we provide a review of the current state of the art in the field of wearable technology, particularly those integrated into IoT paradigm, for healthcare monitoring systems. This encompasses both the stand-alone wearable health devices and hybrid healthcare monitoring systems that synergise with traditional healthcare methods. Furthermore, we delve into the usage of these systems in the context of smart medical applications, including remote patient monitoring, early disease detection, health status prediction, and personalised healthcare delivery. The exploration of these studies helps us understand the present landscape, identify the gaps in the current research, and highlight the potential for future investigations in the area of IoT-based wearable healthcare systems. This evaluation will also contribute to the design and development of an advanced hybrid healthcare monitoring system that leverages the power of wearable IoT devices for innovative medical applications.

One notable work is presented by Wu et al., who developed a wearable device that monitors various physiological signals, such as ECG, HR and BT. BP can be estimated from ECG and PPG by measuring pulse arrival time (PAT). All components are designed in a rigid framework, making it easy for the human body to interact with remote health monitoring programs. This novelty is accompanied by low power consumption and the possibility of communicating wirelessly for customised measurements of a specific physiological

Table 1
Notations and terminology.

Term/symbol	Description
IoWT-HHMS	Internet of Wearable Things-based Hybrid Healthcare Monitoring System
IoWT	Internet of Wearable Things
BP	Blood Pressure
HR	Heart Rate
BT	Body Temperature
SBP	Systolic BP
DBP	Diastolic BP
SpO2	Peripheral Capillary Oxygen Saturation
ECG	Electrocardiography
EMG	Muscle/Electromyography
IoT	Internet of Things
TTN	The Things Network
LoRa	Long Range
LoRaWAN	Long Range Wide Area Network
LPWAN	Low Power Wide Area Network
BSN	Body Sensor Networks
MCU	Microcontroller Unit
Wi-Fi	Wireless Fidelity
GSM	Global System for Mobile Communications
BLE	Bluetooth
GSR	Galvanic Skin Response
PAT	Pulse Arrival Time
IDE	Integrated Development Environment

signal. Physiological measurements can be wirelessly transferred to a gateway using a BLE module. Data encryption is used on both the sensor patch and the gateways to secure data during transmission for privacy and security reasons. A smartphone and a Raspberry Pi module have been used as a gateway to connect the wearable sensor system to the Internet cloud, where health data can be saved and evaluated. Apart from consuming low energy, BLE technology cannot be used for higher data rates and long-distance wireless communications, making it an open issue [24].

The comprehensive review [2] on the Internet of Things in healthcare provides an extensive overview of the current state and future directions of IoT applications in the medical field. Their study emphasises the rapid expansion of IoT in healthcare, highlighting the key areas of research and development. The authors analyse the latest advancements and potential challenges, focusing on how IoT technologies such as wearable sensors, data analytics, and cloud computing are reshaping healthcare delivery. Their findings underscore the crucial role of IoT in enhancing patient care and the efficiency of healthcare systems. This study aligns with our research by reinforcing the importance of IoT, particularly in the development of advanced healthcare monitoring systems like the IoWT-HHMS.

Another group of researchers developed smart healthcare to record patients' vital signs such as HR and BT and some indicators of hospital room conditions, including humidity and CO and CO2 levels. For all cases of the modern healthcare system, the rate of success between observed data and actual data is roughly more significant than 95 %. Authentic medical professionals can monitor the tests in real-time inside and outside the hospital. The technology can also help nurses and doctors in epidemics or crises because raw medical data can be examined quickly. The prototype that was created is incredibly easy to design and use. In the event of infectious diseases, such as a novel coronavirus (COVID-19) treatment, the method is quite helpful. The new system will improve the current healthcare system, potentially saving many lives. However, the system needs to be examined and enhanced by including some epidemic-related sensors [27].

Authors in [10] developed a mobile phone IoT healthcare monitoring system. The system can remotely monitor vital parameters such as ECG signal, HR, SpO2 and the BT of patients. An Arduino has been used for the measurement and process of this system. The data is sent by Wi-Fi to an IoT platform called Blynk. Blynk is used as a cloud service for monitoring in real-time, and they enable Blynk as a mobile app. For security and privacy, they send the results to a specific smartphone to be monitored by the doctor. Thus, two microcontrollers have been used, Arduino and NodeMCU, that need to improve. For long-range transmission, Wi-Fi technology is not the ideal option.

Hamim et al. [6] presented an IoT healthcare monitoring system for patients and older adults based on an Android application. This prototype consists of a heart pulse sensor, BT sensor and galvanic skin response (GSR) sensor. All sensors were compounded together into a single system with Arduino Uno and Raspberry Pi. The data acquired from the sensors is transferred to cloud storage via the Raspberry Pi. An Android application was developed using Android Studio, where the health parameters captured from patients can be visualised. Doctors can prescribe essential prescriptions by using an application to follow the patient's health over time.

Swaroop et al. designed a real-time health monitoring system based on IoT and Raspberry Pi 3. Data origination, acquisition and processing, communication and access are the primary stages of the system's structure. Health vitals like HR, BT, and BP were measured. The data is transmitted through multiple modes like BLE, GSM, and Wi-Fi, which means data transmission using a mobile application, messaging service, and Internet. It was observed that the latency is low, and no considered delay between sending and receiving data. Thus, the system's accuracy is limited to the accuracy of the sensors [14].

Gupta outlines an Internet-of-Things-based healthcare system for obese patients. The prototype is a fully functional device that measures body characteristics such as HR, oxygen saturation, BP, and BT. The system uses an Arduino board to store medical records for multiple patients at once and then transmits the data to healthcare providers through a Wi-Fi module for remote monitoring. This device is excellent for regular surveillance of bodily conditions, and clinicians can utilise the recorded data to study patient health patterns over time in order to monitor any changes that could be a symptom of an underlying undiscovered health issue. Consequently, long-range communication may be a challenge to this system [28].

In [29], the authors designed an IoT vital sign monitoring system to aid medical staff in monitoring and diagnosing patients' issues. The system utilises sensors to collect vital signs like HR, BP and BT. It has used Raspberry Pi to collect sensor data and process it before sending it to the cloud. The data can be accessed remotely using a mobile app that gives simple access to medical personnel. The vital sign data retrieval findings indicate that the instrument was constructed correctly, and the system has been tested and evaluated with good accuracy.

Another group of academics described a real-time health monitoring system based on the IoT. The suggested solution includes a mobile application and GSM for continuous wireless patient monitoring. Vital parameters are tracked using sensors, and the data acquired by the sensors is transferred to the cloud via a Wi-Fi module. There has been developed a wireless healthcare monitoring system that can deliver real-time internet information regarding a patient's condition. Sensors, a data acquisition component, a microcontroller (ESP32), and software make up the system. The system monitors, displays, and stores the patient's temperature, HR, ECG, BP, and SpO2 regularly, and the information is delivered to the doctor's mobile phone, which contains the application. In addition, if any of the parameters exceed the threshold value, a message is delivered to the doctor's mobile phone. As a result, an IoT-based real-time health monitoring system can continuously monitor a patient's health and save their life. On the other hand, the prototype must be examined, tested, and reorganised [30].

In [31], authors explored the diverse applications of IoT in healthcare, emphasising the impact of IoT technology on patient monitoring and healthcare systems. They highlight the evolution and integration of IoT in various healthcare aspects, including remote health monitoring, assisted living, and the management of chronic diseases. The study discusses how IoT enhances patient care by enabling continuous monitoring through Wireless Body Area Networks (WBANs), which consist of small, smart devices that wirelessly communicate patient data. This research underscores the importance of IoT in healthcare, aligning with our work on the IoWT-HHMS, and adds to the understanding of how IoT technologies can revolutionise patient monitoring and healthcare delivery.

Another study presents an IoT-enabled vital sign monitoring system. The technology can track various vital signs in real-time and store the data locally. Data can also be sent to the cloud for further analysis. The system detects abnormalities, sends out alerts, and automatically calculates the early warning score. To eliminate the burden and maintenance costs of the central medical server, an

Table 2
Comparison between the current existing healthcare monitoring system-based IoT.

Ref	Hardware/software technology	Contributions	Advantages	Limitations
Wu, et al. [33]	- Measure ECG, HR, BT, and estimate BP by PAT - Use the BLE module for transmission. - Use a smartphone as a mobile gateway and Raspberry Pi 3 as a fixed gateway.	Develop a small wearable sensor patch that can assess a variety of physiological signals.	- The system is designed in a rigid-flex structure. - Sensors can be disconnected from the central board.to save energy. - Data is encrypted. - Message queuing telemetry transport (MQTT)	Range and Bandwidth limitations
Islam, et al. [27]	- Measure HR, BT, room humidity, and the level of CO and CO2 gases. - Use ESP32 for processing and transmission.	Propose a smart IoT healthcare system that can monitor a patient's basic health signs and room condition in real-time.	The system is useful in case of infectious disease.	- The system appears to be big. - Need to add some vital sensors to be useful in the epidemic.
Al-Sheikh and Ameen [18]	- Monitor HR, SpO_2, ECG and BT. - Use NodeMCU and Arduino to collect, process and send data through Wi-Fi to the cloud.	Design an IoT healthcare monitoring system using a mobile phone.	- For privacy and security, results are sent only to the patient's doctor's mobile phone. - Develop a mobile phone app named Blynk.	- The system used two microcontrollers - Wi-Fi technology is not the best option for long-range.
Hamim, et al. [6]	- Detect HR, temperature, GSR - Utilise Arduino for processing and Raspberry Pi 3 is the gateway.	Develop a prototype of IoT Based Remote Health Monitoring System.	- Design an Android app to access the Google Firebase Database. - Data is encrypted and can be accessed by authorised personnel.	- The system used two microcontrollers that make it quite big.
Swaroop, et al. [14]	- Monitor HR, BT and BP. - Using Raspberry Pi 3 with BLE adaptor and USB GSM module.	Enhance healthcare delivery by communicating multiplexed data over three modes – BLE, GSM and Wi-Fi.	- The data can be accessed in multiple modes. - Sending alerts to caregivers with no delay. - Reduce the risk of losing track of the patient if one mode interrupts or fails.	- Accuracy depends on the sensors. - Raspberry Pi 3 needs adaptors for using BLE and GSM.
Gupta, et al. [28]	-Measure SpO_2, BP, BT and pulse rate. -Using Arduino and ESP8266 Wi-Fi Module.	Design a real-time IoT healthcare for monitoring and evaluating the health conditions of obese adults and storage data for multiple patients.	- The device is efficient, portable and user-friendly. - The doctors and patients are alarmed in abnormal situations.	- Use two microcontrollers for processing and transferring. - For longer-range applications, Wi-Fi is not recommended.
Alamsyah, et al. [29]	- Sensing HR, BP, and BT. - Raspberry Pi for processing and communication with the Internet using Wi-Fi technology	Fabricate an IoT-based vital sign monitoring system to assist medical personnel in diagnosing the patient's illness.	Medical staff can access patients' data through an android device.	Wi-Fi technology is not preferred in the long-range application.
Sangeethalakshmi, et al. [30]	- Detect temperature, HR, ECG, BP and SpO_2. - ESP32 for acquisition and processing. - Send the data to the cloud via a Wi-Fi module.	Develop an IoT-based real-time health monitoring system to monitor the condition of patient's health and save their life on time.	- An application has been developed on a doctor's smartphone to monitor patients' parameters. - A message is sent to the doctors mobile if any of the parameter crosses the threshold value.	System needs to be evaluated, tested and reorganised.
Sahu, et al. [31]	- Monitor HR, SpO_2, temperature and ECG - BLE technology.	Created an IoT-enabled vital sign monitoring system.	- An Android application. - High accuracy.	Not applicable for long-range communication.
The proposed IoWT-HHMS system	- Detect BT, HR, and BP. - Using FiPy Pycom embedded system with five communications technologies.	Design an IoWT-based hybrid network to monitor patients' conditions.	- Short and long range - Real-time system - The data can be accessed in multiple modes. - Useful during the Covid-19 epidemic.	

Android application is designed to store vital sign records on a personal server. The presented system is simple, compact, portable, and easy to use in a personal service application. Also, the system has been tested and evaluated with most other systems in the field [32].

The studies discussed above illustrate the notable advancements and innovations in the field of IoT-based wearable healthcare monitoring systems. However, upon a detailed analysis, a few potential research gaps surface that our proposed system aims to address. First, many of these studies employ devices that have limitations regarding long-range communication and high data rate transmission. Second, while some systems have excelled in monitoring specific health parameters, there is a need for a more holistic approach to health monitoring, integrating a broader spectrum of vital signs and environmental parameters. Third, while many of these systems are capable of real-time monitoring and data transmission, they lack comprehensive and intuitive user interfaces for both patients and healthcare providers. Moreover, there is a need for advanced data analytics to predict health trends and detect anomalies. Lastly, the consideration of privacy and security in these systems, though present, needs further enhancement. By addressing these gaps, our proposed system intends to offer a more efficient, comprehensive, and user-friendly solution for remote healthcare monitoring and smart medical applications. Table 1 summarises and compares the most recent related studies on IoT-based healthcare applications. Table 2 summarises and compares key features of selected recent studies on IoT-based healthcare monitoring systems with the proposed the proposed IoWT-HHMS.

Methods and materials

Research methodology

This The overall methodology adopted in this paper is shown in Fig. 1. The traditional method issues and healthcare systems were identified by conducting a comprehensive literature review on previous remote healthcare monitoring systems studies. Following that, five main phases are adopted for the general descriptive research methodology. These phases include different stages and research activities in conjunction with the detailed hardware and software development environment. The involved research phases in this

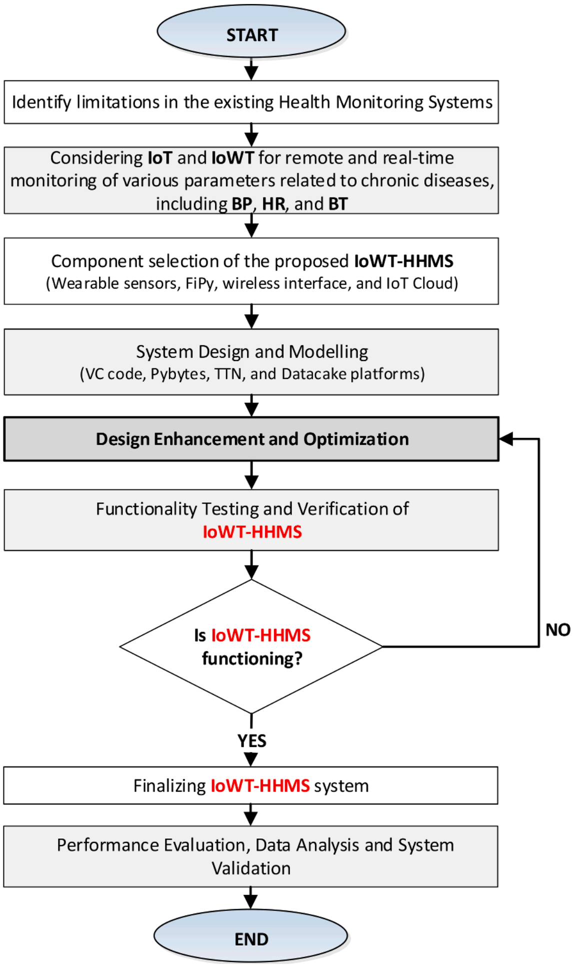


Fig. 1. Flowchart of the research activities.

study can be summarised as follows:

(i) *Phase I* – Considering the remote healthcare system based on IoT technologies as the focus of this study with specific consideration of IoWT since it is the most suitable for real-time monitoring in smart healthcare applications. Parameters related to chronic diseases are also selected due to their direct relation with health problems during the Covid-19 pandemic.

(ii) *Phase II* –Focusing on components selection, including the wearable sensors and all of the hardware components utilised in the construction of this system are compatible with remote monitoring. This includes the selection of wearable sensors, microcontrollers, wireless interfaces, and IoT clouds. The priority is to ensure the safety of people suffering from chronic diseases, reduce the need to travel during pandemic situations and locations such as Covid-19 and improve the accuracy of measurements and the response time for result analysis. Wearable sensors can collect data and send real-time information on the patient's HR, BP, and BT parameters.

(iii) *Phase III* – This phase focuses on the system design and modelling. The overall system layout, architecture, and data flow were designed. Several software tools are involved in this phase such as VS code, Pybytes, and TTN. The system design is carried out to meet the proposed functionalities of the control system. Then, the coding and software phase has been performed according to how the system was proposed.

(iv) *Phase IV* –After the modelling phase, the designed system is enhanced and optimised through several initial tests to achieve the expected outcome. During this phase, the system implementation, verification, and functionality testing are carried out. The validation of each sensor functionality and the entire system is performed. Then, improvement is achieved when needed to ensure system functionality and effectiveness. The test was repeated until the proposed IoWT system is ready for practical testing before finalising and satisfying the research objectives.

(v) *Phase V* – When the functionality and effectiveness of the proposed system architecture is proved via actual implementation, and a series of experiments have been carried out to analyse its performance under various conditions and validate the collected results in pre-defined performance metrics to report the main findings.

Components selection

In this phase, the components are selected for the developed system based on the accuracy and possibility of achieving the developed system objectives. This section is divided into two sub-sections: the first explains the hardware component and the second describes the software components' most critical role.

Hardware Components: This section investigates the wearable sensors used in building the system and the interconnection of wireless communication technologies. This research stage focuses on identifying various components to be used in the design. Sensors are used mainly for detecting and analysing parameter changes. Sensors produce an electrical or optical signal as a result of their output. The sensitivity of sensors indicates how much the sensor's output changes as the measured input parameter changes. High performance is provided with a smaller sensor. This study used HR, BP, and BT sensors. The first sensor is a serial output BP. BP and pulse readings are displayed with serial output for external embedded circuit processing and display projects. Systolic BP (SBP), and Diastolic BP (DBP), and pulse readings are displayed. The watch-like shape fits over the wrist. Pumping is eliminated with this simple wrist design.

The temperature sensor used in IoWT-HHMS is NTC (Negative Temperature Coefficient) thermistor 10KΩ. The NTC *thermistors* are non-linear resistors that change their resistance values regarding temperature. The resistance of NTC decreases with the increase in temperature. The NTC Thermistors are made of ceramics or polymers and are commonly utilised in temperatures ranging from 55 to 200 °Celsius. The NTC thermistors have faster response times and better stability and can operate at a higher temperature. The typical diameters range from 0.075 to 5 mm.

The MCU chosen in this study is FiPy from Pycom company. *FiPy* contains five networks: Wi-Fi, Bluetooth, LoRa, LTE, and Sigfox on a tiny IoT development board. Get started with a board that allows you complete flexibility during testing, installation, and deployment and when you need to swap your airtime network provider in real-time. FiPy includes a lot of capabilities, including a powerful CPU, five networks, and Micro Python support. It fits on a regular breadboard (with headers) and consumes low power compared to other connected microcontrollers. Users can configure which network will be used by activating the FiPy in Pybytes. The FiPy has an internal Wi-Fi, no external antenna, shares an antenna connector between LoRa and Sigfox for 868–915 MHz frequency, and has a separate connector to support LoRa at the 433 MHz frequency. The LoRa frequency was used in this study. Each LoRa nano-gateway has a capacity of up to 100 nodes, and each node range is up to 40 km. The dimension of this development board is 55 mm × 20 mm × 3.2 mm without the headers. It has 4 MB RAM and an external flash of 8 MB, indicating that it stores more code than other processors. It has 8 × 12bits analogue channels and up to 24 GPIO pins.

FiPy is programmable with all Micro Python and Pymakr IDE plugins, enabling the rapid creation of IoT applications. FiPy features a powerful CPU, Bluetooth Low Energy (BLE), and a state-of-the-art Wi-Fi radio. It consumes a negligible amount of power in comparison to other linked microcontrollers. The input power source can be 5 V or 3.3 V, meaning users can power the microcontroller by plugging in a USB connection, which would be ideal for the designed system. The output can source up to 400 mA from a 3.3 V power source.

Software Components: The MCU (FiPy) module uses a powerful software language that can be used in many fields, including biomedical engineering and simulation. Python is a high-level language that can configure variables and process equations *and* calculations to get data ready to transfer to the IoT gateway. Many tools must be installed to conduct the Integrated Development Environment (IDE) with FiPy module. Pybytes is a new device management platform that works with any Pycom (FiPy) development board or module. Pybytes can supply devices in minutes using a smartphone or a computer. After connecting the Pycom module, select what module the system operates and what it is using for. The pre-configured settings enable immediately to see the device and data appear on the portal. To interface with the module, the module needs to install some software on the computer, such as Visual Studio Code or Atom with the Pymakr extension plugin. In this way, the module is now ready to work with Python language using the IDE. Once the coding has been done and tested by Pymakr, it needs a tool to transfer the code from IDE to the FiPy module, which is called expansion. Pycom has several types of expansion regarding the features and depends on the purpose of using it. Pycom has developed six types of expansion Pygate, Pysence, Pysence 2.0 X, Pytrack, Pytrack 2.0 X, and Expansion board 3.0.

System architecture

The overall system layout is drawn in Fig. 2. It includes the main parts of the proposed system and the information flow from the wearable sensors to the patient and doctor. The proposed system aims to monitor four vital parameters: BT, HR, SBP, and DBP. The sensors are connected to the FiPy MCU to gather real-time data and transfer it to the cloud over Wi-Fi and LoRaWAN. The layout also describes the system operation process through five main stages: data gathering (wearable sensors/patient's body), data processing (FiPy MCU and algorithm), data transmission (hybrid wireless medium), data storage (IoT Platform/Server Cloud) and data visualisation (Dashboard/Graphical User Interface (GUI).

Design of IoWT-HHMS

The architectural requirements define the system's features, services, and operating limits. Defining the system requirements helps the designers to make a better choice of components and optimises resources. As it is shown in Fig. 3, the architecture of the IoWT-HHMS for smart applications includes two wearable sensors that collect four vital parameters; these parameters have a deep relation with health conditions that reverse heart disease and give a good sign when something may happen.

Then, the data is processed and calculated by MCU named FiPy from Pycom company. The MCU has special features regards IoT communication technology. The FiPy MCU is a small unit embedded with five IoT network technology LoRa, Wi-Fi, Bluetooth, LTE, and Sigfox, and it gives novelty to use FiPy. After that, FiPy sends the collected data in short and long ranges. The short-range uses Wi-Fi, and the long-range uses LoRaWAN. The LoRaWAN gateway includes long-range data transmission. The IoT gateway is responsible for receiving data from FiPy and transferring it to the cloud. So, doctors or caregivers can monitor patients remotely in real-time using a PC, smartphone, or tablet.

The prototype of the developed system can do many processes, including the monitor patient data using the sensors connected directly to the body patient and doing all functions using the FiPy. The sensors and FiPy are applied together as a sensing unit connected as a wearable device that patients can wear quickly and connect to their bodies. The prototype can send data wirelessly to the cloud without an extra wire. The access point is responsible for receiving data from the wearable device using Wi-Fi or LoRa depending on the patient's location, whether near or far from the access point. The LoRa gateway is responsible for reversing data to the access point in case of FiPy use LoRa to transfer data to the cloud. The schematic diagram of the circuit connection between the development board FiPy and the sensors is illustrated in Fig. 3.

Hybrid connectivity algorithm

The developed system employed a novel algorithm (Algorithm 1) to choose between the built-in technology and the available signal quality during data transmission and whether to send data to the cloud via Wi-Fi or LoRa. The signal quality played an important role in choosing the transmission technology used to transfer the data to the cloud, as the IoWT-HHMS measures the signal quality for Wi-Fi. If the signal quality of the Wi-Fi is suitable for sending data to the cloud, it will send it through the Wi-Fi network unless it searches for the LoRa network and tests the signal quality of the LoRa network. If the signal quality is good, it will send it via the LoRa network unless it searches again until it finds a good signal to send data to the cloud.

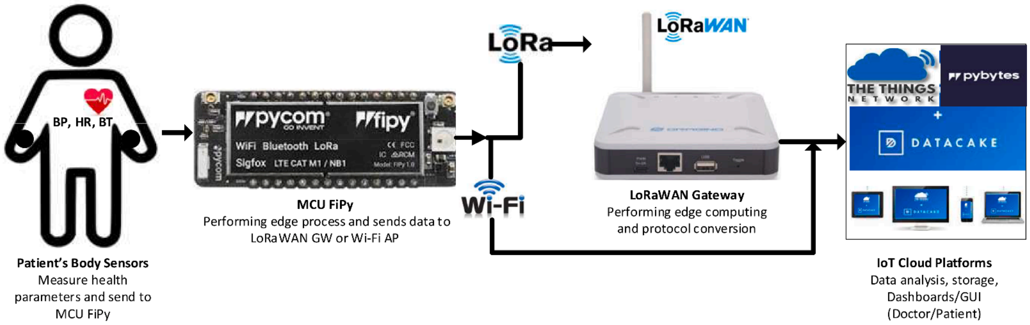


Fig. 2. Overall system architecture.

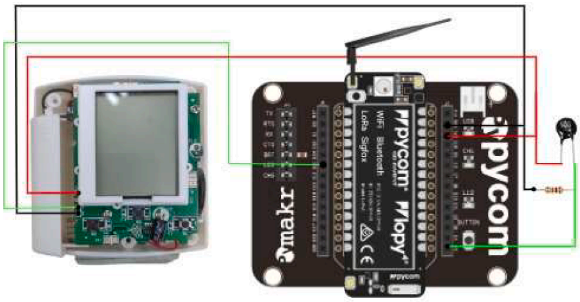


Fig. 3. Schematic diagram of the IoWT-HHMS for smart application.

Algorithm 1
Hybrid connectivity algorithm for IoWT-HHMS.

```
Begin
Set data_sending_data=0, $i = 0$, LoRa_status =0;
While not data_sending_data do
if Wi-Fi SNR is good then
    Send data to pybytes;
    break;
    else
    while $i < 200$ do      //timeout join LoRa network
    if LoRa has joined & SNR is good then
      LoRa_status = 1;
    break;
    $i{+}{+}$;
    time.sleep(1);      // time delay for 1 s
    endwhile
    if LoRa_status = 1 then
    send data to TTN;
    break;
    else
    print ('No Wifi, No Lora, Trying again');
    endif
Endif
Endwhile
End
```

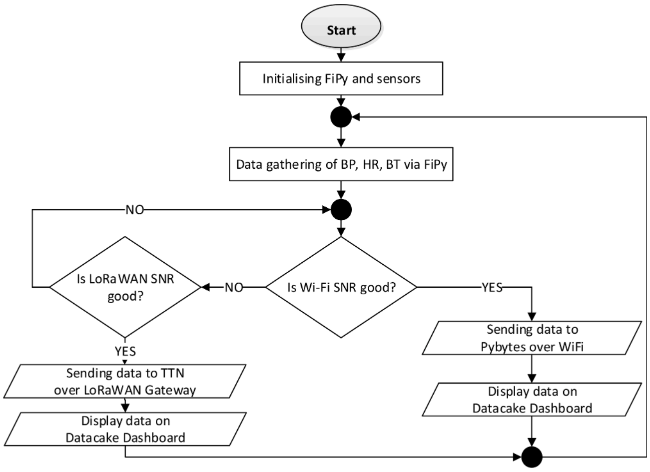


Fig. 4. IoWT-HHMS operational flow.

IoWT-HHMS system operational procedure

The proposed system has been fabricated using a combination of hardware and software components using sensors, MCU, Wi-Fi and LoRaWAN networks, IoT gateway, Pybytes platform, TTN server, and Datacake platform. The proposed system is integrated to read the patient's data and send it to the cloud remotely. The sensors measured the patient's vital parameters and then sent them to the FiPy, which processed the received data and, at the same time, performed other actions such as sending it to the cloud. The FiPy utilised the algorithm proposed in this research to determine the best ways to send data to the cloud by using the technology available at that time, either through a Wi-Fi network or via LoRaWAN. The proposed system used Pybytes and TTN as backend servers to receive data for a short or long-range and the Datacake dashboard as a front-end user. So, the caregiver can easily follow up on their patient's condition remotely.

The flowchart in Fig. 4 explains the operation flow of the proposed system using flow chart code. The code starts by establishing the sensors and the microcontroller unit; this process takes some seconds, then the sensors are ready to read the data from the patient and send it to FiPy. The FiPy now checks the availability of whether to use Wi-Fi or LoRa network. When the FiPy chooses the network, the data will be sent to Pybytes or TTN. If the FiPy is unavailable to choose the network, it will repeat the process until it finds the network. Then, the Datacake will receive the data, display it on the dashboard, and repeat the same process.

Results and discussion

Several experimental tests were considered to evaluate the performance and functionality of the different system components, including the wearable sensors, microcontroller, and communication interface. This stage of research is carried out by utilising the system prototype to investigate and analyse the performance of the IoWT-HHMS system in various smart healthcare scenarios. The results from various experimental tests were validated and compared to the data obtained via conventional healthcare monitoring systems to confirm the system's applicability and suitability to be used in smart medical applications.

The performance evaluation is achieved through comparative measurements for each experiment based on selective performance metrics related to the accuracy, time delay, data reliability, and communication range to prove the accomplishment of the research objectives. Several performance indicators, including throughput, packet delivery ratio, end-to-end delay, and energy consumption, were used to validate the performance of the IoWT-HHMS system.

This section represents the results of the developed system. The final design of the IoWT-HHMS system has been introduced, demonstrating how the system appears and verifying that it is ready for usage in accordance with the study aims. In addition, it covers testing system functioning using the Pymakr terminal, testing Wi-Fi and LoRaWAN networks, testing hybrid network connectivity, and depicting health data monitoring with the Datacake dashboard.

Final IoWT-HHMS system prototype

As a result of this research, the IoWT-HHMS has been built to monitor patient data status as well as the patient's HR, BP, and BTs. Pybytes and TTN incorporated into the Datacake webhook integration are used to monitor each criterion. While TTN and Pybytes serve as the backend of the system, which is the side that developers work on, Datacake serves as the frontend, which is the side that users

Fig. 5. Final design of the IoWT-HHMS - different views.

perform on to monitor a patient's condition. As long as there is a connection to the Internet, medical professionals can keep track of their patient's status regardless of the time or place. The final design in the practical work of the IoWT-HHMS can be seen in Fig. 5. The system has been finalised and applied as a wearable system that can be used easily and worn at the wrist arm.

The prototype device is a wrist healthcare monitor that can be used at home to monitor BP, HR, and BT and is easy to operate. It has a small size of 90 × 90 × 90 mm with a digital display. In addition, the way of using this device makes it unique and helpful for monitoring regularly and giving good signs in case of some urgent measurements. To get an accurate reading from IoWT-HHMS, the user needs to put his or her arm at heart level and place the prototype in the exact position. This device has many features, such as small size, light, comfortable on the wrist, high precision, self-power supply using a battery, large LCD display for a clear view of reading, and is easy to use without needing help from others.

IoWT-HHMS functionality testing

The IoWT-HHMS functionality testing section aims to provide results based on different scenarios such as Pymakr terminal, Pybytes platform, and TTN server, testing the fabricated system algorithm for the hybrid network, and finally, present the health data monitoring dashboard via Datacake.

Functionality testing via Pymakr terminal

The sensors' results have been collected using the Pymakr terminal extension, which begins with the measurement instrument's preparation and the device's verification. The test aims to confirm that the sensors are functioning correctly.

a) *BT Sensor:* The BT NTC sensor was tested by placing the sensor on the arm using sticky tape to ensure the sensor is connected to the body patient directly and by observing whether the sensor can display the temperature in units of degrees Celsius. Temperature test results are displayed in degrees Celsius on the Pymakr extension using VS code. This test is the basis that the NTC sensor is functioning correctly or not. When retrieving data, BT data varies according to the patient's physical condition. The connection between NTC with the arm patient and the FiPy board and the functionality test is described in Fig. 6. The figure shows the results of the monitoring BT in Celsius on the Pymakr terminal.

b) *BP* and HR Device: BP and HR testing are performed by placing the device on the wrist and observing whether the sensor has responded to sensor data by displaying SBP, DBP, and HR values on the Pymakr extension. After including the library to VS code to run and interface the BP and HR device with the FiPy board, the figures describe the results of monitoring the data from the patient's arm. The connection between wrist BP with the FiPy board and the results of the functionality test are illustrated in Fig. 7.

Functionality testing using Wi-Fi network

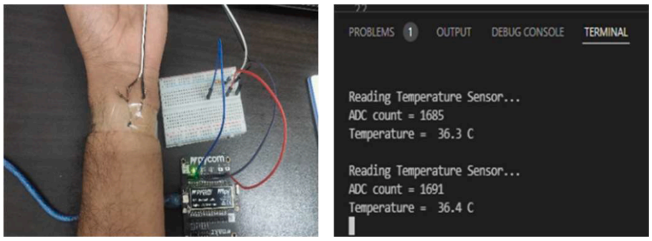
After finishing testing the sensors with the MCU and getting the sensors' results on the Pymakr terminal, the next step is to check the connectivity of the Wi-Fi. As shown in Fig. 8, the Pybytes platform has a good data interface that can see all changes in patient information; the FiPy firmware has been installed and connected to Pybytes during the provisioning. The BT, systolic BP, diastolic BP and HR data can be monitored remotely to see all changes in parameters. The Pymakr terminal shows the connection between the MCU and Pybytes using Wi-Fi and the availability to send the data in short range by using Wi-Fi connectivity as depicted in Fig. 9.

Functionality testing using Lorawan network

Fig. 10 shows when the system is connected to LoRa, the collected data via FiPy is transmitted to the TTN platform via the LoRaWAN gateway. All data has been sent to TTN using one port, field 1 represents the BT while field 2 represents the systolic BP level, field 3 represents the diastolic BP, and the last field represents the HR of the patient. The whole data is represented in hexadecimal form. Moreover, the Pymakr terminal can show the connectivity between the MCU and TTN using LoRa and the availability to send long-range data (Fig. 11).

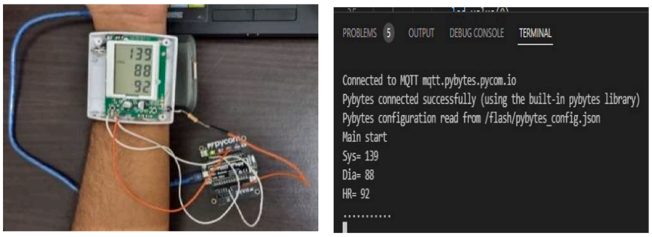
Hybrid network connectivity testing

Based on the design objectives, the system should be applicable to be used in short and long ranges to ensure the data is sent. In this subsection, the fabricated system has been tested to see its ability to switch the data in two modes in case there is no access to the access point in the short range. Fig. 12 proves that the fabricated system can switch between the short and long-range methods depending on



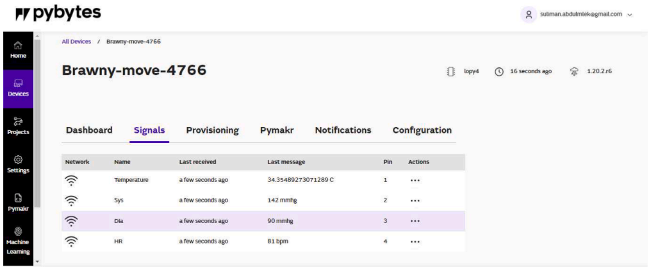
```
Reading Temperature Sensor...
ADC count = 1685
Temperature =  36.3 C

Reading Temperature Sensor...
ADC count = 1691
Temperature =  36.4 C
```

Fig. 6. NTC sensor results with FiPy board and functionality test results on Pymakr terminal.



```
Connected to MQTT mqtt.pybytes.pycom.io
Pybytes connected successfully (using the built-in pybytes library)
Pybytes configuration read from /flash/pybytes_config.json
Main start
Sys= 139
Dia= 88
HR= 92
...........
```

Fig. 7. Result of BP device with FiPy on Pymakr terminal.

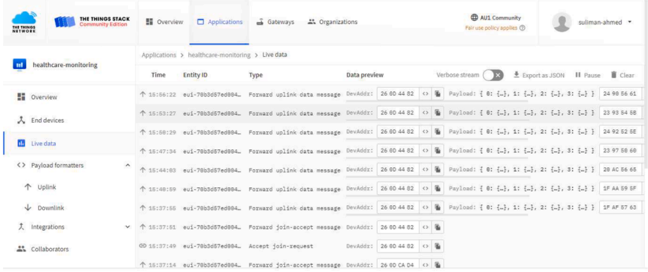


Network	Name	Last received	Last message	Pin	Actions
	Temperature	a few seconds ago	34.35489273071289 C	1	•••
	Sys	a few seconds ago	142 mmhg	2	•••
	Dia	a few seconds ago	90 mmhg	3	•••
	HR	a few seconds ago	81 bpm	4	•••

Fig. 8. Receiving patient’s data on the Pybytes platform using Wi-Fi.

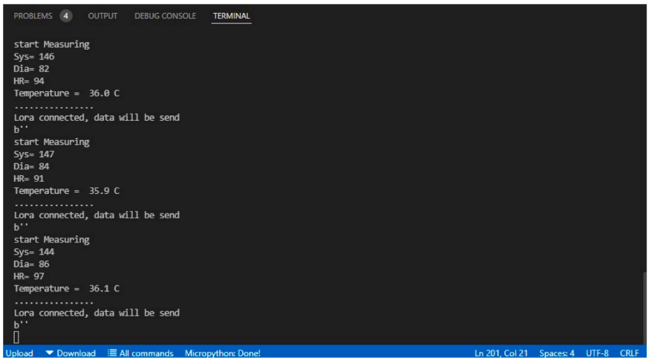
```
WiFi connection established
Connected to MQTT mqtt.pybytes.pycom.io
Pybytes connected successfully (using the built-in pybytes library)
Temperature =  37.9 C
................
('192.168.43.216', '255.255.255.0', '192.168.43.1', '192.168.43.1')
Wifi connected, data will be send
Temperature =  40.6 C
................
```

Fig. 9. Connection between the FiPy and Pybytes using Wi-Fi.



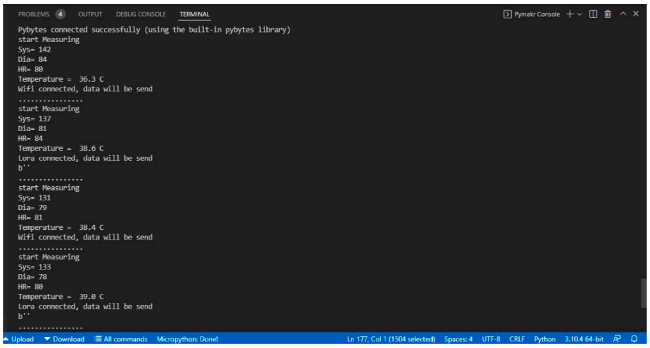
```
Time      Entity ID              Type                          Data preview
15:56:22  eui-70b3d57ed004…  Forward uplink data message   DevAddr: 26 0D 44 82   Payload: { 0: {…}, 1: {…}, 2: {…}, 3: {…} }  24 90 56 61
15:53:27  eui-70b3d57ed004…  Forward uplink data message   DevAddr: 26 0D 44 82   Payload: { 0: {…}, 1: {…}, 2: {…}, 3: {…} }  23 93 54 5B
15:50:29  eui-70b3d57ed004…  Forward uplink data message   DevAddr: 26 0D 44 82   Payload: { 0: {…}, 1: {…}, 2: {…}, 3: {…} }  24 92 52 5E
15:47:34  eui-70b3d57ed004…  Forward uplink data message   DevAddr: 26 0D 44 82   Payload: { 0: {…}, 1: {…}, 2: {…}, 3: {…} }  23 97 50 60
15:44:03  eui-70b3d57ed004…  Forward uplink data message   DevAddr: 26 0D 44 82   Payload: { 0: {…}, 1: {…}, 2: {…}, 3: {…} }  20 AC 56 65
15:40:59  eui-70b3d57ed004…  Forward uplink data message   DevAddr: 26 0D 44 82   Payload: { 0: {…}, 1: {…}, 2: {…}, 3: {…} }  1F AA 59 5F
15:37:55  eui-70b3d57ed004…  Forward uplink data message   DevAddr: 26 0D 44 82   Payload: { 0: {…}, 1: {…}, 2: {…}, 3: {…} }  1F AF 57 63
15:37:51  eui-70b3d57ed004…  Forward join-accept message   DevAddr: 26 0D 44 82
15:37:49  eui-70b3d57ed004…  Accept join-request           DevAddr: 26 0D 44 82
15:37:14  eui-70b3d57ed004…  Forward join-accept message   DevAddr: 26 0D CA D4
```

Fig. 10. Receiving patient’s data on TTN in bytes form.



```
start Measuring
Sys= 146
Dia= 82
HR= 94
Temperature =  36.0 C
................
Lora connected, data will be send
b''
start Measuring
Sys= 147
Dia= 84
HR= 91
Temperature =  35.9 C
................
Lora connected, data will be send
b''
start Measuring
Sys= 144
Dia= 86
HR= 97
Temperature =  36.1 C
................
Lora connected, data will be send
b''
```

Fig. 11. Connection between the FiPy and TTN using LoRa on the Pymakr terminal.



```
Pybytes connected successfully (using the built-in pybytes library)
start Measuring
Sys= 142
Dia= 84
HR= 80
Temperature =  36.3 C
Wifi connected, data will be send
................
start Measuring
Sys= 137
Dia= 81
HR= 84
Temperature =  38.6 C
Lora connected, data will be send
b''
................
start Measuring
Sys= 131
Dia= 79
HR= 81
Temperature =  38.4 C
Wifi connected, data will be send
................
start Measuring
Sys= 133
Dia= 78
HR= 80
Temperature =  39.0 C
Lora connected, data will be send
b''
................
```

Fig. 12. Results of testing hybrid network.

the access point's availability.

Health data monitoring via datacake dashboard

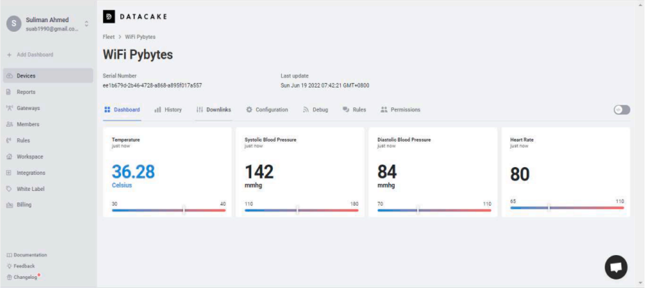
Doctors or caregivers can get the latest sensor reading information through the Datacake platform by selecting the device name in the account. The Datacake can represent all data sent by FiPy using Wi-Fi or LoRa, the short and long-range methods. Datacake can set up the range of the sensor level; thus, the user can read the data easily. Fig. 13 shows the incoming data using the Wi-Fi method, and Fig. 14 shows the incoming data sent using the LoRaWAN. The figures illustrate the monitoring of the patient's parameters condition via Datacake. In the same figure three new parameters are seen down to BT, Systolic and Diastolic BP and Heart Rate data: LoRaWAN Uplink_SNR, LoRaWAN Uplink_RSSI and LoRaWAN_Frequency. The RSSI represents signal strength power, and SNR represents the quality of the received signal ratio. LoRaWAN frequency represents the frequency of the received signal depending on the frequency plan used, AS923, in the designed system. According to the IoWT-HHMS, the caregiver can monitor the data in several ways, such as through the Wi-Fi dashboard or the LoRa TTN dashboard.

Fig. 15 shows the primary way Wi-Fi and LoRaWAN devices represent whole parameters. The latest data sent to Datacake is shown on the dashboard of the user interface. This dashboard lets the user look at patient information without worrying about how the designed system sends data to the cloud. The user interface dashboard is a dynamic method to monitor patients' data on one dashboard. This way, the developed system has solved the hybrid network issue and which network is used to send data to the cloud.

Validation of IoWT-HHMS effectiveness

In this section, we delve into the rigorous validation process of the Internet of Wearable Things-based Hybrid Healthcare Monitoring System (IoWT-HHMS). The effectiveness of the system is a critical factor in determining its potential for broad adoption and real-world application. As such, this validation aims to assess the accuracy, reliability, and latency of the system, providing evidence of its capability to monitor patients' health conditions remotely and in real-time. Various experimental scenarios have been considered to ensure that the IoWT-HHMS performs optimally under different conditions, highlighting its robustness and adaptability. The ensuing discussions will detail the methodology used for this validation process and present the results obtained, thereby establishing the effectiveness of the proposed IoWT-HHMS.

Table 3 presents a series of 22 measurements conducted over a two-hour span, with data samples collected at five-minute intervals. The stability of the IoWT-HHMS is demonstrated through consistent readings of various health parameters such as systolic and diastolic blood pressure, heart rate, and body temperature for individuals under normal health conditions. These results suggest that the system effectively meets the established requirements. Fig. 16 presents a line chart illustrating the fluctuations of these measurements over the two-hour period for a single individual. In Fig. 16(a), The systolic BP, depicted by the blue line, exhibits a maximum value of 125 mmHg and a minimum value of 115 mmHg. These values demonstrate the stability of the developed system, with the systolic BP



WiFi Pybytes

Serial Number
ee1b679d-2b46-4728-a868-a895f017a557

Last update
Sun Jun 19 2022 07:42:21 GMT+0800

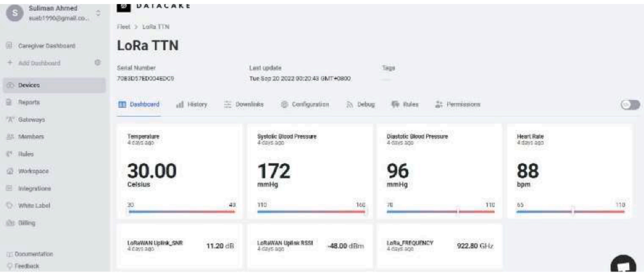
Temperature
just now
36.28
Celsius
30 40

Systolic Blood Pressure
just now
142
mmhg
110 180

Diastolic Blood Pressure
just now
84
mmhg
70 110

Heart Rate
just now
80
65 110

Fig. 13. Incoming data sent using the Wi-Fi.



LoRa TTN

Serial Number 70B3D57ED004EDC9

Last update Tue Sep 20 2022 00:20:43 GMT+0800

Tags

Temperature 4 days ago 30.00 Celsius

Systolic Blood Pressure 4 days ago 172 mmHg

Diastolic Blood Pressure 4 days ago 96 mmHg

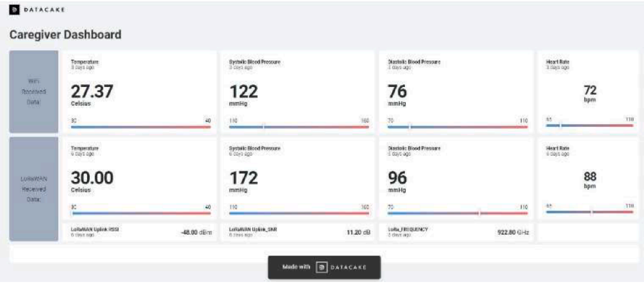
Heart Rate 4 days ago 88 bpm

LoRaWAN Uplink_SNR 4 days ago 11.20 dB

LoRaWAN Uplink RSSI 4 days ago -48.00 dBm

LoRa_FREQUENCY 4 days ago 922.80 GHz

Fig. 14. Incoming data sent using LoRaWAN.



Caregiver Dashboard

WiFi Received Data

Temperature 3 days ago 27.37 Celsius

Systolic Blood Pressure 3 days ago 122 mmHg

Diastolic Blood Pressure 3 days ago 76 mmHg

Heart Rate 3 days ago 72 bpm

LoRaWAN Received Data

Temperature 6 days ago 30.00 Celsius

Systolic Blood Pressure 6 days ago 172 mmHg

Diastolic Blood Pressure 5 days ago 96 mmHg

Heart Rate 6 days ago 88 bpm

LoRaWAN Uplink RSSI 6 days ago -48.00 dBm

LoRaWAN Uplink_SNR 6 days ago 11.20 dB

LoRa_FREQUENCY 5 days ago 922.80 GHz

Fig. 15. User interface dashboard.

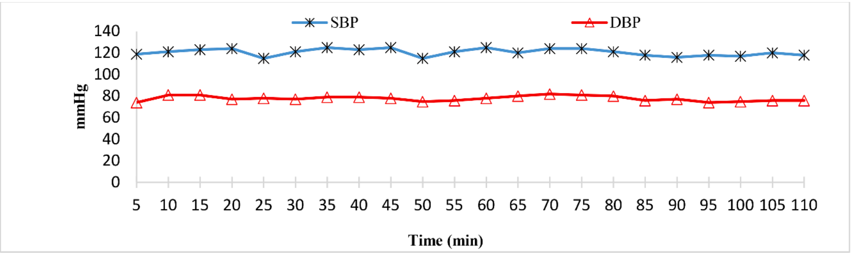
Table 3
Validation IoWT-HHMS measurements.

Time (min)	SBP	DBP	HR	Temp
5	119	74	80	36.11
10	121	81	85	35.7
15	123	81	80	35.9
20	124	77	81	36.3
25	115	78	78	35.3
30	121	77	79	36.2
35	125	79	83	36.4
40	123	79	77	35.9
45	125	78	81	35.8
50	115	75	79	36.3
55	121	76	82	35.7
60	125	78	80	35.23
65	120	80	83	35.99
70	124	82	85	.6.14
75	124	81	83	36.5
80	121	80	79	36.7
85	118	76	81	36.6
90	116	77	83	35.9
95	118	74	80	35.8
100	117	75	81	36.3
105	120	76	83	35.7
110	118	76	82	35.23

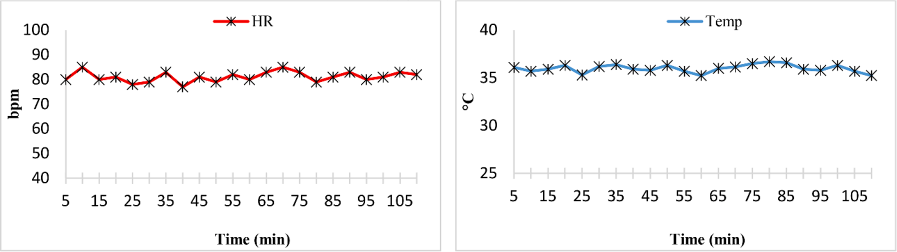
measurements staying within $a \pm 5$ mmHg margin of the average systolic BP value of 120 mmHg. Similarly, the diastolic BP, indicated by the red line, reaches a maximum value of 82 mmHg and a minimum of 74 mmHg. This data suggests the reliability of the developed system, with diastolic BP measurements remaining within $a \pm 4$ mmHg range from the average diastolic BP value of 78 mmHg. The consistency and precision of these readings affirm the normality and stability of the developed IoWT-HHMS.

Fig. 16(b) provides a visual representation of heart rate (HR) measurements over a two-hour period for a single individual. In the graph, the HR fluctuates within a narrow range, with a maximum value of 85 beats per minute (bpm) and a minimum value of 77 bpm. This consistency in measurements underlines the stability and accuracy of the developed IoWT-HHMS. The variations remain within a 4-bpm difference from the mean HR value of 81 bpm, further validating the system's precision and reinforcing its reliability in recording this vital parameter.

Meanwhile, Fig. 16(c) illustrates the continuous monitoring of body temperature (BT) for the same two-hour duration. The



(a) Systolic & Diastolic BP.



(b) Heart Rate

(c) Body Temperature.

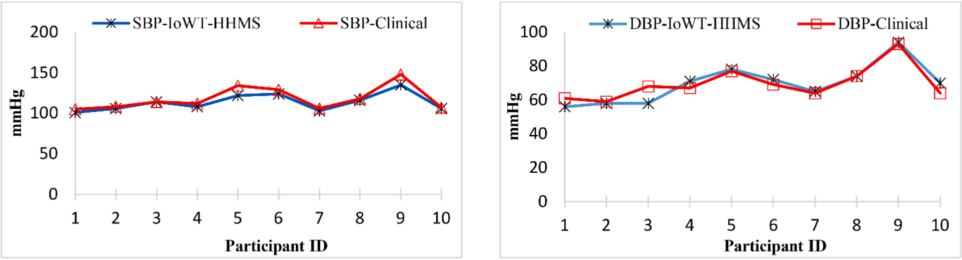
Fig. 16. Validation IoWT-HHMS measurements.

measured temperatures show a maximum value of 36.7 °Celsius and a minimum value of 35.2 °Celsius. These measurements reiterate the stability and accuracy of the developed system, as they closely align with the mean BT value of 36.2 °Celsius. The slight variation in temperature values demonstrates the system's ability to detect even minor fluctuations in BT, which is crucial in identifying potential health anomalies. Overall, the results presented in both figures accentuate the developed IoWT-HHMS's reliability and effectiveness in monitoring vital health parameters.

Data accuracy performance evaluation

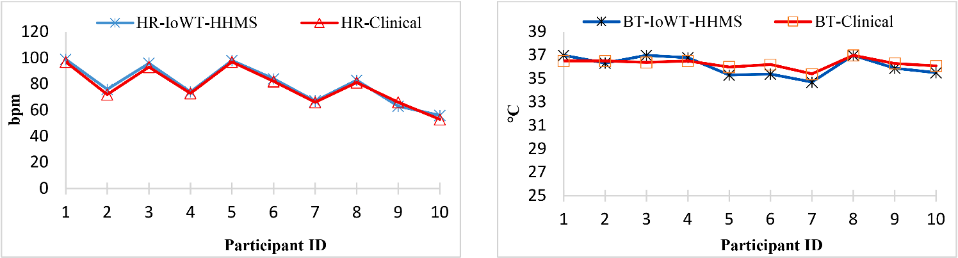
The evaluation of data accuracy constitutes a crucial component of the developed IoWT-HHMS system performance analysis. This facet of the evaluation is fundamental to ensuring that the system is in line with the design requirements and consequently, achieves the desired outcomes. The system was set to measure various health parameters (SBP, DBP, HR, BT). For this evaluation, we enlisted the participation of ten randomly selected male students from the UMP Pekan campus, aged between 18 and 30. The accuracy of data obtained from our system was then compared with reference devices that are well-established in the market.

Fig. 17 and Table 4 compares the collected measurements from the specific scenarios for evaluating the accuracy of Systolic BP,



(a) Systolic BP

(b) Diastolic BP



(c) Heart Rate

(d) Body Temperature

Fig. 17. Comparison of IoWT-HHMS with the reference device measurements.

Table 4
Measurement accuracy comparison between IoWT-HHMS and clinic instruments (SBP, DBP, HR, and BT) for ten participants.

Participant's No.	IoWT-HHMS				Actual SBP	SBP Accuracy%	Actual DBP	DBP Accuracy%	Actual HR	HR Accuracy%	Actual BT	BT Accuracy%
	SBP	DBP	HR	BT								
1	101	56	99	37	105	96.19	61	91.8	97	97.94	36.5	98.63
2	106	58	76	36.34	108	98.15	59	98.31	72	94.44	36.5	99.56
3	114	58	96	37	114	100	68	85.29	93	96.77	36.4	98.35
4	108	71	74	36.79	112	96.43	67	94.03	73	98.63	36.5	99.21
5	122	78	98	35.3	134	91.04	77	98.7	97	98.97	36	98.61
6	124	72	84	35.39	129	96.12	69	95.65	82	97.56	36.2	97.76
7	103	65	67	34.7	106	97.17	64	98.44	66	98.48	35.4	98.02
8	116	74	83	36.99	118	98.31	74	100	81	97.53	37	99.97
9	135	94	63	35.88	148	91.22	93	98.92	66	95.45	36.3	98.84
10	106	70	56	35.5	107	99.07	64	90.62	53	94.34	36.1	98.34
Accuracy Aver. (%)						**96.37**		**95.176**		**97.011**		**98.574**

Diastolic BP, HR, and BT in the IoWT-HHMS. For BP and HR measurements, we used a Fully Automatic Arm BP Machine RAK283 as a reference device. For BT measurements, a digital thermometer (Serial No.10326) was used as the reference device. The accuracy results, along with comparisons with the actual readings, are further elucidated through tables and figures. Remarkably, the developed system demonstrated high accuracy across all parameters, with the accuracy scores for Systolic BP, Diastolic BP, HR, and BT being 96.37 %, 95.17 %, 97 %, and 98.5 %, respectively.

Communication reliability performance evaluation

The communication reliability of the developed IoWT-HHMS system plays a pivotal role in maintaining stable connectivity with the cloud, thereby safeguarding against potential data loss. To evaluate this aspect, we conducted a three-phase test focusing on the quality of received data packets and potential data loss across different distances: 500 m, 1 km, and 1.5 km. In each phase, the Received Signal Strength Indicator (RSSI), Signal-to-Noise Ratio (SNR), and frequency were monitored, with ten readings taken at each distance. The results, displayed in Table 5, demonstrate a high level of communication reliability for the developed system up to a distance of 1.5 km, marking a significant achievement. The system maintained high reliability in transmitting and receiving data to the cloud within this range, without any data loss. Notably, the developed system employed a spreading factor of 10, requiring a minimum SNR of −15 dB for demodulation at this spreading factor. As indicated in the table, the minimum SNR recorded was −14.8 dB, which falls well within the LoRa demodulation range, further attesting to the system's communication reliability.

Wi-Fi network performance evaluation

The developed system has been evaluated and tested in terms of the coverage range for the Wi-Fi network; it shows a good range in the indoor and outdoor tests. The maximum coverage range for the fabricated system using the Wi-Fi network is up to 87 m, which is considered a reasonable range for the Wi-Fi network. Fig. 18(a) represents the evaluation part of the developed system in terms of using the Wi-Fi network to send data to the cloud. Up to 87 m from the access point, the developed system was very stable when using a Wi-Fi network. As the node moved farther away from the access point, the Wi-Fi network stopped sending data to the cloud, and the node switched directly from the Wi-Fi network to the LoRaWAN network for long-range transmission.

LoRaWAN network performance evaluation

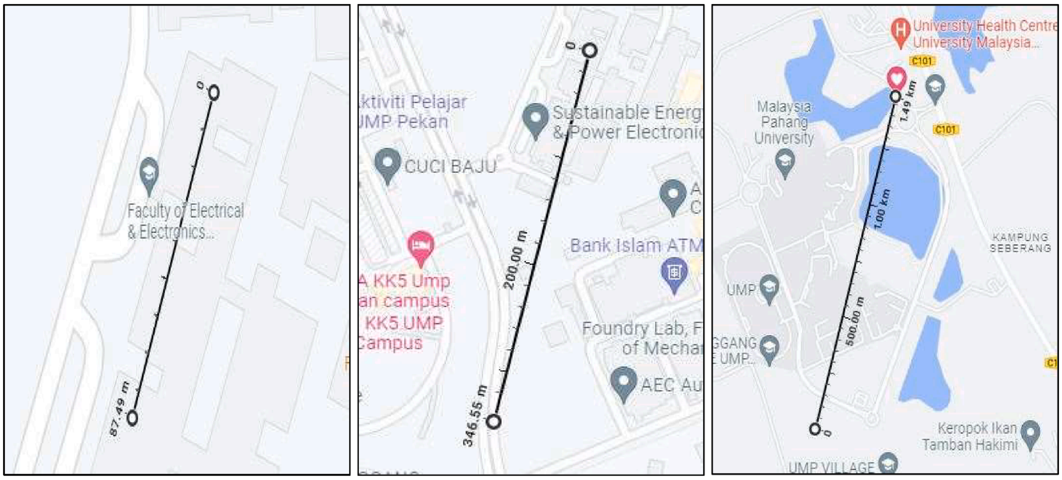
The performance of the IoWT-HHMS was assessed in the indoor environment of the University Malaysia Pahang campus. A gateway node was strategically installed within a first-floor workstation, while a wearable node was attached to the participant's body, who then traversed the campus. Notably, the wearable node, positioned on the participant's wrist, transmitted data to the gateway as the subject moved around the university premises. According to the conducted experiments, the indoor LoRaWAN network demonstrated remarkable stability and achieved coverage extending up to 346 m before the node lost its ability to connect with the LoRaWAN gateway, inhibiting data transmission to the cloud. The spatial coverage of the indoor LoRaWAN network is graphically represented in Fig. 18(b).

On the other hand, outdoor testing of the IoWT-HHMS has also taken place at the University of Malaysia Pahang. The gateway node has been positioned inside the UMP Pekan campus, close to the Akademi Adab UMP building. The wearable node was attached to the participant's wrist and moved freely throughout the campus. While the user was moving, the wearable node sent data to the IoT gateway and cloud. Outdoor evaluation using the LoRa network is depicted in Fig. 18(c). Based on the experiments, the outdoor LoRaWAN network evaluation of the IoWT-HHMS delivered high stability and can cover up to 1.5 km before the node cannot join the LoRaWAN gateway, and data cannot be sent to the cloud.

Moreover, the performance of the developed system was further assessed through extended distance data to determine the quality of the packets received on The Things Network. Among the various parameters of received packets, SNR was chosen as the metric to gauge signal quality due to its ability to encapsulate both signal strength and noise within a single parameter. Fig. 19 illustrates the evaluation of the received signal on TTN at nine distinct distances, leveraging SNR values as the principal measure. The results suggest

Table 5
IoWT-HHMS communication reliability performance evaluation.

	500 m			1 Km			1.5 Km		
	RSSI (dBm)	SNR (dB)	FREQUENCY (MHz)	RSSI (dBm)	SNR (dB)	FREQUENCY (MHz)	RSSI (dBm)	SNR (dB)	FREQUENCY (MHz)
1	−103	8	923.4	−117	−2	923.4	−116	−2.8	923
2	−112	3.8	922.2	−119	−6.2	923.2	−118	−3.5	923.4
3	−119	−4.8	922.4	−116	−3.2	923.2	−129	−10	922.6
4	−112	2.5	923.4	−116	−2.5	923.2	−130	−11.2	923.4
5	−110	3.2	923.4	−124	−11.2	922	−120	−4.8	922.2
6	−109	3.2	922	−125	−10.2	923	−122	−7.2	923
7	−111	3	922	−133	−14.8	922.4	−129	−10.8	923.2
8	−111	2	922.8	−131	−13.2	922.4	−124	−5.8	923.4
9	−105	3.8	923	−132	−12.5	923.4	−131	−14.8	922.8
10	−116	−1.5	922.2	−129	−14.2	922	−129	−10	923



(a) (b) (c)

Fig. 18. Network connectivity coverage evaluation: (a) Wi-Fi network, (b). Indoor LoRaWAN network, and (c) Outdoor LoRaWAN network.

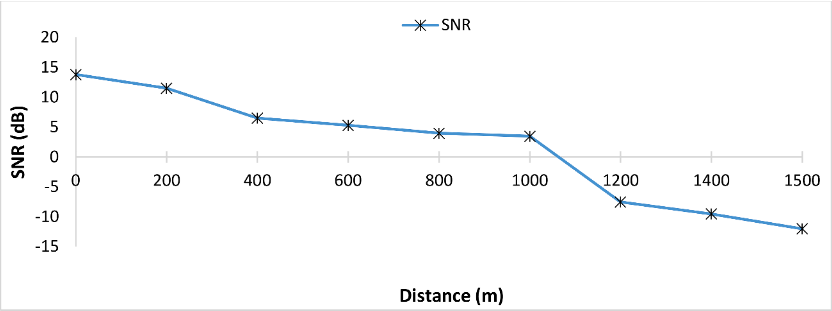


Fig. 19. Comparison of SNR at different distances.

that LoRa is capable of demodulating the packets efficiently up to a distance of 1.5 km before data loss begins to occur.

Power consumption performance evaluation

The power consumption evaluation of the developed system was carried out using a USB voltage/amps power meter tester multimetre, as depicted in Fig. 20. Each measurement period lasted for a total of 45 s. During the initial phase, which involved the measurement of BP and HR, power consumption surged to 5.75 W before transitioning to 4.07 W. Therefore, the aggregate power consumption for BP and HR measurements stood at 9.82 W. The evaluation also considered the power usage associated with Body Temperature measurement, which compiled data within a span of 3 s and accounted for a total power consumption of 0.279 W. Consequently, the overall power consumption for a single measurement was computed as 10.099 W. The developed system employed a

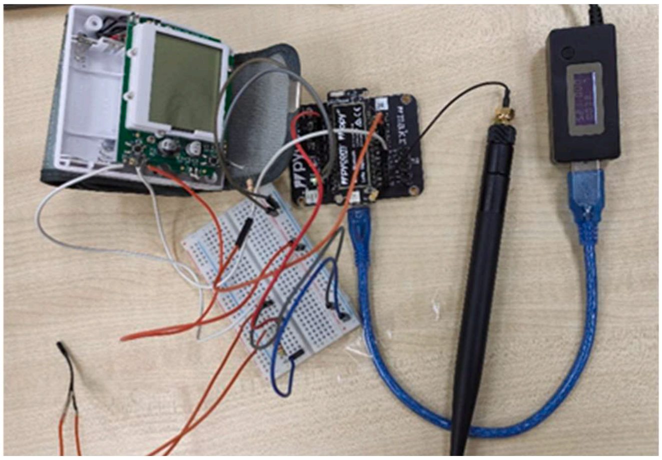


Fig. 20. Power consumption meter connected with the developed system.

rechargeable battery of 3.7 v and 1800 mAh, ensuring compatibility with the objectives of the wearable device. With a full charge, the battery provided approximately 13 h of operation before requiring recharging. To enhance convenience and efficiency, the developed system was equipped with a power button for activation and deactivation, as well as a provision for direct battery charging via a compact USB cable without necessitating disconnection from the prototype.

Time latency performance evaluation

The data time latency of the developed system has been meticulously evaluated concerning delay across both Wi-Fi and LoRa networks. Initial tests revealed a higher latency when using the Wi-Fi network, with data transmission to the cloud taking approximately 2 s. Further, the system's interaction with the LoRaWAN network was also examined to ascertain the prototype's capability for data exchange with the cloud. It was observed that the IoWT-HHMS required a varying interval of about 7–9 s to establish a connection with the gateway during the initial LoRaWAN gateway join, which serves as an alternative method for cloud data transmission in the absence of Wi-Fi access. However, subsequent connections to the LoRaWAN gateway were significantly quicker as the connection had been previously established during the initial join.

Hence, the connection process to the LoRa gateway was found to take a longer duration compared to the Wi-Fi network. Detailed latency comparisons across the two networks are provided in Table 6.

Data security, privacy and ethical considerations

In enhancing the IoWT-HHMS, particular attention has been paid to the critical aspect of data security and privacy. Recognising the sensitivity of health-related data, the integration of robust security measures within the utilised IoT platform, specifically The Things Network (TTN), has been a paramount focus.

Our system employs the standard security features of TTN, which include data encryption and user authentication protocols. TTN's built-in security mechanisms, such as end-to-end encryption, play a crucial role in ensuring the confidentiality and integrity of data transmitted from the wearable devices to the cloud server. This encryption ensures that the data remains secure, preventing unauthorised access and tampering.

Furthermore, the implementation of secure access keys and device authentication within TTN adds a crucial layer of protection against unauthorised data access. To bolster these initial security measures, future iterations of the IoWT-HHMS will integrate advanced encryption algorithms and implement more stringent authentication processes, along with regular security audits to identify and mitigate potential vulnerabilities.

Compliance with international health data regulations, such as HIPAA (Health Insurance Portability and Accountability Act) or GDPR (General Data Protection Regulation), will be a focal point in our ongoing efforts to enhance data security. This approach is integral to reinforcing user confidence and trust in the IoWT-HHMS.

Our commitment to fortifying the security and privacy aspects, especially within the TTN platform, is aimed at elevating the IoWT-

Table 6
Time latency response for Wi-Fi and LoRaWAN network.

Network	Time latency response
Wi-Fi	~ 2 s
LoRaWAN	7–9 s (for first join only) ~2 s (for the next join)

HHMS to meet the high expectations of security and reliability required in smart healthcare applications. This comprehensive approach to data security ensures that sensitive health information is handled with the utmost care, providing users with the assurance that their data is protected in the IoWT-HHMS environment.

In our research, we place significant emphasis on the ethical implications of IoT-based healthcare systems, particularly in the context of patient data handling. Recognising the sensitivity of health data, our approach adheres to strict ethical guidelines that govern patient consent, data anonymisation, and compliance with healthcare regulations. We ensure that all patient data collected and processed by our IoWT-HHMS is done so with explicit consent and is anonymised to maintain confidentiality. Furthermore, our system design and research methodologies align with ethical standards established by healthcare regulatory bodies, safeguarding patient privacy and rights. By integrating these ethical considerations into our system, we aim to foster trust and reliability, ensuring that our technological advancements in healthcare align with the ethical obligations owed to patients and healthcare providers.

Conclusion and future work

The concept of the Internet of Wearable Things (IoWT) presents a transformative approach in healthcare, offering cost-effective solutions while enhancing data accessibility and sharing through IoT servers in the cloud. This research introduces a novel IoWT-based smart healthcare monitoring system, adept at remotely tracking patients' physiological parameters—Heart Rate (HR), Blood Pressure (BP), and Body Temperature (BT). Central to our system is the use of the FiPy microcontroller unit, which facilitates seamless interoperation among sensors and cloud services, embodying the IoT vision of interconnectedness.

Our developed system stands out for its ability to monitor physiological parameters in real-time and consistently update this data on the cloud. The system's compact design allows it to be conveniently worn on a patient's wrist, ensuring efficient data transmission of HR, BP, and BT to the FiPy for remote accessibility. A significant innovation in our work is the implementation of a hybrid network mechanism, leveraging the FiPy microcontroller. This mechanism allows for both short- and long-range communication and includes an integrated algorithm for optimal data comparison and transfer to the cloud, based on predefined conditions.

The hybrid nature of our system offers a multifaceted approach to data exchange with the cloud, surpassing the limitations of single-method systems. It provides a range of solutions for network issues, ensuring reliable data transmission. In scenarios where Wi-Fi access is limited or unavailable, the system can seamlessly switch to the LoRaWAN network, maintaining consistent cloud connectivity. The effectiveness of this system has been demonstrated across all stages of data processing, from the Pymakr extension and Pybytes platform to the TTN server and Datacake platform. By testing under various scenarios, the system successfully addresses current challenges in remote monitoring, showcasing its potential as a versatile and reliable solution in smart healthcare applications.

This research comprehensively evaluated every facet of the developed Internet of Wearable Things-based Hybrid Healthcare Monitoring System (IoWT-HHMS). The system demonstrated exceptional data accuracy for vital parameters—Systolic Blood Pressure (SBP), Diastolic Blood Pressure (DBP), Heart Rate (HR), and Body Temperature (BT)—with accuracy rates of 96.37 %, 95.17 %, 97 %, and 98.5 % respectively. Notably, the communication reliability with the cloud was high, achieving an impressive range of 87 m for Wi-Fi and 1.5 km for LoRaWAN without any data loss. Additionally, the system's power consumption was found to be efficient, sustaining up to 13 h of continuous operation. The response time to the cloud was rapid, with a noteworthy latency of only 2 s. Furthermore, the system leverages the Datacake IoT platform for intuitive data visualisation, offering caregivers a comprehensive and easy-to-use dashboard for remote monitoring of all parameters, including Wi-Fi and LoRaWAN data. Overall, the IoWT-HHMS has proven to be a robust and user-friendly system, enabling effective remote health monitoring.

Looking ahead, this study opens several pathways for future research:

- *Integration of Additional Health Parameters*: Expanding the IoWT-HHMS to include more health metrics such as blood glucose levels, oxygen saturation, and ECG readings would offer a more holistic view of a patient's health, thereby augmenting the system's functionality.
- *Enhancing Power Efficiency:* Investigating advanced low-power computing techniques and efficient power management algorithms could further extend the system's operational duration, a crucial factor for patients requiring continuous monitoring.
- *Scalability Analysis*: As the user base grows, exploring strategies to efficiently manage data and resources while maintaining system performance becomes imperative, ensuring the system's scalability.
- *Data Security and Privacy Enhancements*: With the increasing reliance on IoT in healthcare, there is an amplified need for stringent data security and privacy measures. In response to this, research into robust encryption methodologies and secure data transmission protocols is planned to be initiated, with a focus on safeguarding patient information in cloud-based IoT environments. Efforts will encompass not only the implementation of robust encryption and secure authentication protocols but also the conducting of regular security audits. These audits are intended to proactively identify and address potential vulnerabilities. Furthermore, there is an aim to enhance user education and awareness about data security in IoT healthcare applications. Adopting this holistic approach to security and privacy is anticipated to enhance the protection of sensitive health data, ensuring alignment with global standards and best practices in healthcare data management.
- *User Experience Improvements*: Enhancing the wearable device's design for comfort, refining the cloud platform's user interface for ease of use, and integrating AI-driven alert systems for abnormal health readings would significantly improve the user experience. These enhancements aim to elevate the IoWT-HHMS as a more effective tool in remote health monitoring, aligning with the overarching goal of advancing healthcare accessibility and efficiency.

Our future research endeavours will significantly expand the scope of evaluation for the IoWT-HHMS. Recognising the imperative role of end-user feedback in healthcare technology, we plan to conduct comprehensive trials involving actual patients and caregivers. This phase of our research will focus on assessing the user experience, comfort, and overall usability of the system. By gathering qualitative and quantitative data on how patients and caregivers interact with the IoWT-HHMS, including their satisfaction levels and any challenges faced, we aim to glean insights that are critical for refining the system. This user-centric approach will not only validate the technical efficacy of our system in real-world scenarios but also ensure it aligns with the practical needs and preferences of its end-users. Ultimately, the incorporation of user-based testing is expected to enhance the IoWT-HHMS's applicability, user acceptance, and effectiveness in smart healthcare environments, thereby contributing to its broader adoption and success.

CRediT authorship contribution statement

Suliman Abdulmalek: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Data curation, Conceptualization. **Abdul Nasir:** Visualization, Supervision, Resources, Project administration, Data curation. **Waheb A. Jabbar:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

This work was supported in part by Universiti Malaysia Pahang Sultan Abdullah (UMPSA) under Grant PGRS210330 and PDU203229 and in part by Birmingham City University (BCU).

References

[1] Y. Liu, W. Yu, W. Rahayu, T. Dillon, An evaluative study on IoT ecosystem for smart predictive maintenance (IoT-SPM) in manufacturing: multi-view requirements and data quality, IEEE Internet of Thing. J. (2023).
[2] A. Rejeb, et al., The Internet of Things (IoT) in healthcare: taking stock and moving forward, Internet of Thing. (2023) 100721.
[3] S.M. Alghamdi, et al., Healthcare providers' perception and barriers concerning the use of telehealth applications in saudi arabia: a cross-sectional study, Healthcare 10 (8) (2022) 1527. MDPI.
[4] S. Abdulmalek, A. Nasir, W.A. Jabbar, M.A. Almuhaya, D. Babu, An Internet of Wearable Things (IOWT) Based System for Smart Healthcare Monitoring, 2022.
[5] S. Abdulmalek, et al., IoT-based healthcare-monitoring system towards improving quality of life: a review, Healthcare 10 (10) (2022) 1993. MDPI.
[6] M. Hamim, S. Paul, S.I. Hoque, M.N. Rahman, I. Baqee, IoT based remote health monitoring system for patients and elderly people, in: 2019 International Conference on Robotics,Electrical and Signal Processing Techniques (ICREST), 2019, pp. 533–538, https://doi.org/10.1109/ICREST.2019.8644514, 10-12 Jan. 2019.
[7] L. Bailey, Wearable Internet of Things healthcare systems, virtual care, and real-time clinical monitoring in assessing and treating patients with COVID-19 symptoms, Am. J. Med. Res. 8 (1) (2021) 91–100.
[8] U. Jain, A. Gumber, D. Ajitha, G. Rajini, B. Subramanian, A review on a secure IoT-based healthcare system, in: Advances in Automation, Signal Processing, Instrumentation, and Control: Select Proceedings of i-CASIC 2020, Springer Singapore, 2021, pp. 3005–3016.
[9] R. Rogers, Internet of Things-based smart healthcare systems, wireless connected devices, and body sensor networks in COVID-19 remote patient monitoring, Am. J. Med. Res. 8 (1) (2021) 71–80.
[10] A. Haleem, M. Javaid, R.P. Singh, R. Suman, Telemedicine for healthcare: capabilities, features, barriers, and applications, Sensor. Int. (2021) 100117.
[11] W.A. Jabbar, T. Subramaniam, A.E. Ong, M.I. Shu'Ib, W. Wu, M.A. de Oliveira, LoRaWAN-based IoT system implementation for long-range outdoor air quality monitoring, Internet of Thing. 19 (2022) 100540.
[12] W.A. Jabbar, S. Annathurai, T.A.A. Rahim, M.F.M. Fauzi, Smart energy meter based on a long-range wide-area network for a stand-alone photovoltaic system, Expert Syst. Appl. 197 (2022) 116703.
[13] M.A. Almuhaya, W.A. Jabbar, N. Sulaiman, S. Abdulmalek, A survey on Lorawan technology: recent trends, opportunities, simulation tools and future directions, Electron. (Basel) 11 (1) (2022) 164.
[14] K.N. Swaroop, K. Chandu, R. Gorrepotu, S. Deb, A health monitoring system for vital signs using IoT, Internet of Thing. 5 (2019) 116–129, 2019/03/01/.
[15] N.Y. Philip, J.J. Rodrigues, H. Wang, S.J. Fong, J. Chen, Internet of Things for in-home health monitoring systems: current advances, challenges and future directions, IEEE J. Sel. Ar. Commun. 39 (2) (2021) 300–310.
[16] M.R. Etherton, et al., Regional Changes in Patterns of Stroke Presentation during the COVID-19 Pandemic, Stroke 52 (4) (2021) 1398–1406.
[17] D. Xu, J.Q. Sheng, P.J.-H. Hu, T.-S. Huang, C.-C. Hsu, A deep learning–based unsupervised method to impute missing values in patient records for improved management of cardiovascular patients, IEEE J. Biomed. Health Inform. 25 (6) (2020) 2260–2272.
[18] M.A. Al-Sheikh, I.A. Ameen, Design of mobile healthcare monitoring system using IoT technology and cloud computing, in: IOP Conference Series: Materials Science and Engineering 881, IOP Publishing, 2020 012113.
[19] D. Hasan, A. Ismaeel, Designing ECG Monitoring Healthcare System Based on Internet of Things Blynk Application, J. Appl. Sci. Technol. Trend. 1 (3) (2020) 106–111.
[20] R. Saha, S. Biswas, S. Sarmah, S. Karmakar, P. Das, A working prototype using DS18B20 temperature sensor and Arduino for health monitoring, SN Comput. Sci. 2 (1) (2021) 1–21.
[21] P. Bora, P. Kanakaraja, B. Chiranjeevi, M.J.S. Sai, A. Jeswanth, Smart real time health monitoring system using Arduino and Raspberry Pi, Mater. Today: Proc. (2021).

[22] L. Greco, G. Percannella, P. Ritrovato, F. Tortorella, M. Vento, Trends in IoT based solutions for health care: moving AI to the edge, Patt. Recognit. Lett. 135 (2020) 346–353.

[23] L.O. Aghenta, T. Iqbal, Design and implementation of a low-cost, open source IoT-based SCADA system using ESP32 with OLED, ThingsBoard and MQTT protocol, AIMS Electron. Electric. Eng. 4 (1) (2019) 57–86.

[24] S. Saif, R. Saha, S. Biswas, On development of MySignals based prototype for application in health vitals monitoring, Wirel. Person. Commun. (2021) 1–18.

[25] A. Ullah, M. Azeem, H. Ashraf, A.A. Alaboudi, M. Humayun, N. Jhanjhi, Secure healthcare data aggregation and transmission in IoT—A survey, IEEE Access 9 (2021) 16849–16865.

[26] C. Butpheng, K.-H. Yeh, H. Xiong, Security and privacy in IoT-cloud-based e-health systems—a comprehensive review, Symmet. (Basel) 12 (7) (2020) 1191.

[27] M.M. Islam, A. Rahaman, M.R. Islam, Development of smart healthcare monitoring system in IoT environment, SN Comput. Sci. 1 (2020) 1–11.

[28] D. Gupta, A. Parikh, R. Swarnalatha, Integrated healthcare monitoring device for obese adults using internet of things (IoT), Int. J. Electr. Comput. Eng. (2088-8708) 10 (2) (2020).

[29] M.S. Alamsyah, M. Ikhlayel, E. Setijadi, Internet of things–based vital sign monitoring system, Int. J. Electr. Comput. Eng. (IJECE) 10 (6) (2020) 5891–5898.

[30] K. Sangeethalakshmi, U. Preethi, S. Pavithra, Patient health monitoring system using IoT, Mater. Today: Proc. 80 (2023) 2228–2231.

[31] M.A. Akkaş, R. Sokullu, H.E. Çetin, Healthcare and patient monitoring using IoT, Internet of Thing. 11 (2020) 100173.

[32] M.L. Sahu, M. Atulkar, M.K. Ahirwal, A. Ahamad, Vital sign monitoring system for healthcare through IoT based personal service application, Wirel. Person. Commun. (2021) 1–28.

[33] T. Wu, F. Wu, C. Qiu, J.M. Redouté, M.R. Yuce, A rigid-flex wearable health monitoring sensor patch for IoT-connected healthcare applications, IEEE Internet of Thing. J. 7 (8) (2020) 6932–6945, https://doi.org/10.1109/JIOT.2020.2977164.