An Ultra-Low-Power IoT-based Remote Monitoring System for COVID-19 Patients

Xenofon Georgitsaros
200922308
Dr Sukhpal Singh Gill
MSc FT Big Data Science

Abstract—**Recently, the COVID-19 pandemic has been one of the leading causes of death around the globe. Especially in Greece, a large percentage of the population is over 65 years old. People having a health history with chronic diseases make up a significant portion of this group, and this makes them more vulnerable to COVID-19 disease. The only defence for their well-being is constant monitoring of their health condition and prevention. However, current healthcare facilities are insufficient and cannot provide these people with the necessary medical care. As a result, an ultra-low-power Internet of Things (IoT)-based remote monitoring system for COVID-19 patients is presented in this paper. The goal is to develop a sensor node, which will enable monitoring patients' health status in real-time. For this purpose, an AD8232 ECG module, a MAX30100 heart rate - pulse oximeter and a LM35 body temperature sensor are connected to a low-cost and low-power NodeMCU board to obtain the biomedical data. Message Queuing Telemetry Transport (MQTT) protocol is utilized to publish biomedical data from sensor node to a channel/topic of ThingSpeak IoT platform. Then, MQTT clients can publish/subscribe to that topic of the MQTT broker to read or write data from that channel in real-time. This enables clinicians to monitor, process and store patients' data. Moreover, a Blynk app is developed to allow patients to monitor their health status with ease in real-time.**

Keywords—Internet-of-Things, remote monitoring system NodeMCU, ESP8266, blood oxygen, heart rate, Electrocardiogram, body temperature, MQTT protocol, ThingSpeak IoT platform, Blynk app, real time application.

I. INTRODUCTION

Since late December 2019, a new epidemic has come out in Wuhan, China, provoked by Severe Acute Respiratory Syndrome Coronavirus 2. The sickness caused by this virus has been dubbed COVID-19 by the World Health Organization (WHO). With the emergence of this disease as a pandemic, healthcare providers face a huge difficulty of overburdening patients, which might put their health in danger because healthcare providers may be unable to adequately treat them. Prompt diagnosis and monitoring of COVID-19 patients using the Internet of Things (IoT) will help limit the disease's transmission rate and lighten the workload in the healthcare sector [1]. As a result, demand for telehealth services has risen in order to fill this gap, particularly at a period when social distancing mechanisms are applied almost everywhere. Telehealth is a set of technologies that combines communications, sensing, computing, and human-computer interaction features to diagnose, treat, and monitor patients without interfering with their quality of life [2].

The most common symptoms at admission, according to the latest International Severe Acute Respiratory and Emerging Infections Consortium (ISARIC) report on hospitalized COVID-19 cases from 43 countries, were fever (68.7%), cough (68.5%), and/or shortness of breath (65.8%), fatigue (46.4%), confusion (27.3%), and muscle pain (20.1%), diarrhoea (19.1%), nausea and vomiting (18.8%), headache (13.0%), sore throat (10.5%), loss or altered sense of taste (7.2%) or smell (6.2%) [3]. According to these stats, the primary sign of infection is pulmonary-related effects and breathing problems, which can affect some biomedical values in the patients' body, such as oxygen level, and this, in turn, may have serious effects on the function of various organs such as the heart, lungs, and brain. At this point, it is important to add that the vaccine against covid-19 can protect people from getting the virus, but it is much likely to have side effects, and in some cases, they can be severe [4].

Internet of Things (IoT) is a network of interconnected devices and operations that comprises all network elements such as hardware, software, network connectivity, and any other electronic/computer means that makes them responsive by assisting in gathering and manipulating data. If we get into further details about the Internet of Things, it is more of a concept that creates the general architectural backdrop that enables the incorporation, efficient flow and exchange of data between the individual, who is in need and the various healthcare service providers. In the current typical circumstance, the majority of issues arise as a result of ineffective patient reachability. The IoT idea makes it possible to reach out to patients, which eventually aids in providing them with important treatment so that they can recover from their condition [5,6].

IoT is a cutting-edge technology, which can guarantee that all individuals who have been contaminated by this virus are quarantined. It is beneficial to have a proper monitoring system in place during their quarantine. The internet-based network allows all high-risk patients to be readily monitored. Biometric measures such as heart rate, body temperature, blood oxygen and glucose level are measured using this technology [7,8]. With the effective deployment of this technology, we may expect an enhancement in medical staff effectiveness by reducing their burden. The same might be done in the event of the COVID-19 pandemic, with fewer costs, errors, and effort [9].

A. Motivation

It is a fact that a large percentage of the population in Greece is over 65 years old. A significant portion of this group has a health history with chronic diseases [10]. These health issues, along with the infection of the virus, have caused a massive number of hospitalizations in Greece so far and are now one of the country's leading causes of mortality because of deficient medical care. Reflecting on the above, I have considered proposing a complete remote monitoring system for individuals affected by COVID-19 disease and may be in danger. Of course, this system may also be used for those who have been vaccinated and are experiencing some concerning side effects or may have an allergic reaction [4].

B. *Aims and Objectives*

Individuals affected by COVID-19 disease typically stay at home and ask for help if they are not feeling well. However, most patients think that they can overcome the disease at home, without consulting the healthcare service providers, until their health condition has become severe. The majority of these patients die before receiving proper care and treatment. Commuting to healthcare facilities has become extremely difficult, due to restriction measurements and the poor functioning of public transport, especially after the coronavirus epidemic. As a result, transforming the existing passive mode of healthcare provision into a pervasive approach is the key to improving medical care efficiency and reducing the mortality rate. This means that patients' health status will be monitored by doctors who will assess their biological data in real-time and decide whether to provide healthcare services or take any actions based on the patients' clinical picture. This pervasive type of healthcare is not feasible without a real-time monitoring system. On the other hand, cloud may be utilized to process and store the biological data of patients effectively and at much lower cost.

Using the technology of the Internet of Things (IoT) makes it feasible to monitor the vital activities of human beings wherever they are and whatever they do. Furthermore, the collected data from the sensor node is sent to the cloud so that clinicians are always informed of their patients' health status. This paper proposes a real-time IoT-based remote monitoring system for COVID-19 patients who have a medical history with heart, lung or other chronic diseases. The system offers several degrees of monitoring, ensuring that demands for connectivity and computing resources are as low as possible. Users can monitor their biomedical values through a smartphone Blynk app, and doctors can monitor patients' biomedical data in real-time thanks to MQTT protocol and ThingSpeak IoT platform. This wearable monitoring system satisfies the basic criteria of remote healthcare provision for COVID-19 patients with underlying diseases or commuting difficulties while also considering power consumption and implementation costs to make it ultra-low-power and cost-efficient.

The **key contributions** of this paper are:

- Develop a low-cost and low-power system to monitor the health status of COVID-19 patients.
- Create a Blynk smartphone app to process, store and monitor the biomedical values in real-time for the purpose of self-monitoring.
- Create a channel on ThingSpeak IoT platform to enable clinicians monitor, process and visualize the biomedical data of their patients in real-time.
- Demonstrate the results of the sensor values and analyse their performance in terms of accuracy metric.

In the rest of the paper, the following sections are presented: Section 2 presents the Related Work. Section 3 presents 'Hardware and Protocol Background', which describes the hardware parts and protocols I utilize for my system. Section 4 presents 'Proposed System'. Section 5 presents 'Discussion and Results', which demonstrate the advantages and experimental analysis of the Proposed System and finally, Section 6 presents 'Conclusion and Future Work'.

II. Related Works

Emokpae et al. proposed a non-intrusive Internet of Things remote monitoring system that has multimodal physiological sensing abilities. The aim is to identify COVID-19 symptoms and other infectious diseases, and it is equipped for use by 1) Individuals that have been diagnosed with COVID-19 and are being treated at their home; and 2) Individuals that have been isolated, because they have been exposed to contaminated persons. For this, it uses a mixture of communications, sensing, computing, and human-computer interaction methodologies to diagnose, treat, and monitor patients without interfering with their quality of life. The system consists of a mesh of multiple wireless sensors such as photoplethysmograph (PPG), electrocardiograph (ECG), electromyograph (EMG), acoustic cardiograph (ACG), and acoustic myograph (AMG) including a pulse oximeter and a microphone that are used to measure the patients' bio signals. The system relies on Zigbee to facilitate inter-node connectivity and the sensors provide data to a gateway node, which acts as the body area sensor network's (BASN's) interface. Also, this system utilizes particular deep learning algorithms to identify the COVID-19 based on features collected from the sensors. Finally, this system has a feature for energy conservation purposes, which minimizes the number of transmissions without compromising data accuracy by employing a machine learning model that periodically predicts a possible set of samples (in-network data processing) [11].

Hanoon and Aal-Nouman proposed an inexpensive IoT-based solution that aims to reduce the potential of COVID-19 virus spread, and their primary goal is to assist organizations to conform to the COVID-19 policy for safety and instructions in order to prevent the virus from spreading. This system can assist patients by assessing the condition of their health while clinicians are monitoring this data remotely. The proposed system comprises sensors that monitor the heart rate, blood oxygen level (MAX30100), and body temperature (MLX90164). These connect to the ATmega 2560 microprocessor via synchronous serial communication protocol inter-integrated circuit (I2C). The microprocessor accesses the Internet through ESP8266-01 using Wi-Fi technology and TCP protocol. The collected biodata is subsequently sent to an IoT cloud. Finally, by analyzing sensor data, the system may detect life-threatening situations and instantly warn clinicians [12].

Ashraf et al., presented an intelligent edge surveillance system that is used effectively for remote monitoring, early warning, and detection of a person's temperature, heart rate, heart status, and some radiological indicators for the detection of the suspected contaminated individual utilizing wearable smart devices. The main goal of the proposed architecture is to assist public health organizations, academics, and doctors manage and control the disease by developing such intelligent edge surveillance systems. Furthermore, the proposed architecture consists of 4 layers. The first one is the device layer, which comprises two main parts (wearable and non-wearable sensors), connected to an Arduino, used to measure vital signals such as body temperature, pulse rate, respiratory rate, and blood pressure. Then vital signals measured in the first layer are sent to the edge layer. The edge layer is divided into two layers, edge layer 1 and edge layer 2. The edge layer 1 is used to process the signals from the wearable sensors, while edge layer 2 is used for the processing of the signals obtained from the non-wearable sensors. The processed data from the multi-edge layers is then sent to the cloud layer, which uses GPS and event to graph mapping terms to monitor the suspected individual and gives the total user medical condition to the application layer. Finally, the front-end/application layer is made up of several modules, including a notification module, QR scanning and a recommendation system [13].

Priambodo and Kadarina proposed a monitoring system for COVID-19 patients, who are in self-isolation to monitor biomedical data, as well as patients' position information and the treatment response recovering from the disease. They created health monitoring system based on IoT that includes wireless body sensor networks and a gateway for data collection and transmission and suggested the utilization of the open-source ELK stack to identify possible coronavirus cases using real-time data promptly. Elasticsearch, Logstash, and Kibana (ELK) app is a technology, which collects massive amounts of log and other data from multiple sources and displays it in graphs and maps. The proposed architecture consists of 3 modules, the Wireless Body Sensor Networks (WBSN), the IoT gateway and the ELK stack. The WBSN module includes an SPO2 sensor, a heart rate sensor and a body temperature sensor that monitor patients' biodata. This data is transmitted and collected to an Android device that has GPS and location API via Bluetooth Low Energy protocol. The Android smartphone that serves as a gateway will also add a patient ID before sending data to the server. This patient ID is necessary to authenticate and identify ownership of receiving data among patients.. The procedure of transferring the data to the server might occur in real-time or be delayed based on the availability of an internet connection, because the Android device communicates with the program on the server is achieved over an HTTP or HTTPS connection. Finally, the data is retrieved and collected to the server with the help of logstash application and then is stored and indexed using Elasticsearch database and displayed on the Kibana dashboard with the proper visualization that can display patient geographical location and their health status [14].

Raposo et al. proposed e-CoVig, a mHealth application created as an alternative to the conventional monitoring approach, in which patients are followed up by phone. The e-CoVig offers a collection of features enabling remote reporting of symptoms, biological signals, and other medical data to the healthcare providers who are watching these patients. The system consists of a smartphone app, a web/cloud platform, and an inexoensive device for measuring temperature and SPO2. Firstly, mobile app is intended to record and transmit signals such as the heart rate, body temperature, blood oxygen saturation (SPO2), respiration, and cough. Mobile app also offers in-app self-reporting questionnaires allowing the collection of additional clinical data for better pathology characterization. The mobile application can conduct optical character recognition (OCR) on photos taken to a digital display using the camera and is utilized to obtain temperature values from thermometers or blood oxygenation value from pulse oximeters. Moreover, it has the capability to capture the patients' breathing or coughing using the microphone and photoplethysmography signals by using the device camera and flash and share it with the clinicians. Furthermore, the system is also equipped with a specialized device used to measure body temperature, heart rate, and SpO2. The application can communicate with this device to retrieve the measurements from the onboard sensors. Finally, the application can send all the data to a cloud-based platform, which includes algorithms for feature extraction and risk assessment of the patients being watched, and it can be shared with the clinicians [15].

A. *Critical Analysis*

A comparison of the proposed system to 5 different monitoring systems can be seen in Tables I and II. In particular, Table I compares the sensors used by each monitoring system. As can be seen, the aforementioned monitoring systems employ a variety of sensors, each of which offers separate data to healthcare services and users. However, just because some of them utilize more sensors than others, it does not indicate they are better or worse systems. Depending on the purpose and type of monitoring, most of the monitoring systems discussed achieve different goals and objectives. The common element across these architectures and systems is that they enable remote patient monitoring in the healthcare sector.

Table II compares the proposed system's features (technologies and protocols) to the other five monitoring systems. While looking at this table, it is clear that some protocols and technologies are used that are not available in all systems. Edge computing technology is only utilized in the proposed system and one more system. In the proposed system, MQTT protocol is used to publish the biomedical data from sensor node to MQTT clients in real-time. On the other hand, one monitoring system does not use a smartphone or computer app to display data and is the only one that employs the Zigbee wireless communication protocol. Finally, the proposed system is the only one that emphasizes real time data transmission, ultra-low energy consumption and low implementation cost.

Table I. Comparison of proposed sensing layer with existing work.

	Works					
Sensing layer	**Proposed system (this work)**	**Emokpae et al [11]**	**Hanoon and Aal-Nouman [12]**	**Ashraf et al [13]**	**Priambodo and Kadarina [14]**	**Raposo et al [15]**
ECG sensor	✓	✓				
Blood oxygen	✓		✓		✓	✓
Body temperature sensor	✓	✓	✓	✓	✓	✓
Respiratory Rate sensor				✓		✓
Microphone	✓	✓				✓
Heartbeat/ Heartrate	✓		✓	✓	✓	✓
Photoplethysmograph	✓	✓				✓
Blood pressure		✓		✓		

Table II. Comparison of proposed features with existing work.

	Works					
Features	**Proposed system (this work)**	**Emokpae et al [11]**	**Hanoon and Aal-Nouman [12]**	**Ashraf et al [13]**	**Priambodo and Kadarina [14]**	**Raposo et al [15]**
WiFi	ESP8266		✓			✓
Zigbee		✓				
Bluetooth					✓	✓
MQTT protocol	✓					
Edge computing	✓			✓		
Cloud computing	✓		✓	✓		✓
Smartphone/Web app	✓		✓	✓	✓	✓
Alert system	Manually	✓		✓		Manually
Data acquisition microcontroller	NodeMCU	Arduino	Arduino Mega 2560	Arduino	Gateway	Smartphone
Processing algorithms	Data filtering, Feature extraction, calibration	ML classifiers	N/A	N/A	Indexing	Feature extraction, risk assessment
Low power	Ultra	✓	N/A	N/A	✓	N/A
Low cost	✓					

III. Proposed System

This paper proposes a remote monitoring system based on the Internet of Things (IoT), designed for people who are polluted with the COVID-19 disease or vaccinated against it, especially those belonging to vulnerable groups. The purpose of the system is to monitor the patients' biomedical signals such as cardiac activity, body temperature, heartbeat, and blood oxygen in real-time, through many interconnected sensor devices. Each sensor/device senses different biomedical signals, which then some of them are amplified and converted into digital form by a microcontroller. These biomedical values are published to the MQTT broker, and then the MQTT broker publishes the data to the ThingSpeak IoT platform for additional processing, visualisation and storage, so that healthcare service providers can monitor the patients' health condition entirely remotely in real-time. Moreover, the sensor node can send the biomedical data to Blynk app. In this way, users may self monitor their biological data on their smartphones easily and in real-time. This system satisfies the essential criteria of remote healthcare provision for COVID-19 patients with heart or lung disorders while also considering the implementation costs and energy consumption to make this system as cost-effective and low-power as possible.

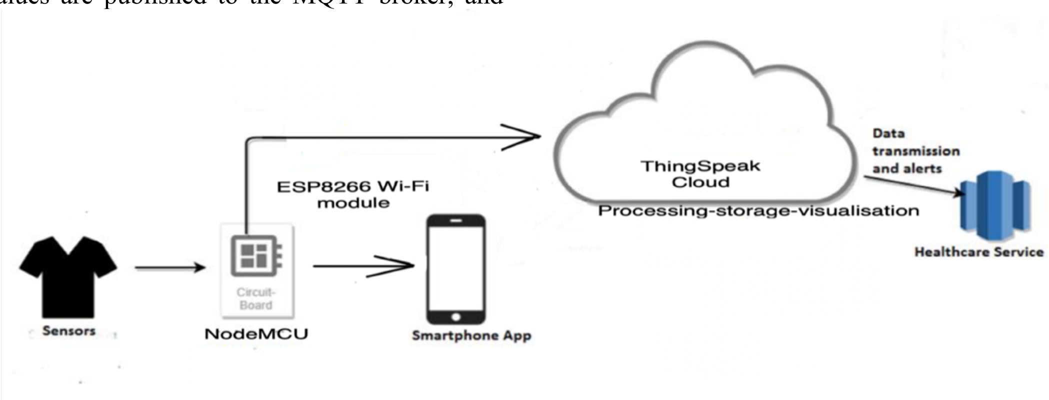

Fig. 1. Architecture of the proposed system [16].

A. *Hardware and Protocol Background.*

MQTT protocol

The MQTT is a messaging protocol of publish/subscribe, operating on top of the TCP/IP protocol and only requires a minimum network bandwidth. Because of its simplicity, it is utilized in IoT applications. The MQTT Protocol is comparable to the Constrained Application Protocol (CoAP). Both are designed for IoT devices with constraints. The difference is that the MQTT protocol is a many-to-many communication protocol, while CoAP is a one-to-one communication protocol. MQTT can handle multiple clients via a central broker, and subsequently, messages may be published to multiple clients [17,18]. In MQTT protocol, the broker is in charge of sending all messages between senders and receivers. A MQTT client can be any device that connects to the broker and may publish/subscribe to its topics in order to get the information. A topic includes the broker's routing information. To transmit messages, a client publishes them to a specific topic. The clients that want to receive these messages can subscribe to the specific topic. The broker sends all messages to the relevant clients with the matching topic [19].

NodeMCU ESP8266

NodeMCU is an open-source software and development board designed specifically for Internet of Things (IoT) applications. It comprises firmware that operates on Espressif Systems' ESP8266 Wi-Fi SoC, and its hardware is based on the ESP-12 module. The NodeMCU can be programmed with the Arduino IDE. It is an open-source Arduino software, which allows programming code to be composed and transferred to the board [20,21]. The sensors that are used to collect the patients' biomedical data are connected to the NodeMCU board. The NodeMCU board serves as a data acquisition module that collects the signals from the sensor modules. The gathered and converted data is then processed using the relevant libraries for each sensor to calculate the values. Following that, these sensor values are published to gateway smartphone and cloud for further processing and visualization using the MQTT protocol (Fig. 2).

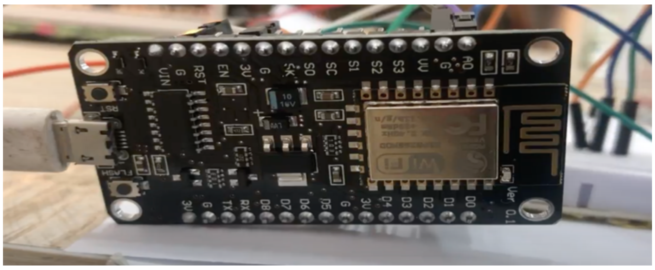

Fig. 2. NodeMCU board.

ESP8266EX Wi-Fi module

The ESP8266EX from Espressif is a highly integrated Wi-Fi SoC solution that meets consumers' ongoing requirements for ultra-low energy consumption, small design, and dependable performance on the Internet of Things sector. The ESP8266EX may function as an independent application or as slave to a host MCU due to its comprehensive and self-contained Wi-Fi networking capabilities. When the program is hosted by the ESP8266EX, it immediately starts up from the flash. The inbuilt high-speed cache aids in improving the performance and memory optimization of the system. ESP8266EX may also be used as a Wi-Fi adaptor in any microcontroller architecture via SPI/SDIO or UART interfaces. Also, for energy-saving purposes, a quick changeover between sleep and wake-up mode is provided [22].

B. Sensing Layer

The sensing layer is composed of a collection of sensors. These sensors can detect biological signals such as cardiac electrical activity, heartbeat, blood oxygen and body temperature and are chosen based on the parameters that the patients are monitored for (Fig. 3).

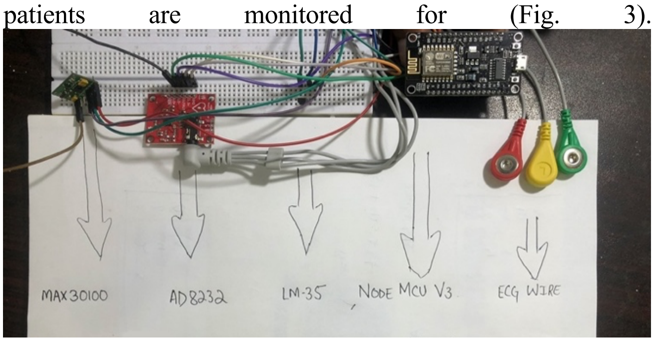

Fig. 3. Sensing layer of the system.

MAX30100 Pulse Oximeter and Heart rate sensor

The MAX30100 pulse sensor is used to obtain heart rate signal and blood oxygen (SPO2) level values in the human body, using the volumetric non-invasive photoplethysmogram (PPG) transmission technique, which is a measurement approach that employs single detection. The PPG signal is obtained through the irradiation of two distinct wavelengths of light through the body tissue and the comparison of the light absorption features of blood under these wavelengths. The sensor is comprised of two LEDs, a photodetector, improved optics, low-noise analog signal processing, and a built-in 50Hz filter. When only the infrared LED is turned on, only the pulse rate is being recorded. Both red and infrared LEDs must be switched on in order to detect oxygen saturation. To enable easy and convenient measurement, the MAX30100 sensor is connected to a finger clip that may fit the thumb. The patients' thumb will be placed on the red and infrared LEDs on the sensor's surface. The clip aperture is intended to be flexible in order to fit a user's typical size thumb. The acquired signal is then passed from the sensor to the amplifier [23] (Fig. 4).

Fig. 4. MAX30100 heart rate and pulse oximeter sensor [24].

Electrocardiograph electrodes with AD8232 module

An electrocardiograph sensor (ECG) with the AD8232 chip is used to identify and record heart muscle electrical activity by sensing electrical potentials on the body's surface and creating a database of electrical currents related to heart muscle activity in order to diagnose heart abnormalities. The user's body is equipped with three electrodes. One electrode is attached on the left arm, one on the right arm, and one on the right leg. This configuration avoids measurement noise. The electrical signals generated within the body of human does not have pure electrical nature. from one point to another. Before the bioelectric signals are recorded or displayed, they must be collected from the body's surface and sent into the amplifier and microcontroller initially. This is accomplished with the use of electrodes. Advances in wireless heart monitor (WHM) technology have considerably improved the performance of previous WHMs. These improvements also increase the patients' comfort and confidence in the monitoring [25] (Fig. 6 and Fig. 7).

The signal that is obtained from the Electrocardiogram (ECG) sensor electrodes is conditioned by using an integrated signal conditioning block, the AD8232 (Analog Company). It is created to obtain, amplify, and filter small bio-potential signals that include noisy components, like the sound produced by the patients' various motions or remote placement of the electrodes. The output signal may be easily obtained by using an analog-to-digital converter (ADC) or the built-in microcontroller in this architecture. The AD8232 incorporates a two-pole, high-pass filter to remove motion artefacts and the electrode half-cell potential. This filter is coupled with the instrumentation amplifier design in order to enable massive gain and high pass filtering in just one stage, thus reducing space and cost. An uncommitted functioning amplifier allows the AD8232 to build a three-pole, low-pass filter to remove extra noise. The frequency cut-off of all filters may be adjusted by the user to suit various application types. The AD8232 offers a right leg drive (RLD) amplifier for electrode driven applications to improve the common-mode rejection of line frequencies in the system as well as other undesirable interference. A quick restore feature on the AD8232 also reduces the duration of the long settling tails of the high-pass filters. Following a sudden shift in the signal that rails the amplifier (a lead off condition), the AD8232 automatically adapts to a higher filter cut-off. This feature allows the AD8232 to recover quickly and so take reliable readings immediately after connecting the electrodes to the user. Its performance ranges from 0 ° C to 70 ° C, and it may run between 40 ° C and 85 ° C [26] (Fig. 5).

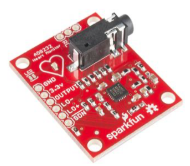

Fig. 5. The AD8232 ECG module [27].

Fig. 6. ECG electrode pads [28].

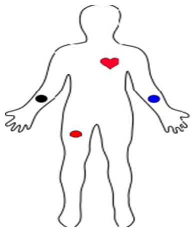

Fig. 7. Placement of the ECG electrodes on the human body [29].

Body temperature sensor

The LM35 is a precision integrated-circuit temperature sensor that can measure temperature more precisely than a conventional thermistor and shows temperature in Celsius degrees. The LM35 is able to operate in temperatures ranging from -55 to 150 degrees Celsius. The LM35 temperature sensor does not require an amplifier and has a higher output voltage than a thermocouple. The three pins of the LM35 temperature sensor are VCC, GND, and analog output [30] (Fig. 8).

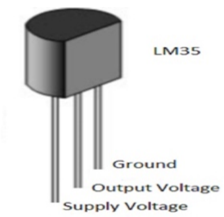

Fig. 8. LM35 temperature sensor [31].

C. Edge Layer

Worker Node (NodeMCU)

NodeMCU contains data processing and filtering techniques. Specifically, it contains libraries and code to calculate and calibrate input data from sensors and produce an accurate value.

MQTT broker

A typical MQTT setup requires MQTT clients and a broker. The MQTT broker is a server that receives messages from clients and distributes them to the appropriate destination clients [32]. Any device that runs a MQTT library and communicates to the MQTT broker across a network is a MQTT client [33]. MQTT clients can subscribe and publish to the broker's various topics, and the broker is responsible for handling the connections of the clients [18]. In the proposed system the sensing layer is the MQTT client, which publishes the data to the broker topic (Fig. 9).

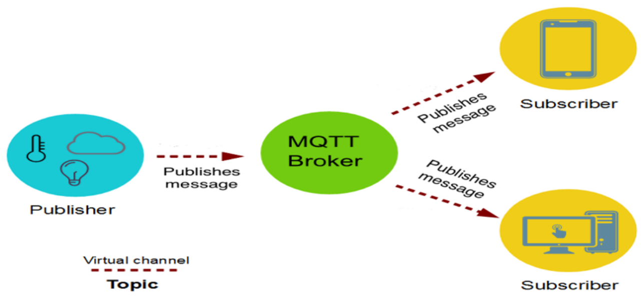

Fig. 9. Concept of MQTT protocol [34].

Smartphone (Blynk App)

The data from sensors is sent to the gateway smartphone via the ESP8266 NodeMCU board. Blynk is an Internet of Things (IoT) platform for iOS and Android devices that allows users to control Arduino, and other microcontrollers through the Internet. This application compiles and provides the appropriate address on the available widgets to develop the Grapfical User Interface or Human Machine Interface of the proposed system. Blynk was created with the Internet of Things in mind. It can operate hardware remotely, show sensor data, visualize it, store it, and do a variety of other operations. The platform is made up of three primary components [35]:

Blynk App: It enables to develop interfaces by utilizing the numerous available widgets [35].

Blynk Server: This server handles all communications between the gateway smartphone and the hardware [35].

Blynk Libraries: It allows communication with the server and processing of all receiving and outgoing commands [35].

D. Cloud Layer (ThingSpeak)

ThingSpeak is a cloud-based IoT analytics platform that aggregates, visualizes, and analyzes real data streams. Users can send data from their devices to ThingSpeak, generate live data visualizations, and send alerts [36]. In the proposed architecture, the collected biomedical values from the sensing layer are published to the MQTT broker. The MQTT broker publishes the data to the specified ThingSpeak topic. In turn, clinicians can publish/subscribe to that topic through the proposed ThingSpeak IoT cloud platform in order to monitor, process, and visualize the patients' data. The advancement of cloud computing technology has allowed for the efficient, reliable, secure, and cost-effective storage and processing of biomedical data in the cloud without needing a computing unit in each healthcare service providers' or users' physical environment. There are also a number of functions and characteristics that come with the Cloud layer implementation:

Data processing and storage: As described in the sensing layer, a set of biomedical values, including ECG, heart rate, blood oxygen (SPO2), and body temperature, are acquired through the relevant sensors attached to the users' body. ThingSpeak saves data on channels, which clinicians and others may then monitor. When data is on a ThingSpeak channel, it may be analyzed, displayed, as well as used to compute new data [37]. There are several important characteristics that may be derived from the gathered biological data in order to detect and recognize potential heart, pulmonary disorders provoked by covid-19 or an allergic reaction that may occur after the vaccination.

Prompt disease identification: Anyone infected by COVID-19 disease with heart or lung disease faces a high risk of having an unexpected critical health condition. The primary goal of this system is to safeguard patients from such unanticipated medical emergencies, and it is also important that their health condition can be tracked and identified at all times. Furthermore, any odd or suspicious sensor readings can be monitored by doctors to take an immediate action.

Visualization of data: A ThingSpeak web-based app, providing a variety of visualisation graphs, is developed for authorized doctors and users to monitor patients' biomedical data in real-time and access their medical history anytime.

IV. Discussion and Results

Hardware: The NodeMCU has significant advantages over the other available options, such as Arduino and RaspberryPi. It is a board that can connect to the Internet directly with its integrated ESP8266 Wi-Fi SoC without needing any external modules. Also, NodeMCU provides low energy consumption and reduced board size compared to Arduino board. These advantages make the NodeMCU, the best option for the proposed system, because of the enhanced practicality and efficiency [38,39].

Protocols: ThingSpeak IoT platform offers two different communication protocols. The first one is REST API, and the second one MQTT API. REST is an architectural style for representational state transfer structured as a request/response model, which communicates over HTTP. MQTT is a publish/subscribe paradigm that uses TCP/IP sockets or WebSockets to communicate. Also, SSL may be used to secure MQTT over WebSockets. However, the choice depends on the type of IoT application. MQTT is intended for applications, which have some of the following scenarios. The first is to send data with low power consumption. In addition to this scenario, a MQTT 'publish' action is generally faster. The second is to have a restricted bandwidth usage and intermittent connectivity. The third scenario is real-time changes to data posted to a channel, and the last one is to push messages to recipients rather than having to query the server for new ones [40].

As it is clear, the above scenarios are perfectly matching with the ones of the proposed system. Thus, MQTT was the optimum option for its implementation.

A. Blynk app

Fig. 10 and 11 shows the values from sensors in real-time. Hardware may send data to the available widgets over the Virtual Pin. Virtual Pins is a method for exchanging data between the hardware and the Blynk app. Virtual Pins is like channels for transmitting data [41]. Each Virtual Pin corresponds to a sensor connected to the Physical Pins of the hardware (Fig 10 and Fig. 11).

Fig. 10. Screenshot of Blynk app showing temperature, heart rate and ECG values.

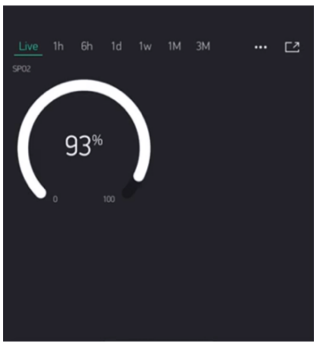

Fig. 11. Screenshot of Blynk app showing blood oxygen level (SPO2).

B. ThingSpeak IoT platform

Fig. 12 and Fig. 13 shows the recorded sensor values in four different fields in real-time. Each sensor is configured, via Arduino IDE code, to publish its values to a specific field of the ThingSpeak channel. Users may choose among a variety of plots/graphs for the visualization of the sensors' biomedical values. The figures below are not representative of an actual patient monitoring case. They are used to demonstrate that the proposed system is fully functional, and that sensor data is published to each channel field successfully in real-time (Fig. 12 and Fig. 13).

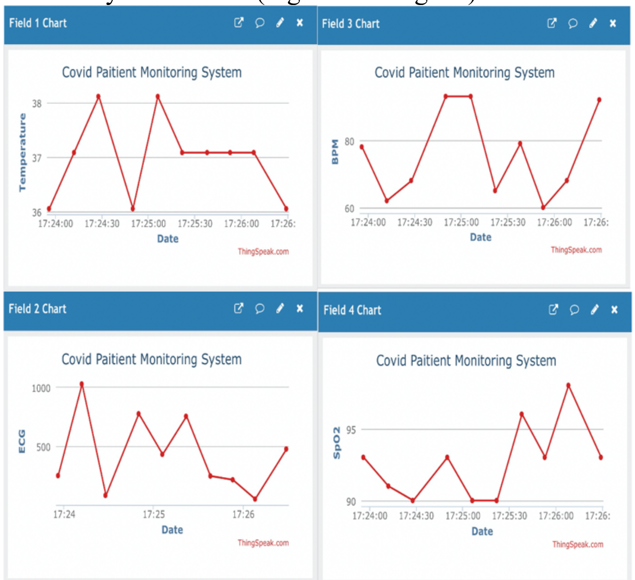

Fig. 12. ThingSpeak fields showing sensor values in real-time in line charts.

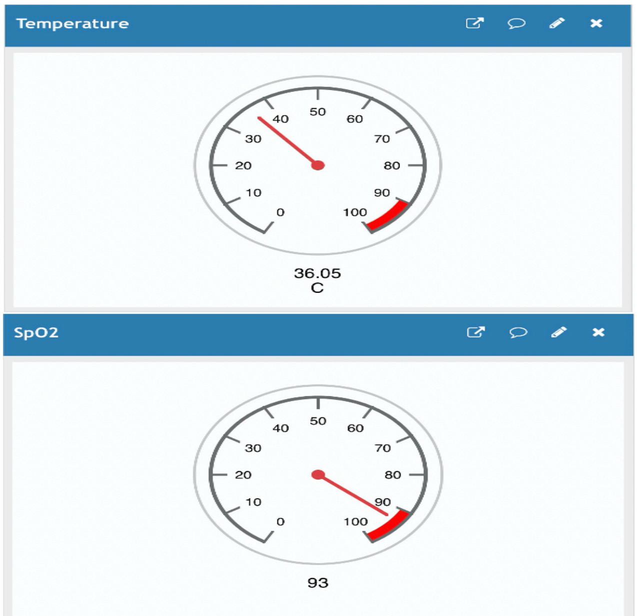

Fig. 13. Showing sensor values in real time using display widgets.

C. Experimental analysis

The proposed system was tested on one individual in various times of the day. For the test cases, the actual and observed data from the sensors for the heartbeat, body temperature, and blood oxygen sensor values are manually measured. The error rate of the observed data is calculated to demonstrate the system's efficiency. Because there were no other means to measure the actual ECG data, it is only just displayed in the ThingSpeak platform and Blynk app. Tables III, IV, and V show the actual and observed data along with their error rates for blood oxygen level, heart rate and body temperature, respectively.

As the proposed system is a prototype, it is reasonable that external factors may have a small effect on the output of sensor value measurements. Figures 14, 15 and 16 depict the deviation between the data acquired from the proposed system and actual data obtained from commercial devices. They show a small deviation between the actual and observed data. Data is gathered from one individual in different times of the day. The deviations may occur because of motion artefacts induced by individual's finger or body movement (for ECG electrodes) during measurement. Furthermore, light scattering from external sources can produce deviation in values as well. Finally, small deviation in body temperature values can be explained by sensor misplacement on the human body and environmental effects.

TABLE III. Measured SPO2 error rate.

No. of experiments	Actual data-Microlife Oxy 300 (SPO2%)	Observed data-MAX30100(SPO2%)	Error rate (%)
1	97	98	1.03
2	99	99	0.00
3	96	95	1.04
4	98	96	2.04
Avg. error rate for SPO2 (%)	1.03		

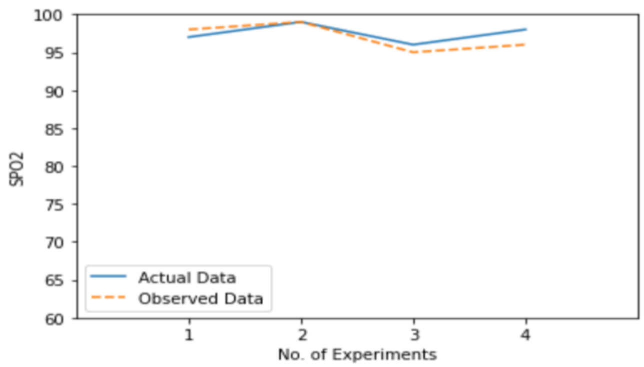

Fig. 14. Deviation between the observed and actual values of SPO2.

TABLE IV. Measured heart rate error rate

No. of experiments	Actual data-Microlife Oxy 300 (BPM)	Observed data-MAX30100(BPM)	Error rate (%)
1	71	73	2.81
2	86	89	3.48
3	95	94	1.05
4	78	82	5.12
Avg. error rate for BPM (%)	3,11		

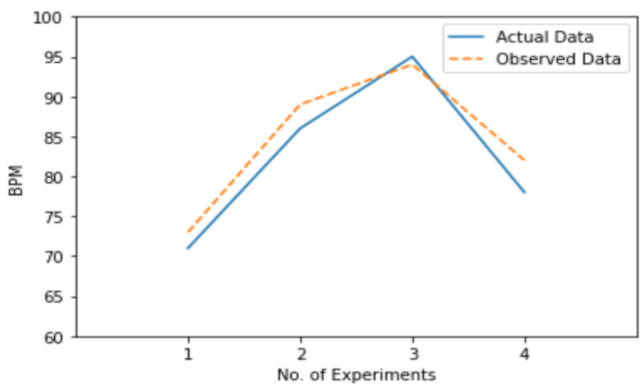

Fig. 15. Deviation between the observed and actual values of BPM

TABLE V. Measured body Temperature error rate

No. of experiments	Actual data-Microlife MT 808 (BPM)	Observed data-LM35(Body temp.)	Error rate (%)
1	36.5	36.1	1.09
2	36.9	37.3	1.08
3	36.7	36.2	1.36
4	37.1	37.3	0.53
Avg. error rate for body temp (%)	1.01		

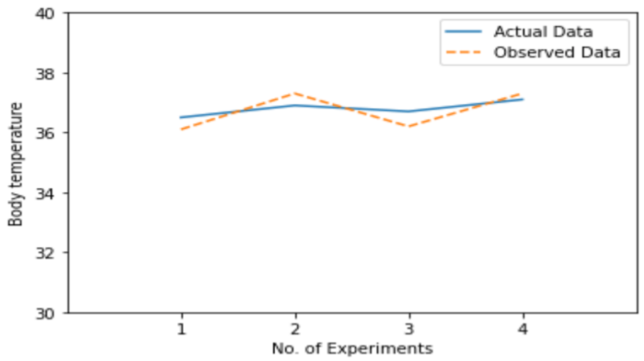

Fig. 16. This figure shows the deviation between the observed and actual values of body temperature.

V. CONCLUSIONS AND FUTURE WORK

In this paper, I proposed an ultra-low-power and low-cost Internet-of-Things-based smart system for remotely monitoring the health status of COVID-19 patients with chronic diseases. The monitoring system consists of the sensing layer, edge layer, and cloud layer. Several ultra-low-power and low-cost sensors and hardware make up the sensing layer, which is responsible for the acquisition of the patients' biomedical data and its transmission to clinicians in real-time by utilizing the MQTT protocol. The MQTT broker, is responsible for publishing the biomedical data transmission to ThingSpeak cloud. The patients' biological data is then further processed, visualized and stored in order to allow clinicians to monitor the health status of their patients in real-time. Also, a gateway smartphone with a specially designed Blynk application is used to enable users' monitor and visualize their biomedical data locally. Furthermore, I have made an experimental analysis of the proposed system regarding the accuracy performance metric. The results of the experiments demonstrated that the proposed system is reliable as it keeps low error rates and achieves a high accuracy correspondingly.

My future work will include an implementation of a special mechanism that uses in-network data processing to reduce the number of transmissions in the system. The objective is to reduce the number of sample transmissions while preserving data accuracy. When there is no serious illness, there are little variations in the monitored biological parameters and, as a result, in the gathered data. Thus, it will reduce the energy consumption and the resources. Also, I will embed a Fuzzy Rule Neural Classifier to enable the prediction and detection of an unforeseen medical emergency in its early phases, as well as its severity level.

REFERENCES

[1] Sandeepa, C., Moremada, C., Dissanayaka, N., Gamage, T. and Liyanage, M., 2020. Social Interaction Tracking and Patient Prediction System for Potential COVID-19 Patients. *2020 IEEE 3rd 5G World Forum (5GWF).*

[2] Riazul Islam, S.M., Kwak, D., Humaun Kabir, M., Hossain, M. and Kwak, K-S., 2015. The Internet of Things for Health Care: A Comprehensive Survey. *IEEE Access*, 3, pp.678-708.

[3] Pritchard, M., 2021. COVID-19 symptoms at hospital admission vary with age and sex: ISARIC multinational study.

[4] Centers for Disease Control and Prevention. 2021. *What to Expect after Getting a COVID-19 Vaccine*. [online] Available at: <https://www.cdc.gov/coronavirus/2019-ncov/vaccines/expect/after.html> [Accessed 4 June 2021].

[5] Wang, Y., Hu, M., Li, Q., Zhai, G., Zhang, X. and Yao, N., 2020. Abnormal respiratory patterns classifier may contribute to large-scale screening of people infected with COVID-19 in an accurate and unobtrusive manner. *arXiv:2002.05534*.

[6] Haleem, A., Javaid, M., Vaishya, R. and Deshmukh, S., 2020. Areas of academic research with the impact of COVID-19. *The American Journal of Emergency Medicine*, 38(7), pp.1524-1526.

[7] Vaishya, R., Javaid, M., Khan, I. and Haleem, A., 2020. Artificial Intelligence (AI) applications for COVID-19 pandemic. *Diabetes & Metabolic Syndrome: Clinical Research & Reviews*, 14(4), pp.337-339.

[8] Mohammed M., Syamsudin H., Al-Zubaidi S, Sairah, A., Ramli R., Yusuf E., 2020, Novel COVID-19 detection and diagnosis system using IOT based smart helmet. International Journal of Psychological Rehabilitation, 24(7).

[9] Singh, R., Javaid, M., Haleem, A. and Suman, R., 2020. Internet of things (IoT) applications to fight against COVID-19 pandemic. *Diabetes & Metabolic Syndrome: Clinical Research & Reviews*, 14(4), pp.521-524.

[10] Ec.europa.eu. 2019. [online] Available at: <https://ec.europa.eu/health/sites/default/files/state/docs/2019_chp_gr_english.pdf> [Accessed 6 June 2021].

[11] Emokpae, L., Emokpae, R., Lalouani, W. and Younis, M., 2021. Smart Multimodal Telehealth-IoT System for COVID-19 Patients. *IEEE Pervasive Computing*, 20(2), pp.73-80.

[12] Hanoon, I. and Aal-Nouman, M., 2021. Cloud-based COVID-19 Patient Monitoring using Arduino. *2021 3rd East Indonesia Conference on Computer and Information Technology (EIConCIT)*.

[13] Ashraf, M., Hannan, A., Cheema, S., Ali, Z., Jambi, K. and Alofi, A., 2020. Detection and Tracking Contagion using IoT-Edge Technologies: Confronting COVID-19 Pandemic. *2020 International Conference on Electrical, Communication, and Computer Engineering (ICECCE)*,.

[14] Priambodo, R. and Kadarina, T., 2020. Monitoring Self-isolation Patient of COVID-19 with Internet of Things. *2020 IEEE International Conference on Communication, Networks and Satellite (Comnetsat)*.

[15] Raposo, A., Marques, L., Correia, R., Melo, F., Valente, J., Pereira, T., Rosário, L., Froes, F., Sanches, J. and Silva, H., (2021). e-CoVig: A Novel mHealth System for Remote Monitoring of Symptoms in COVID-19. *Sensors*, 21(10), p.3397.

[16] Stretchsense, 2018. System architecture. [image] Available at: https://stretchsense.com/article-resources/blog/real-time-stretch-sensor-data-processing- with-amazon-web-services-kinesis/ [Accessed 25 June 2021].

[17] Kotak, J., Shah, A., Shah, A. and Rajdev, P., (2019). A Comparative Analysis on Security of MQTT Brokers. *2nd Smart Cities Symposium (SCS 2019)*.

[18] Wu, F., Wu, T. and Yuce, M., (2018). An Internet-of-Things (IoT) Network System for Connected Safety and Health Monitoring Applications. *Sensors*, 19(1), p.21.

[19] Mathworks.com. 2021. *MQTT Basics*. [online] Available at: <https://www.mathworks.com/help/thingspeak/mqtt-basics.html> [Accessed 25 August 2021].

[20] Yuan, M., 2017. *Archived | Getting to know NodeMCU and its DEVKIT board*. [online] IBM Developer. Available at: <https://developer.ibm.com/tutorials/iot-nodemcu-open-why-use/> [Accessed 2 July 2021].

[21] Tamilselvi, V., Sribalaji, S., Vigneshwaran, P., Vinu, P. and GeethaRamani, J., 2020. IoT Based Health Monitoring System. *2020 6th International Conference on Advanced Computing and Communication Systems (ICACCS)*.

[22] 2020. ESP8266ex. [ebook] Espressif, p.1. Available at: <https://www.espressif.com/sites/default/files/documentation/0a-esp8266ex_datasheet_en.pdf> [Accessed 20 July 2021].

[23] Yusof, M., Xin Fung, S., Li Low, W., Wen Lim, C. and Wen Hau, Y., (2019). Miniaturized and Portable Home-Based Vital Sign Monitor Design with Android Mobile Application. *International Journal of Integrated Engineering*, 11(3).

[24] topelectronics.gr, 2021. *MAX30100 HEART-RATE OXIMETER PULSE SENSOR MODULE*. [image] Available at: <https://topelectronics.gr/electronics/sensors/heart/max30100-heart-rate-oximeter-pulse-sensor-module/> [Accessed 25 July 2021].

[25] Alfarhan, K., Mashor, M. and Saad, A., (2016). A REVIEW OF WIRELESS ECG MONITORING SYSTEMS DESIGN. *International Acadmey of Engineering and Medical Research (IAEMR)*, 1(2).

[26] Analog.com. 2021. *AD8232 Datasheet*. [pdf] p.1. Available at: <https://www.analog.com/media/en/technical-documentation/data-sheets/ad8232.pdf> [Accessed 26 July 2021].

[27] grobotronics.com, n.d. *AD8232 Single Lead Heart Rate Monitor*. [image] Available at: <https://grobotronics.com/ad8232-single-lead-heart-rate-monitor.html?sl=en> [Accessed 27 July 2021].

[28] grobotronics.com, n.d. *Sensor Cable - Electrode Pads*. [image] Available at: <https://grobotronics.com/sensor-cable-electrode-pads-3-connector.html> [Accessed 27 July 2021].

[29] Chhabra, M. and Kalsi, M. (2017). *ECG Electrodes Placement*. [image] Available at: <https://www.researchgate.net/publication/327273062_Real_Time_ECG_monitoring_syst em_based_on_Internet_of_Things_IoT> [Accessed 27 July 2021].

[30] Sarierao, B. and Prakasarao, A., 2018. Smart Healthcare Monitoring System Using MQTT Protocol. *2018 3rd International Conference for Convergence in Technology (I2CT)*,.

[31] opzlab.com, 2020. *LM35 Temperature Sensor*. [image] Available at: <https://www.opzlab.com/product/lm35-analog-temperature-sensor/> [Accessed 27 July 2021].

[32] Yuan, M., 2021. *What is MQTT? Why use MQTT?*. [online] IBM Developer. Available at: <https://developer.ibm.com/articles/iot-mqtt-why-good-for-iot/> [Accessed 31 July 2021].

[33] The HiveMQ Team, 2019. *MQTT Client and Broker and MQTT Server and Connection Establishment Explained - MQTT Essentials: Part 3*. [online] Hivemq.com. Available at: <https://www.hivemq.com/blog/mqtt-essentials-part-3-client-broker-connection-establishment/> [Accessed 2 August 2021].

[34] 8bitwork, 2019. *MQTT protocol*. [image] Available at: <https://8bitwork.com/2019/04/13/messaging-protocol-for-iot-mqtt-coap-amqp-xmpp-and-dds-1/> [Accessed 2 August 2021].

[35] Media's, E., Syufrijal and Rif'an, M., 2019. Internet of Things (IoT): BLYNK Framework for Smart Home. *KnE Social Sciences*, 3(12), p.579.

[36] Mathworks.com. 2021. *ThingSpeak Documentation*. [online] Available at: <https://www.mathworks.com/help/thingspeak/> [Accessed 4 August 2021].

[37] Thingspeak.com. 2021. *How To Collect, Analyze, and Act on IoT Data - ThingSpeak IoT*. [online] Available at: <https://thingspeak.com/pages/how_to> [Accessed 5 August 2021].

[38] IoT-Ignite Devzone. n.d. *NodeMcu and Arduino IDE*. [online] Available at: <https://devzone.iot-ignite.com/knowledge-base/nodemcu-and-arduino-ide/> [Accessed 15 August 2021].

[39] Bento, A., 2018. IoT: NodeMCU 12e X Arduino Uno, Results of an experimental and comparative survey. *International Journal of Advance Research in Computer Science and Management Studies*, 6(1).

[40] Mathworks.com. 2021. *Choose Between REST API and MQTT API*. [online] Available at: <https://www.mathworks.com/help/thingspeak/choose-between-rest-and-mqtt.html#bvk_ucm-5> [Accessed 16 August 2021].

[41] Docs.blynk.cc. n.d. *Documentation for Blynk, the most popular IoT platform for businesses.*. [online] Available at: <https://docs.blynk.cc/#blynk-firmware-virtual-pins-control> [Accessed 17 August 2021].