LoRaware Optimized Wireless Patient Monitoring

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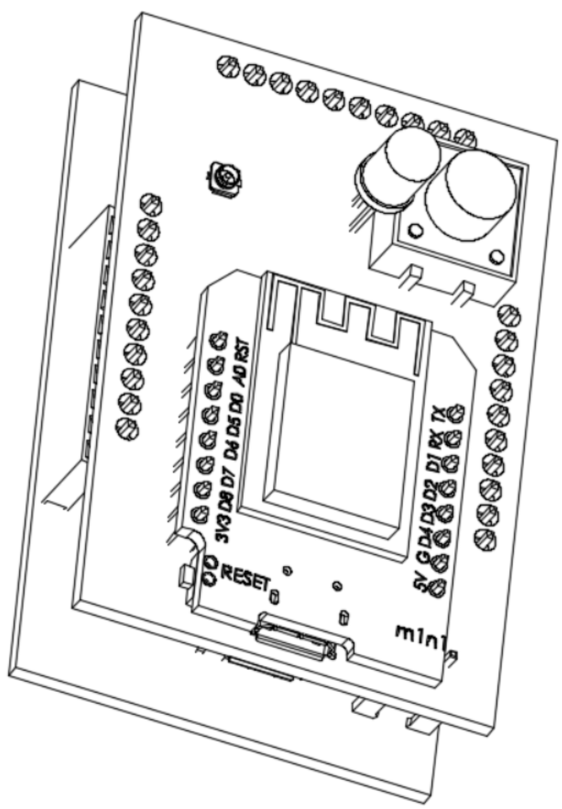
Abstract

This capstone project represents the culmination of the Master of Science in Electrical Engineering with specialization in Wireless Communication program at National University. This project focused on the development of a wireless network for use in a medical environment. The developed system consists of four wireless biometric sensing node devices networked through a Long-Range Wide Area Network (LoRaWAN). The observed biometric data can first be obtained by a combination of sampling, reading analog and digital voltage values, and conversions performed by each device's processor, then transmitted to a centralized LoRaWAN Gateway; which forwards the information to a network server to be stored and displayed by hosted services and applications, forming a lightweight and functional management platform. The project team developed and successfully tested the proposed LoRaware system throughout the course of a three-month duration.



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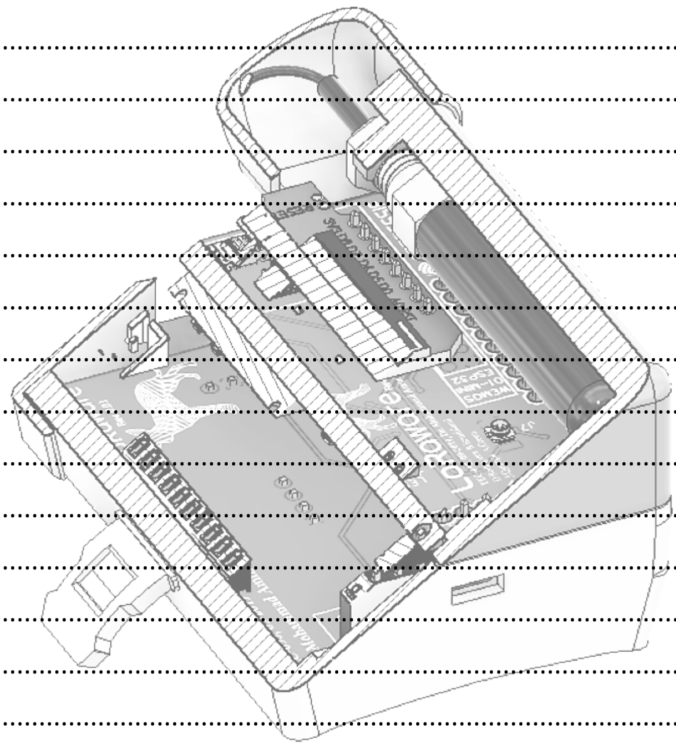


LoRaware Optimized Wireless Patient Monitoring

1. Introduction

This project report describes the project's purpose, design concepts, research performed, development efforts, testing process and analysis of a wireless sensor network to monitor patients' biometric information in a medical treatment environment. The development of this sensor network is meant to provide an alternative method of monitoring patients in transit for further treatment or in situations where medical staff are resource-challenged in emergency situations.

2. Purpose

The purpose of this project is to fulfill the Master of Electrical Engineering (MSEE) program requirements for graduation at National University (NU). The NU MSEE program specializes all students in wireless communications. This capstone project requirement provides project participants the opportunity to apply knowledge gained in the curriculum through their exposure to project research, design, development and implementation; skills that will be required for working in the industry.

3. Project Team

The Team is composed of four students in the MSEE curriculum at National University. Their assignment to this team was a result of sharing a common interest in wireless networking. All team members come from different engineering backgrounds with broad work experience that contributed significantly to the various requirements of the project. Team member's academic and work experience backgrounds are highlighted below.

3.1 Team Members

Babatope (Sam) Erinfolami is a graduate of the Federal Polytechnic Ado-Ekiti, Nigeria with a Higher National Diploma, a Bachelor of Science in Electrical Engineering (BSEE) equivalent. Sam has experience as an agricultural machinery operator, as a High School math and physics instructor, and as an Electrical Technician for the US Navy. Sam has significant experience leading personnel in the execution of scheduled maintenance and repairs on board Navy ships and as a shipboard electrical systems instructor.

Antwan Green is a graduate of the University of San Diego (USD) with a BS in Electrical Engineering (BSEE). He has worked extensively with troubleshooting electronic circuits, control systems, Digital Signal Processing (DSP) and has assembled a variety of electronic devices with strong electronics soldering skills. Antwan has work experience as a sales engineer and as a claim's assistant in the workers compensation division of an Insurance company.

David Rodriguez is a graduate of New Mexico State University with a Bachelor of Science degree in Engineering Physics with a concentration in Mechanical Engineering. He currently works at National University as a Systems Administrator and Engineering Academic and Laboratory Support Assistant. He has extensive experience helping students with their laboratory work and in project execution through technical support and manufacturing of prototype tools and devices. David is an avid programmer and electronics hobbyist and has designed, built and successfully operated several personal electronic projects.

Jorge Quiroga is a graduate of San Jose State University with a BSME. Jorge is also a graduate of the Naval Postgraduate School with a Master of Science in Operations Research (MS OR) with specialization in Logistics, and a graduate of University of Phoenix with a Master of Business Administration (MBA). Jorge has over 30 years of work experience as a military officer and project manager. Jorge has mentored numerous subordinates in a wide spectrum of leadership roles, some of these include project teams addressing technical and non-technical endeavors.

3.2 Team Advisor

Per university requirements, Dr. Mohammed Amin was assigned as the team advisor for the development of this capstone project. Students and advisor met weekly from August to October 2019 to address project selection, technical design, as well as discussing project challenges, solutions and progress with the goal of developing a technical solution as a proof of concept design.

4. Project Assignments

Project work was distributed among team members based on their individual strengths and learning interests. David Rodriguez is the team leader and lead system designer; Antwan Green and Babatope Erinfolami were in charge of market research and complemented David with hardware design; Jorge helped set objectives, track progress and design of tests. All team members participated in the assembly and testing of LoRaware system components at each stage of development, as well as in the documentation of project deliverables as required by the MSEE curriculum.

5. Project Selection

The MSEE capstone project at NU is intended to complement the academic program to ensure every student can use acquired knowledge through the development and exercise of a practical solution. Since the MSEE program at NU specializes in wireless communications, the project must consist of a wireless system application. In fulfillment of this requirement, the team focused its attention on wireless networks.

Wireless networks are used in a variety of activities and applications in the realm of human activity; however, existing applications in any focus area do not generally address all the focus area's needs or they are performance limited. Because of this, there is always room for improvement. With this in mind, the team focused in a wireless network system for medical application.

5.1 Contributing Factors

With up to 75% of preventable hospital deaths occurring outside of the ICU in unmonitored beds and up to 60% of all hospital patients spending the duration of their stay in an unmonitored environment (Haraden, 2012), the demand for the implementation of a new system of autonomous patient monitoring exists with higher urgency than ever before.

Timely response to the slightest abnormalities in a patient's vital signs truly means the difference between a positive outcome and the loss of life. With global populations slated to continue increasing and the constant circumstance of patients outnumbering doctors and staff, a time-dependent, widely integrated, and convenient solution will always be a necessity in hospitals.

6. Project Objectives

The main objective of this capstone project is the development of a functional Optimized Wireless Patient Monitoring System proof-of-concept called LoRaware*,* a low-power, long range, wireless network biometrics measurement and monitoring system, through a systematic technical approach with due consideration to the following focus areas:

6.1 System Design Requirements

The LoRaware System and its constituent components shall be comprised of a wireless sensor set for physiological metrics, a wireless network Gateway accessible via a computer-based application for centralized monitoring of the networked sensors and for the distribution of acquired information when connected to medical servers via internet connections. In addition, the system must meet the following performance requirements:

- Reliable Storage, Monitoring, and Data Visualization Access
- No Reliance on pre-existing Wi-Fi Infrastructure
- No Interference with pre-existing Wi-Fi Infrastructure
- Secure Transfer of Patient Biometric Data
- Portable system for easy deployment in locations with internet access and one available ethernet port

6.1.1 Sensor Set Physical Features

The sensor sets shall be portable and wrist wearable, and they must include sensors for biometric measurements, a microcontroller, a battery, an RF chip and antenna for data transmissions. All these items must fit in a low-profile enclosure. Dimensions of the enclosure shall be approximately 2x1.5x2.5 inches.

6.1.2 Power Features

The sensor set and wireless device shall possess and support self-powered for continuous use for a minimum of 16-hours. The Gateway shall be portable and deployable at any location with 110 to 220 VAC power and one available ethernet port with network connectivity.

6.1.3 Interface Requirements

The majority of wireless data transfer shall occur within the region of unlicensed spectrum known as the 915 MHz ISM band. The network gateway shall maintain a connection with an external network server, which will handle a majority of the management services, The network server must also contain an application to parse and clean received data, host Database services, as well as host a data visualization dashboard that is both accessible to others, and easy to use.

6.1.4 Software Requirements

The list of software requirements for our project begins with our wireless sensor devices, upon which, their embedded firmware and integrated set of runtime instructions shall support the inclusion of debugging capabilities to control all sensor set functions and for self-diagnostics. The Network Gateway shall have its own management software for normal operation and self-diagnostics.

6.1.5 Security Requirements

The LoRaware wireless devices must be able to transmit measured data securely to the LPWAN Gateway. Based on the fact that the data to be collected for the LoRaware system is primarily biometric, it should be noted that there are a few special considerations that must addressed when defining the security requirements. Since the data being transmitted from wireless devices encompasses a wearer's heart rate, blood oximetry, temperature, and humidity, it can be categorized as Level 4 of the Harvard Information Security Policy, with Level 5 representing the most stringent and severe data security requirements (Harvard Information Security Policy, 2019). Some of the major Server-side requirements defined by Harvard's Information Security Policy include the following:

- Application owner and classification level - Server operators must be able to identify a responsible party, known as the business application owner, for each application on the server and the data classification level of the information that the application stores and processes.
- Server communication - Communications between servers or applications and client machines must be protected.
- Server-application communication - Communications between servers or applications must be protected.
- Appropriate user access - Users must only be permitted to access a server or application after their current business need for access has been established.
- Password Management - Mechanisms for users to set or change passwords must be secure. Systems that manage passwords must be configured securely. Storage and management of passwords requires L4 security.
- Logging access - User and administrator access to servers and applications must be logged.

It will be the aim of our project to honor many of these particular security policy entries in order to retain as much real-world usability within the establishment and deployment of the LoRaware System.

7. Research

Vital sign monitors are medical devices used for the continuous monitoring of biometric measurements as indicators of a patient's health status. The more common measurements among these are heart rate (pulse rate), blood oxygen concentration, and core temperature. Neither require invasive probing to obtain the metric.

In practice, instruments used in medical care to capture biometric information are generally used once during initial patient assessment. Observations are manually recorded and are only reviewed when the patient is in post-admittance care. Following admittance, medical personnel may use portable non-networked, stand-alone thermometers and tensiometers, or hook the patient to a multi-function monitor on a stand which must be energized through a wall AC outlet. If these instruments are not connected to an IT network, the data will only be collected or monitored sporadically during medical personnel rounds. These conditions create a gap of medical monitoring coverage and simultaneously create an opportunity to close it though the implementation of a networked, continuous monitoring, portable, low-cost system. A wireless networked sensor provides the simplest solution to the coverage gap. They can be used to track vital signs under various conditions, such as during physical activity or, more frequently, during medical treatment. The following provides an additional perspective for the need and potential use of such devices.

According to the findings of the World Health Organization (WHO) in 2015 over 17.7 million people died from cardiovascular diseases representing 31% of the global deaths; among these 82% of the total deaths occurred were in the low and middle-income countries.

The global market for heart rate monitors is expected to grow at a Compound Annual Growth Rate of 13.50% (According to the Market Research Future MRFR press release) during forecast period 2017-2023. Some of the major players in this market are Apple (U.S), Garmin Ltd (U.S.), Visomed Group (France), Omron healthcare (Japan). These players are tapping new regions in developing economies across the globe to take hold of the market. End users of these products include Hospitals and clinics, sports medicine centers, professionals and individuals

In the U.S clinical wireless heart rate monitors and oximeters used in hospitals are robust, medical grade and FDA approved but mostly not cost effective, with this project we are designing a system with similar capability that will be cost effective and less cumbersome in size and in operation that will also provide wireless remote monitoring capability (Market Research Future, 2018) .

7.1 Similar Products Currently Available

The following illustrates a few portable commercial devices that provide information similar to the goals of this project. Some of these products do not have remote monitor capability and some do have remote monitoring capabilities but not with wireless access. If they have wireless access, they are costlier and less flexible.

Hopkins Hand-Held Pulse Oximeter

Pulse Tensiometer

Hopkins Handheld Pulse Oximeter (Hopkins Medical Products, 2019)

- Excellent for spot-check applications and continuous monitoring
- Antimovement digital signal processing technology
- Accurate pulse oximetry measurements during motion and low perfusion
- Perfusion index and signal quality index indication
- SpO2 measurement range: 35%-100%; Pulse-rate measurement range: 30-250bpm
- Audible and visual alarms for high/low SpO2 and pulse rate
- Low signal-quality and battery indicators
- Includes Y-probe neonatal sensor (39" long)
- Requires three AA batteries (included)

Visi Mobile

Per Sotera Wireless, 2019, "ViSi Mobile is a system designed to enhance patient safety, allowing early detection of patient deterioration and connecting clinicians with their patients anywhere, any time."

This system is the only portable networked system available in the market. It provides multiple biometric measurement including heart rate from electro-cardiogram, oxygen saturation skin temperature and cuff-less blood pressure. It connects to a monitoring system via Wi-Fi. (Sotera Wireless, 2019)

Visi Mobile System & Architecture

8. Wireless System Selection

There are three types of wireless networks: Wireless Wide Area Networks (WWAN), Wireless Local Area Network (WLAN), and Wireless Personal Area Network (WPAN).

WWANs offers a means to remain connected even when the user is distant from other wired or Wi-Fi form of network access. These networks are typically enabled by use of mobile phone signals; which are typically provided and maintained by mobile phone (cellular) service providers. WLANs are wireless networks that use radio waves. The support network typically uses cables, with one or more wireless access points connecting the wireless users to the wired network. The range of a WLAN can be anywhere from a single room to an entire campus. WPANs are short-range networks that use Bluetooth technology. They are commonly used to interconnect compatible devices near a central location, such as a desk. A WPAN has a typical range of about 30 feet (Agarwal, 2010).

There are quite a few wireless protocols in the market. The most common protocols used are Zigbee, Sigfox Bluetooth, Wi-Fi and LoRa. This project employs LoRa Wide Area Network (LoRaWAN). The LoRaWAN open specification is a low power, wide area networking (LPWAN) protocol based on LoRa Technology. It is designed to wirelessly connect battery operated things to the Internet in regional, national or global networks (Semtech, N.D.).

When compared to a protocol like SigFox, both the endpoint and the Gateway are relatively inexpensive with LoRa-enabled devices. This is primarily because the same radio can be used as a receiver on the Gateway and at the endpoint. While the LoRaWAN Gateway tends to be more expensive than the endpoint, it is inexpensive in comparison to a SigFox Gateway (Ray, 2018).

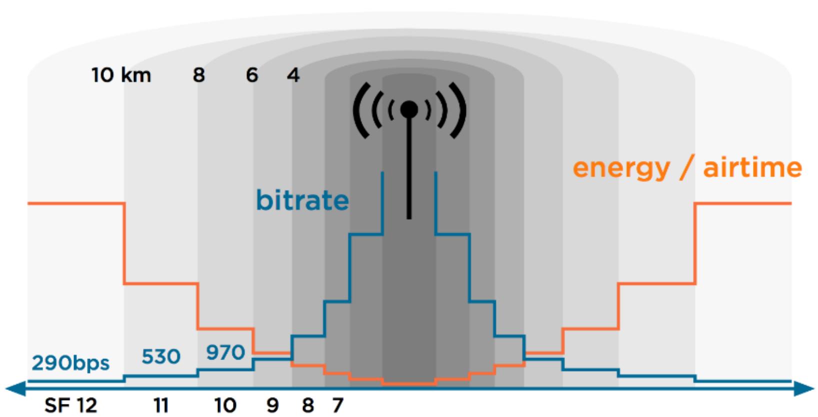


Figure 1 LoRaWAN Relation between Bit Rate, Range, Spreading Factor, and Bandwidth

LoRaWAN uses a modified Chirp Spread Spectrum Modulation Technique borrowed from IEEE 802.15. The spread spectrum is also known as the spreading factor and is used to improve range and data rate by adjusting transmission power to distribute data across wider bandwidth of the spectrum. Other benefits include multiple forms of Forward Error Correction for each transmitted packet, with individual Cyclical Redundancy Checks applied to the entire packet frame, as well as the data payload of the packet.

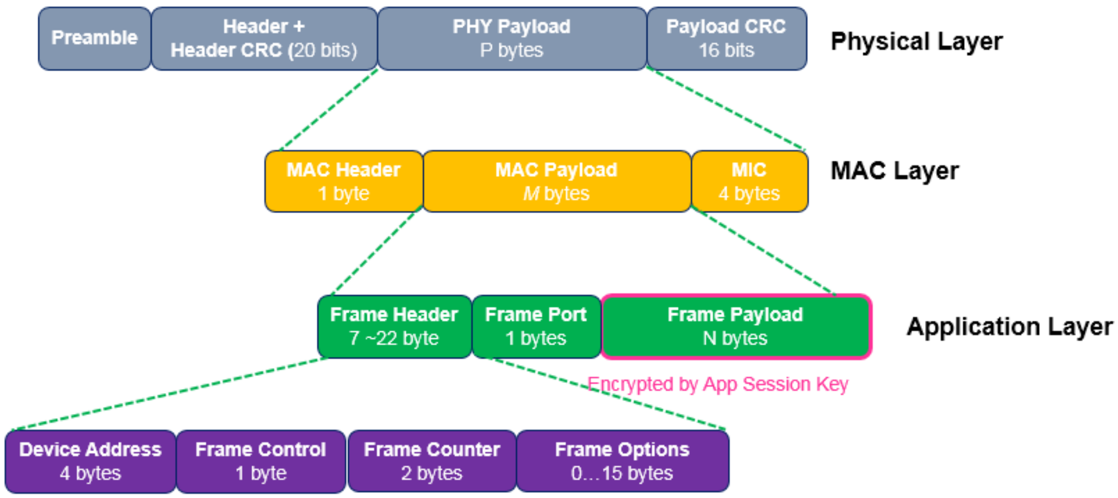


Figure 2 Standard LoRaWAN Frame

9. The LoRaware Optimized Wireless Patient Monitoring System

The LoRaware system comprises a set of patient wearable sensor sets wirelessly networked with a Gateway in a hub-and-spoke arrangement (Star Topology), in which devices are deployed around the periphery of a central collecting gateway. The LoRaware System consists of a Long Range (LoRa) Gateway planted at the hierarchal center of the wireless devices and acts as both the translator and liaison relaying packets from each of the LoRaware Wireless Devices to the Network Server and world wide web. Each wireless device comprises two multi-function digital sensors that include the ability to measure heart rate, blood oxygenation sensors, temperature and ambient pressure, battery voltage, and transmission signal strength. Each device is designed to provide wireless asynchronized signal feeds to the LoRa Gateway which communicates with an adjacent server supporting a range of applications and services that consolidate all inputs to form a dynamically responsive and interactive Graphical User Interface (GUI) for centralized monitoring.

Each wireless device in the LoRaware system is comprised of the following elements:

- RFM95W Transceiver LoRa Module
- ESP 32 Microcontroller

- MAX 30102 Heart Rate Sensor (HRT) and Oxygen Level Sensor (O2T)
- BME280 Temperature and Humidity Sensor
- Printed Circuit Board (PCB)

The overall system architecture is established by three major components, the wireless sensor devices, the LoRaWAN Gateway, and the Network Server. The input of the system begins with the LoRaware wireless devices, in which biometric measurements are obtained by its digital sensors, encrypted with two separate 128-bit AES encryption keys, and transmitted to the LoRa Gateway in accordance to the LoRaWAN wireless standard. The Gateway fulfills the purpose of translating LoRaWAN packets containing wireless device sensor data into published MQTT messages that are sent to the Network Server and decrypted. The data can then be housed within a database and made accessible to predefined user accounts in the form of a near-real-time biometric data visualization platform, from which, the decision to deploy emergency notifications can be made based upon preconfigured biometric thresholds.

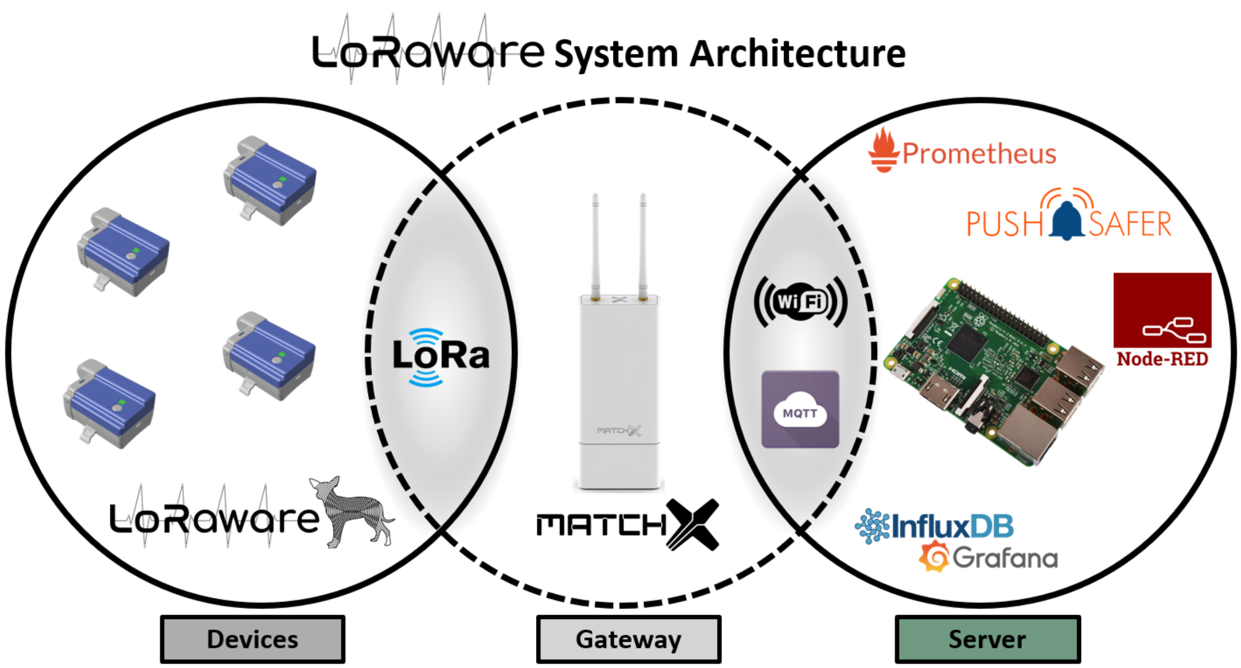


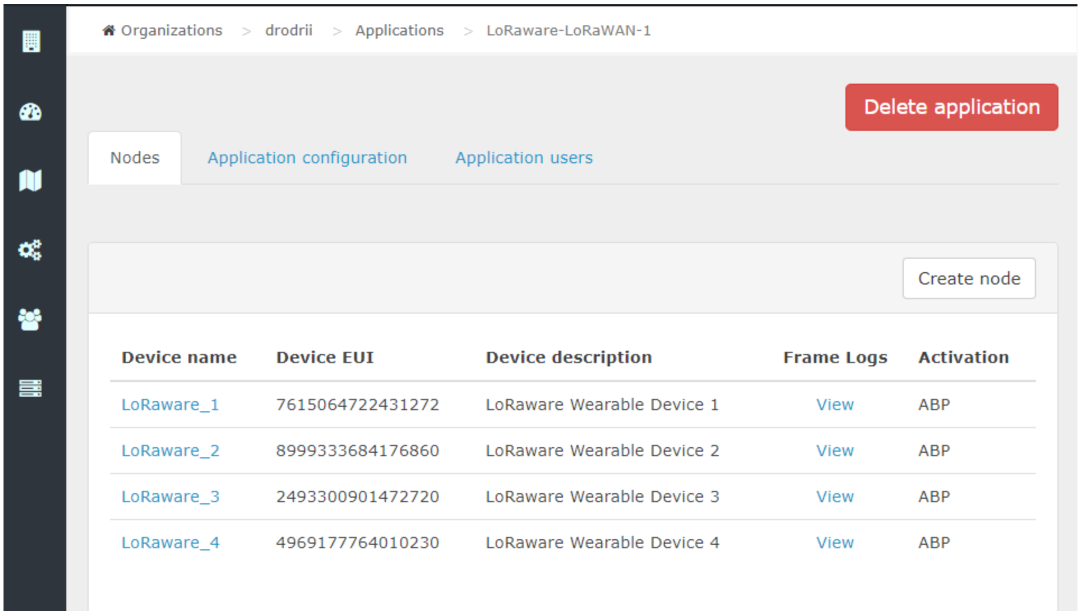
Figure 3 LoRaware System Architecture

9.1 LoRa Gateway

The LoRa Gateway selected for this project is the MatchX LoRa Gateway, a commercially available plug-and-play component, designed for various long-range, low power wireless applications including automated meter reading, home and building automation, wireless alarm and security systems industrial monitoring and control, and long-range irrigation systems (HopeRF, 2018). It has a range of approximately 20 km (12 mi) and was be modified to work with the sensor set in this project. This component requires some software adjustments to accept and process the signals provided by the LoRaware Wireless Device.

Figure 4 MatchX LPWAN Gateway

The MatchX LPWAN is a LoRaWAN gateway with multiple features. It uses Listen-Before-Talk technology and is built to avoid data-collision, to ensure reliable transmission of sensor generated data. It is designed to be energy efficient, which makes it effective for use in physically remote applications at low-cost. It provides end-to-end encryption to increase the security of the data collected remotely; it relays information to a ground-based system for further processing, but it does not decrypt the data by itself.



Device name	Device EUI	Device description	Frame Logs	Activation
LoRaware_1	7615064722431272	LoRaware Wearable Device 1	View	ABP
LoRaware_2	8999333684176860	LoRaware Wearable Device 2	View	ABP
LoRaware_3	2493300901472720	LoRaware Wearable Device 3	View	ABP
LoRaware_4	4969177764010230	LoRaware Wearable Device 4	View	ABP

Figure 5 MatchX Gateway Management Interface

9.2 LoRaware Wireless Device

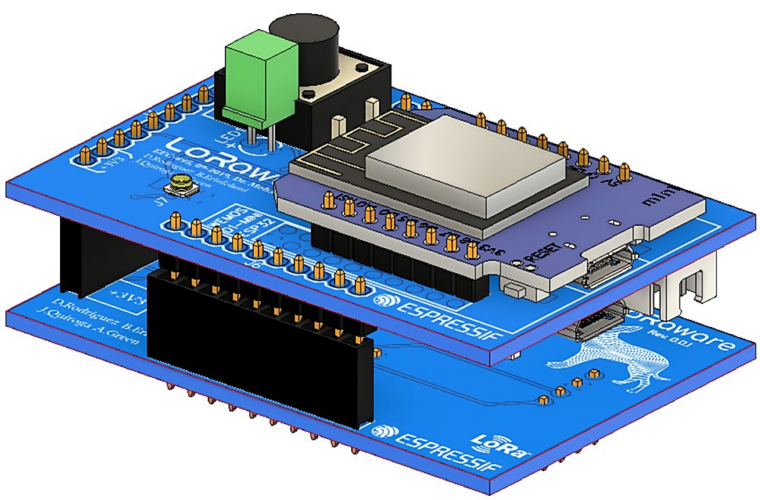


Figure 6 CAD Rendering of Completed Electrical Assembly for LoRaware Wireless Device

The LoRaware Wireless Device consists of the following components: RFM95W LoRa module, LoRa 915 MHz Antenna. ESP32 microcontroller, MAX30102 combined heart rate and blood oxygenation level Sensor, BME208 Temperature/Pressure sensor, 2000 mAh Lithium (Li) ion polymer battery, TP4056 Li-ion charge protection integrated circuit (IC), IOX ULF connector, and a Printed Circuit Board (PCB). Figure 6 depicts the combined arrangement of these components.

9.2.1 RFM95W Module

Figure 7 RFM95 LoRaWAN Chipset

The RFM95W module delivers ultra-long-range spread spectrum communication and high security through an easy to use SPI interference. It has low battery and current consumption which makes it ideal for low power consumption applications. It uses a LoRaTM modulation technique and is designed to achieve a sensitivity of over -148dBm. This combined with an integrated +20 dBm power amplifier yields a link budget that makes it optimal for applications with long range or robust transmission requirements.

The LoRaTM modulation technique provides advantages in blocking and selectivity over conventional modulation techniques, while avoiding a design compromise between range, interference immunity and energy consumption. These modules support high performance Gaussian Frequency Shift Keying (GFSK) modulation (aka pulse shaping) for systems including Wireless M-Buss Protocol Software (WMBus) compliant with IEEE802.15.4g); pulse shaping makes pulses smooth and thus limits the modulated spectrum width. The RFM95W offers excellent phase noise, selectivity, receiver linearity and Third Order Input Intercept Point (IIP3), a useful parameter to predict low-level intermodulation effects, for a much lower consumption of power and current (HopeRF, 2018).

9.2.2 LoRa 915 MHz Antenna

Designed to radiate or receive electromagnetic waves, it is ideal for operation in the 915 MHz (unlicensed ISM band). It is compatible with ESP 32 and uses an IPEX connector. Specifications include:

- Standing wave ratio: < = 1.5
- Gain: 3dBi, Maximum power: 10W
- Input impedance: 50Ω

Figure 8 LoRa 915MHz Antenna

The antenna is electrically connected to the communications module through a transmission line. The antenna diameter hardly has any importance, as long as the antenna stays in the spline form. The most effective antenna has the same length as the length of the wave it is used for. For practical purposes, half or a quarter of that length will suffice. Most LoRa antennas are a 1/4 wavelength.

The wavelength of a frequency is calculated as v / f, where v is the speed of the transmission and f is the (average) transmission frequency. In air, v is equal to c, the speed of light, which is approximately 300,000,000 m/s. The wavelength for the 915 MHz band is thus 300,000,000 / 915,000,000 = 32.8 cm. Half of this is 16.4 cm and a quarter is 8.2 cm.

A piece of wire of 8.2 cm therefore will do for a LoRa application in the 915 MHz band. The exact length is a major factor in the quality of an antenna. However, when taking into account the effective antenna length with increased accuracy within the calculation, it can be noted that ¼ Wavelength LoRaWAN 915 MHz antennas can also be reliably functional when constructed at 3.1 inches in length, or 78 mm in length (Grusin, 2019).

9.2.3 ESP32 Microcontroller

The ESP32 module is used in a wide variety of applications ranging from low-power sensor networks to more demanding tasks, such as voice encoding, music streaming and MP3 decoding. At the core of the module is the ESP32-D0WD chip which is designed to be scalable and adaptive in clock frequency and power. Each of the two CPU cores can be individually controlled, the CPU clock frequency is adjustable from 80 MHz to 240 MHz. The CPU can be powered off to make use of the low-power co-processor to constantly monitor peripherals for changes or exceeding threshold settings. The ESP32 integrates a variety of peripherals, ranging from capacitive touch sensors, Hall sensors, SD card interface, Ethernet, high-speed SPI, UART, I²S and I²C.

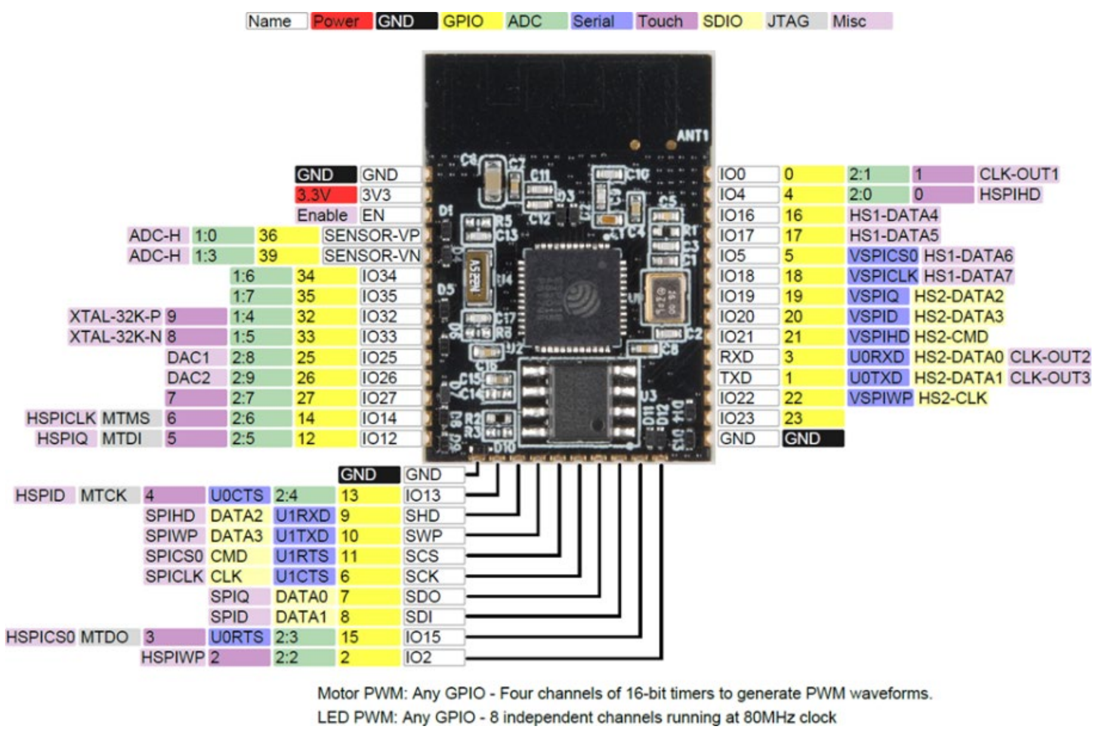


Figure 9 ESP32 Pinout Diagram

The integration of Bluetooth, Bluetooth LE and Wi-Fi ensures that a wide range of applications can be targeted, and that the module is all-around: using Wi-Fi allows a large physical range and direct connection to the Internet through a Wi-Fi router, while using Bluetooth allows the user to conveniently connect to the phone or broadcast low energy beacons for its detection. The sleep current of the ESP32 chip is less than 5 μA, making it suitable for battery powered and wearable electronics applications. The module supports a data rate of up to 150 Mbps, and 20 dBm output power at the antenna to ensure the widest physical range. As such the module does offer industry-leading specifications and the best performance for electronic integration, range, power consumption, and connectivity.

The component is designated as ESP32-WROOM-32D. The ESP32 is a series of low-cost, low-power system on a chip microcontroller with integrated Wi-Fi and dual-mode Bluetooth. It is a successor to the ESP8266 microcontroller (Espressif Systems, 2019).

9.2.4 Heart Rate Sensor (HRT) and Oximetry Sensor (O2T)

Figure 10 MAX30102 Heart Rate and Blood Oximetry Sensor Breakout

Our choice of the heart rate Sensor (HRT) and the Oxygen level Sensor (O2T) is the MAX30102 integrated pulse oximetry and heart-rate monitor biosensor module.

It is a heart-rate and oximeter sensor planted on an 8-pin breakout board. We are using this to measure heart rate or pulse (number of heart bits per minutes) and also the amount of oxygen present in the blood (percentage of oxygenated hemoglobin of the total hemoglobin within the body).

The biosensor module itself (MAX30102) consists of internal LED, Photodetectors, Optical elements and low-noise electronics with ambient light rejection, it operates on 1.8V power supply and a separate 3.3V power supply for the internal LEDs. The tiny sensor has dimension of 5.6mm x 3.3mm x 1.55mm with 14 pins (7 per side). Communication is through a standard I2C compatible interface. Other features include fast data output capability, high sample rates, programmable sample rate, low power consumption (less than 1mW) with operating temperature between -40C to 85C (Maxim Integrated, 2019).

The MAX30102 was mainly selected for the LoRaware wireless devices based on the combination of low price, accuracy, measuring capabilities, and market accessibility. One of the most significant benefits to health monitoring that the MAX30102 provides is allowing for the LoRaware wireless device to measure and detect signs of hypoxemia, organ deterioration, and also cardiac arrest. By being able to use two lines of communication with the microcontroller, Serial Data (SDA) and Serial Clock (SCL), while simultaneously having the ability to measure quantities such as blood oxygen concentration, heart rate, and even proximity, PCB board space could be more efficiently utilized, allowing for the overall LoRaware wireless device to be designed with a more compact formfactor in mind.

9.2.5 BME208 Temperature/Humidity Sensor

This integrated environmental sensor was developed specifically for mobile applications where size and low power consumption are key design constraints. Its integration in this design is to determine its applicability to biometric measurements. The humidity measurement function is an added feature whose biometric application cannot be determined in the context of this project.

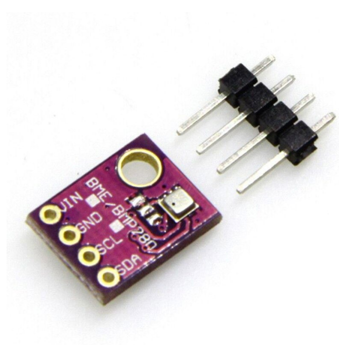


Figure 11 BME280 Sensor Breakout Board

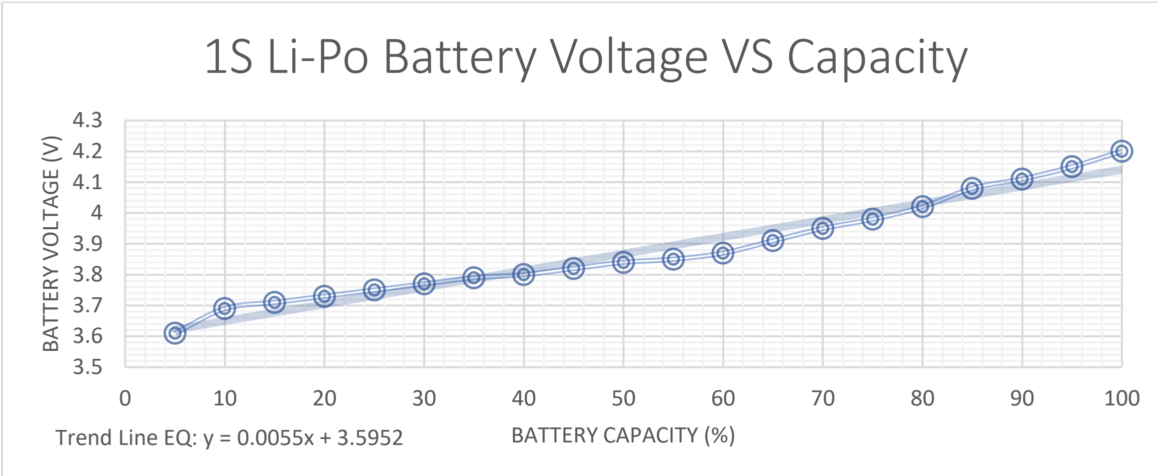
BME280 Specifications:

- I2C & SPI, Supply Voltage: 1.71V to 3.6V
- Temperature Range: -40 to +85°C
- Humidity Range: 0% to 100% relative humidity
- Pressure Range of 300hPa to 1100hPa

9.2.6 2000 mAh Lithium Polymer Battery

Figure 12 2000 mAh 1S Lithium Polymer Battery

Establishing a battery-life and power consumption benchmark value equal to the Wireless ViSi Patient Monitoring System Battery Life of between 14-16 hours, we planned for our system to improve on power consumption by offering a battery life of greater than 16 hours. The 2000 mAh Lithium Polymer Battery was selected to power to the LoRaware system wireless devices since it had the greatest capacity to last beyond the target battery life. This battery, while not the smallest in size, provides power to the LoRaware Wireless Devices well in excess of 16 hours.



In order to yield a percentage value corresponding to the battery's instantaneous capacity for use in the Grafana dashboard, a relationship between the battery voltage and its capacity needed to be established by plotting tabulated values obtained from a blog post by the electronics manufacturer AMPOW. Once graphed, a linear equation representing a trendline could be ascertained, and once rearranging terms, the subsequent equation for battery capacity percent with battery voltage as an input. This equation was later used in a JavaScript function node within Node-Red to convert battery voltage to percent, which was added as a new column within the infulxDB database hosted on the network server.

The 2000 mAh capacity value of the battery was able to be initially determined by researching the datasheets corresponding to each component used within the LoRaware wireless device (ESP32, RFM95, TP4056, MAX30102, BME280, & LED), and summing together the combined maximum current draw to form a current draw value representing a "worst-case-scenario" power usage value for the LoRaware wireless device, which in our case, was determined to be roughly 137.5 mA. Once this value had been established, we could then multiply it by our target battery-life value of 16 hours, to generate a battery capacity value that could then form the basis for us to purchase a battery rated to a similar capacity value. For our project, the calculated battery capacity value was determined to be 2200 mAh. However, we did encounter some difficulty sourcing a 2200 mAh battery to be purchased, so we decided to pick a 2000 mAh battery instead, since many could be readily found for purchase.

According to electronics distributer, Adafruit Industries, Lithium Ion Polymer batteries are very powerful, thin, compact and lightweight. The voltage range, output range, is up to about 3.7V. The capacity of the battery is 2000mAh. Most vendors provide this type of battery which include protection circuitry the helps keep the battery voltage from over charging or going too high as well as over use; essentially the battery will cut-out when completely dead at 3.0V. This protects against output shorts.

1S 2000 mAh Li-Po Battery Additional Specifications:

- Dimensions: 60mm x 36mm x 7mm / 2.4" x 1.4" x 0.3"
- Weight: 34g
- Nominal Capacity: 2000mAh ±2%
- Nominal Voltage: 3.7V
- Standard Charge Current: ~0.2C / 0.5A
- Charge Cut-Off Voltage: 4.2V
- Standard Discharge Current: ~0.2C / 0.5A

9.2.7 TP4056 Li-ion Charge Protection Integrated Circuit (IC)

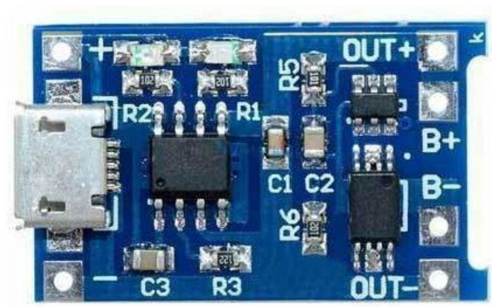


Figure 13 TP4056 Charge Protection IC

According to electronics manufacturer, Addicore, the TP4056 is a complete constant-current/constant-voltage linear charger for charging rechargeable single cell lithium-ion batteries. Its small outline package and low external component count make the TP4056 ideally suited for portable applications.

Thermal feedback regulates the charge current to limit the die temperature during high power operation or high ambient temperature. The charge voltage is fixed at 4.2V, and the charge current can be programmed externally with a single resistor. The TP4056 automatically terminates the charge cycle when the charge current drops to 1/10th the programmed value after the final float voltage is reached.

TP4056 Other features include current monitor, under voltage lockout, automatic recharge and two status pins to indicate charge termination and the presence of an input voltage.

9.2.8 IPX ULF connector

Figure 14 IPX Coaxial Connector (Left), IPX UFL Connector (Right)

To connect the antenna with the RFM95 LoRa module, we decided to use the IPX ULF connector. The IPX or IPEX connector is a female connector that is surface-mounted and soldered directly to the printed circuit board. It has an impedance of 50 ohms and can transmit or receive RF signals. These types of connectors are the smallest of the coaxial RF connectors; it is an electrical connector designed to work at radio frequencies in the multi-megahertz range.

Typically, radio frequency connectors are used with coaxial cables; they are designed to maintain the shielding that the coaxial design offers. The user function library (UFL) is a DLL (Dynamic-link library). These libraries comprise all the functions and formulas for Crystal Reports (IDAutomation, 2015).

9.2.9 Printed Circuit Board (PCB)

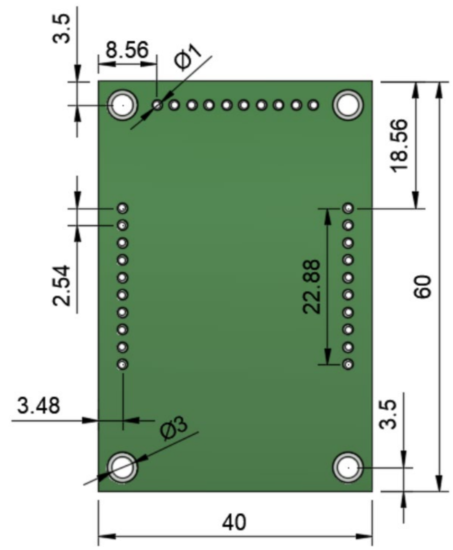
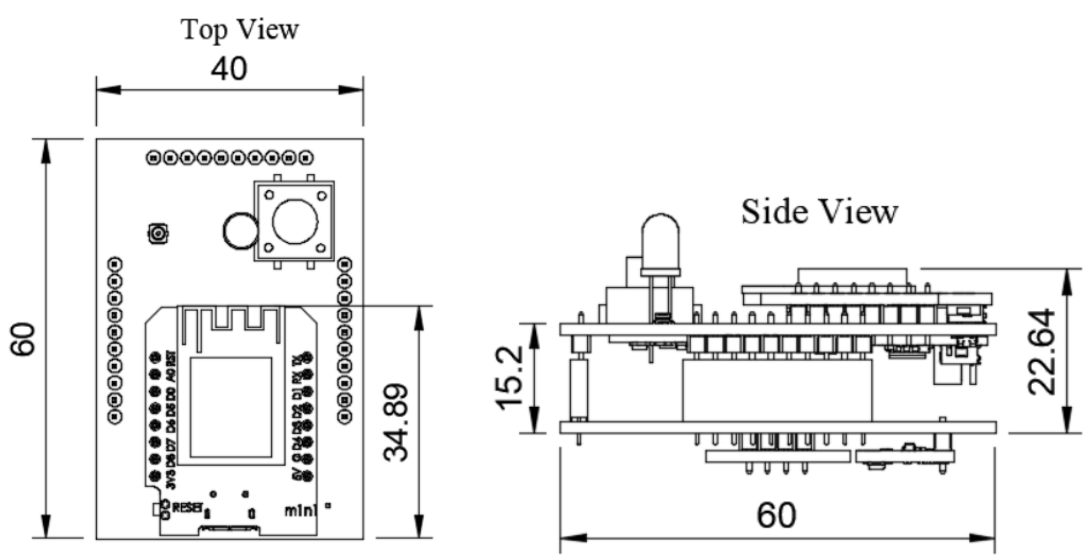


Figure 15 Proposed PCB Dimensions (mm)



In order to maintain a more compact final prototype for our LoRaware wireless devices, the next natural phase in development to pursue was to design and manufacture printed circuit boards. These boards would be a reliable and permanent solution in conjoining all components and peripherals into one small package. Improvements within the field of prototype circuit board manufacturing services were also a significant driving factor in our decision to create out own boards. After researching various PCB manufacturing services, we decided to use a Chinesebased manufacturing service called JLCPCB, which resulted in our project's board design produced, shipped, and received within a timeline of two weeks at a cost of $0.50 per board.

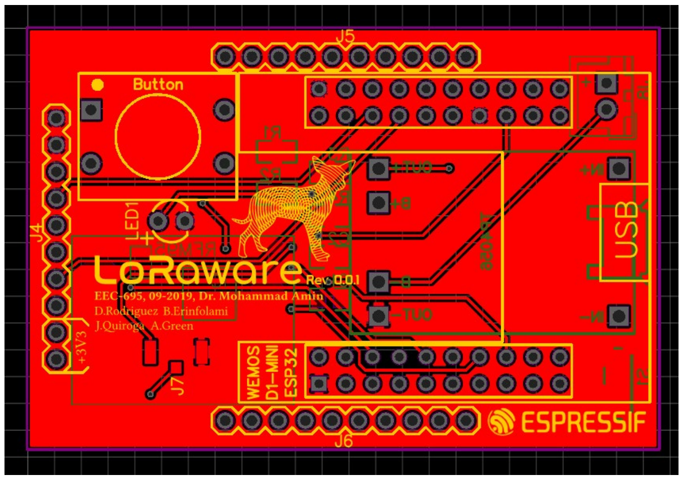


Figure 16 Top PCB for LoRaware Wireless Device

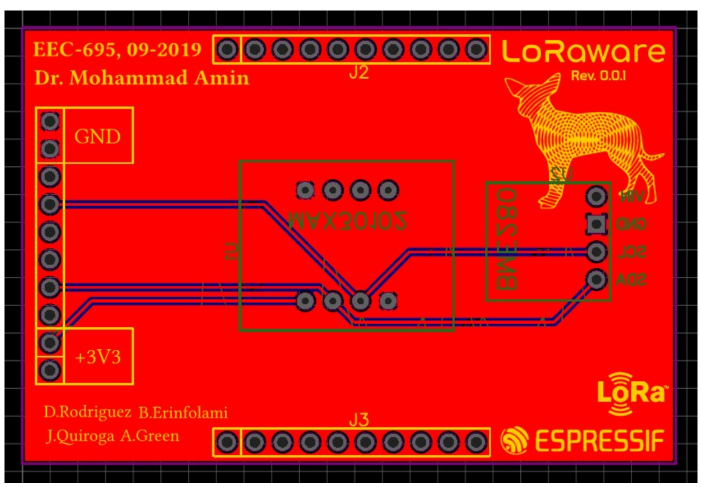


Figure 17 Bottom PCB for LoRaware Wireless Device

Design of the two system PCBs was accomplished using open source software EasyEDA. The system requires two boards because it allows the final assembly to be shorter and thus more compact for portability. The bottom PCB serves as the mount for the two sensors and is connected to the top board using header pins. The top PCB contains all the other components of our design. Upon completion, EasyEDA produces a set of PCB blueprints ready for production.

- Dimensions: 40 mm x 60 mm

9.3 Network Server

Figure 18 Raspberry Pi 3B

The system server was hosted by Raspberry Pi, due to its low cost and small size. Raspberry pi is typically used for experiments as a computing device. It serves to configure system software for various application in various configuration and as a platform for learning program languages such as Python. It has the ability to perform as a desktop computer and it enables internet browsing as well as playing high-definition video, hosting spreadsheets, word-processing, etc. Because Raspberry Pi enables networking through Wi-Fi, Bluetooth and Ethernet, it is capable of external interaction and has been used in a wide array of digital projects. (Raspberry Pi Foundation, N.D.).

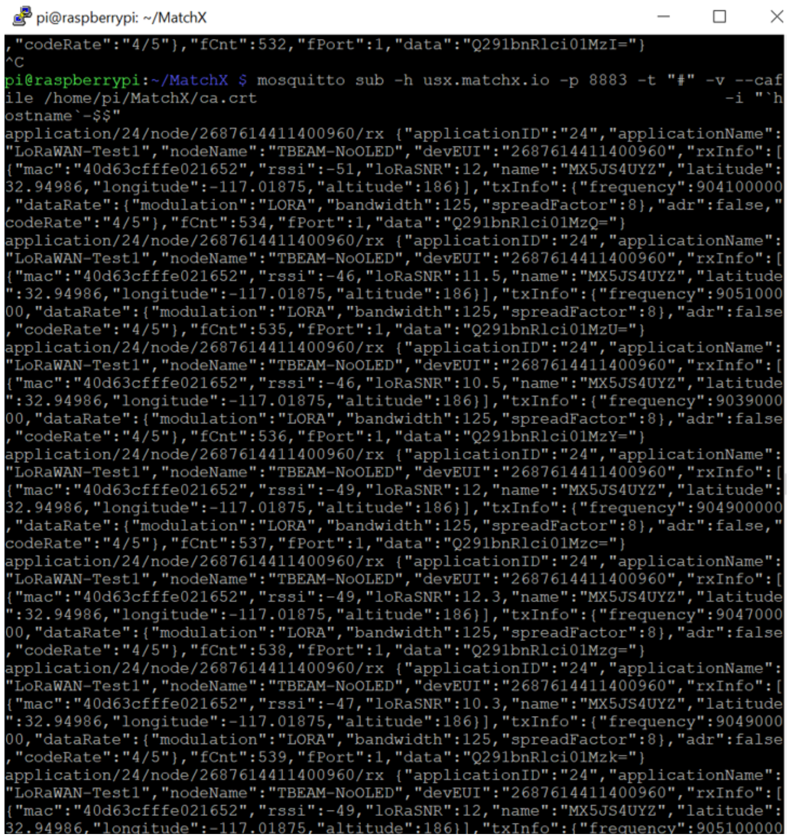
It is the job of the LoRaWAN Network Server to receive LoRaWAN Gateway communications via IEEE 802.11 network connection and relay message payloads to other server-hosted services and applications to be stored and processed. It is within the network server, that a majority of the important user-interface driven functions occur.

The services and applications hosted and regulated by the LoRaware System Network Server include the following:

- Mosquitto MQTT Broker (Service)
- InfluxDB (Application)
- Node-Red (Application)
- Grafana Dashboard (Application)
- Pushsafer API (Application)

Mosquitto MQTT Broker

The Mosquitto MQTT Broker allows the Server to communicate with the MatchX Gateway by way of subscribing to published MQTT messages containing the forwarded LoRaWAN packets. It was very convenient to discover that the default application running on the MatchX LoRaWAN Gateway, Application 24, includes TLS encrypted MQTT Packet Forwarding. We were able to download the SSL Certificate to properly decrypt these MQTT messages from LoRaWAN Gateway Management platform, MatchX Cloud. We then were able to use Secure Copy Protocol (SCP) to transfer t\he downloaded SSL Certificate onto the Raspberry Pi Network Server. This Certificate was then appended to the MQTT Subscribe Command as an additional input argument within the Raspberry Pi Terminal Window.



```
pi@raspberrypi: ~/MatchX
,"codeRate":"4/5"},"fCnt":532,"fPort":1,"data":"Q291bnRlci01MzI="}
^C
pi@raspberrypi:~/MatchX $ mosquitto sub -h usx.matchx.io -p 8883 -t "#" -v --caf
ile /home/pi/MatchX/ca.crt                                                  -i "`h
ostname`-$$"
application/24/node/2687614411400960/rx {"applicationID":"24","applicationName":
"LoRaWAN-Test1","nodeName":"TBEAM-NoOLED","devEUI":"2687614411400960","rxInfo":[
{"mac":"40d63cfffe021652","rssi":-51,"loRaSNR":12,"name":"MX5JS4UYZ","latitude":
32.94986,"longitude":-117.01875,"altitude":186}],"txInfo":{"frequency":904100000
,"dataRate":{"modulation":"LORA","bandwidth":125,"spreadFactor":8},"adr":false,"
codeRate":"4/5"},"fCnt":534,"fPort":1,"data":"Q291bnRlci01MzQ="}
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{"mac":"40d63cfffe021652","rssi":-49,"loRaSNR":12,"name":"MX5JS4UYZ","latitude":
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codeRate":"4/5"},"fCnt":537,"fPort":1,"data":"Q291bnRlci01Mzc="}
application/24/node/2687614411400960/rx {"applicationID":"24","applicationName":
"LoRaWAN-Test1","nodeName":"TBEAM-NoOLED","devEUI":"2687614411400960","rxInfo":[
{"mac":"40d63cfffe021652","rssi":-49,"loRaSNR":12.3,"name":"MX5JS4UYZ","latitude
":32.94986,"longitude":-117.01875,"altitude":186}],"txInfo":{"frequency":9047000
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,"codeRate":"4/5"},"fCnt":539,"fPort":1,"data":"Q291bnRlci01Mzk="}
application/24/node/2687614411400960/rx {"applicationID":"24","applicationName":
"LoRaWAN-Test1","nodeName":"TBEAM-NoOLED","devEUI":"2687614411400960","rxInfo":[
{"mac":"40d63cfffe021652","rssi":-49,"loRaSNR":12,"name":"MX5JS4UYZ","latitude":
32.94986,"longitude":-117.01875,"altitude":186}],"txInfo":{"frequency":905100000
```

Figure 19 Published MQTT translated LoRaWAN Packets from MatchX Gateway, received in Terminal Window of Raspberry Pi Network Server

Once the MQTT messages could be reliably subscribed to and accessed in the terminal window, the same Mosquitto command could be implemented within the MQTT Input Source Node found within Node-Red.

Node-Red

Node-Red is a JavaScript-based, visual programming development environment and flow process manager designed for IOT applications, with each node within the entire process flow represents a specific function in JavaScript code. The flow process diagram can be read from left to right starting at its input. Node-Red was a server-side software tool which allowed our group to convert the initial received large strings of LoRaWAN packets and metadata into more compact and easier to manipulate JavaScript Objects represented in JSON format, which was also compatible with InfluxDB.

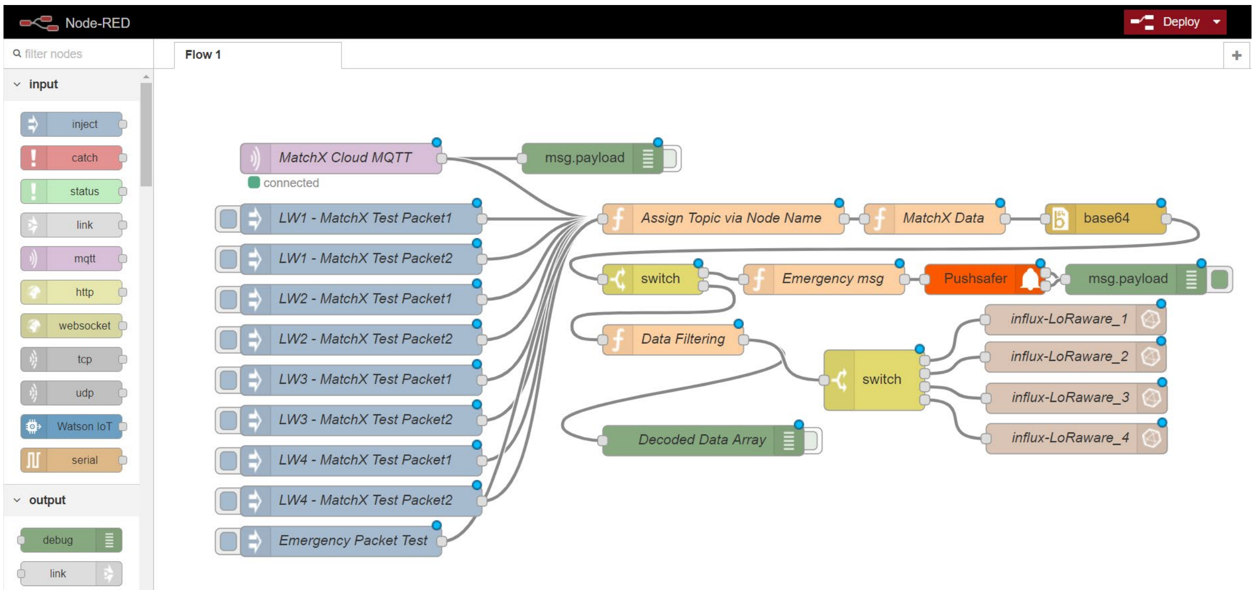


Figure 20 Node-Red Flow support LoRaware System Backend

The orange function nodes found within the middle section of the flow process were used to carry out the following operations:

- Label imported messages based on the LoRaware device that had sent the packet
- Remove extraneous metadata from imported LoRaWAN packets
- Reduce extraneous decimal places and measurement errors
- Write received data to the InfluxDB Database
- Determine whether the message was an Emergency Notification Alert Message or standard data to be cataloged
- If Emergency payload detected, Send an Emergency Notification with a call to the Pushsafer API

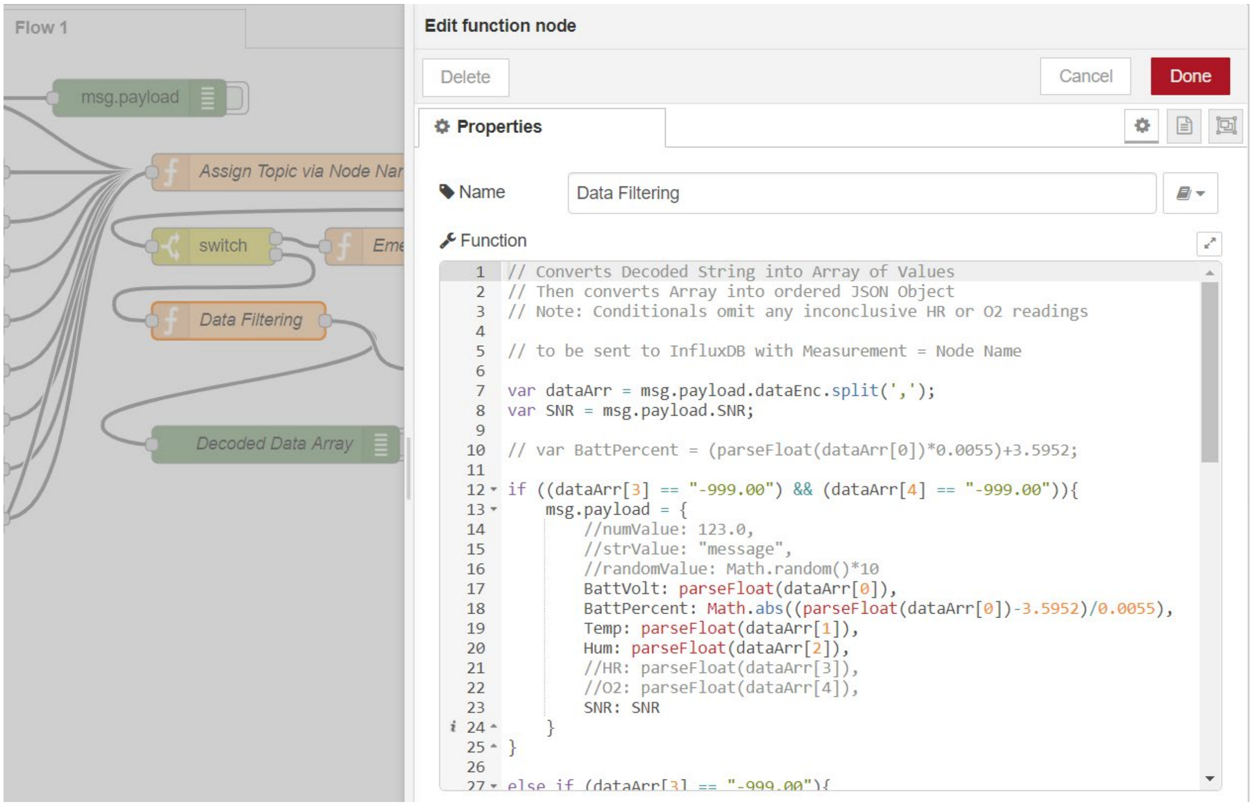


Figure 21 User-Defined JavaScript LoRaware Data Filtering Function within Node-Red Function Node

InfluxDB

Instead of picking a more common and ubiquitous form of a database, such as any of the standardized relational applications ranging from mySQL to Oracle Database, our project group decided it would be more relevant to the LoRaware use-case to use a relatively new type of database, called a timestamp database. The most notable of which for our Raspberry Pi's ARMv7 Linux Architecture being the application InfluxDB. InfluxDB paves the way in terms of ease of integration, simplistic query syntax, and long-term data maintenance through retention policies. Since the LoRaware system relies on collecting patient biometric data over respectable durations of time, the decision was clear to use timestamp database, based on the fact that they are optimized for time-dependent forms of data. InfluxDB follows an "SQL-ish" form of query syntax with a key-value pair system for database elements, collimated by measurements.

Retention Policies in InfluxDB are one of the more interesting aspects implemented within the application. These policies can be defined as time-dependent rules established at any time by an administrator that can assist with reducing the storage footprint of very old and antiquated datasets. This concept works by setting a time limit threshold that can for example, once a set of data values recorded one minute intervals had been stored for over a month, be averaged down to one data value for every hour, yielding a reduction ratio of 1/60 in terms of the number of data points that are older than one month. By reducing the storage footprint imposed by legacy data with tools like retention policies, historical data can still be accessed and analyzed in many important ways, while the database can remain agile and responsive, despite containing very large amounts of information.

For the LoRaware system, with four separate wireless devices collecting multiple types of data simultaneously, it made the most organizational sense to assign each wireless device its own InfluxDB database, with the columns of each database represented by each measured value, including battery voltage (V), battery capacity (%), heart rate (BPM), Blood Oximetry (%), Temperature (°F), and Humidity (%RH). It can be observed within the depiction of the LoRaware System Node-Red flow (Figure 11), that the message payload goes through a large yellow node, called a switch node, which acts as a large conditional “If-Statement” which sends the payload to one of four separate InfluxDB write queries, corresponding on which LoRaware Device had originally sent the message. InfluxDB is hosted on Port 1886 by the LoRaware System Network Server.

Grafana Dashboard

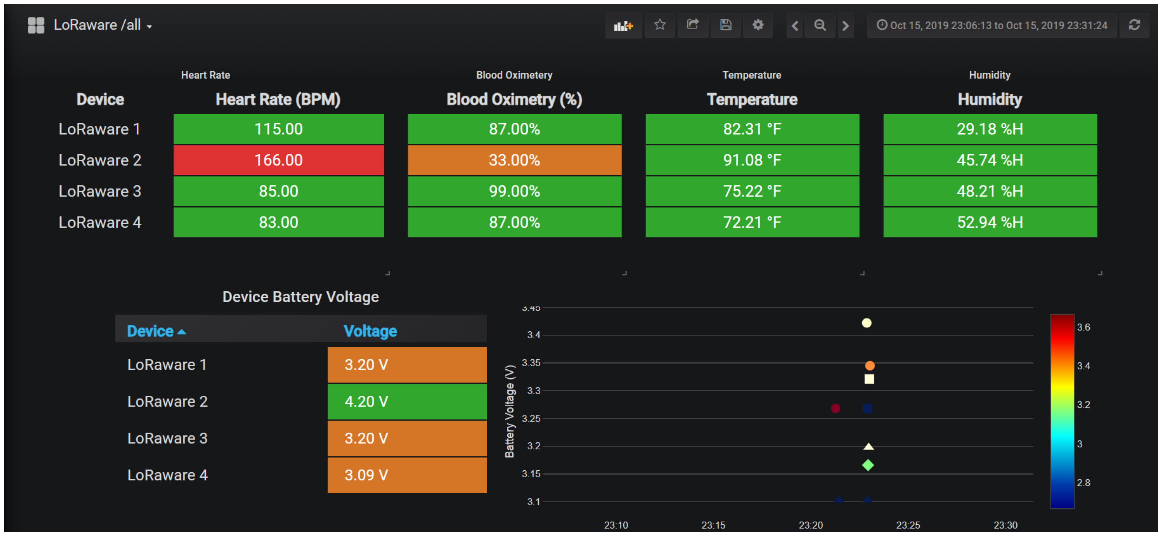


Figure 22 Grafana Dashboard Configured for LoRaware System

The Grafana Dashboard is a separate standalone application, hosted on Port 3000 by the LoRaware System Network Server and offers a wide variety of metric visualization options that can be shared with others or protected by user accounts and login credentials. Grafana operates by first, configuring the data sources, which in our case, were the four separate InfluxDB databases representing the data collected from each of the LoRaware wireless devices. Grafana updates its graphs and displayed metrics at a set time interval by sending read queries to InfluxDB, which by default, auto-refreshes every ten seconds. Once these sources had been configured, new graphs and plots could be added and fine-tuned, while the physical layout of the graphical user interface could also be manipulated. For the LoRaware System, we started by setting up a table displaying the most recent values obtained for all significant biometric data types from each LoRaware wireless device. After this foundation had been established, threshold values could be assigned to the background color of the table's cells that would react depending on the severity of the measurement value. For example, in Figure 21, the heart rate value for Device LoRawaree 2 shows 166 BPM with a red colored cell, indicating a high heart rate detected, which could therefore alert any medical professional actively monitoring the dashboard to assist the wearer. Other plots included within the LoRaware system include the wireless device battery voltages, wireless device battery capacities, skin-surface temperatures, and even the Signal-to-Noise Ratio for each LoRaware device, measured by the MatchX LoRa Gateway.

Aside from its ability to support different user accounts with varying levels of permissions, Grafana Dashboard also supports interactive graphs which can be zoomed in, time intervals adjusted, plot images generated and download, and CSV files containing the data being examined downloaded with one push of a button on the user interface. We feel that a platform like this offers benefits that extend well beyond the scope of immediate monitoring of patients, by being able to also serve as tool medical researchers could utilize to inspect, analyze, extract, and report on potential correlations found within the sets of aggregated biometric data.

Pushsafer API

As an added feature to benefit our Project Demo, we also decided to implement more direct forms of emergency notifications to be sent through the LoRaware system. In this case, we chose to incorporate the Pushsafer API within our Node-Red flow process which could quickly send out emergency push notifications to a large group of mobile devices and computers whenever the pushbutton on any of the LoRaware wireless devices had been pressed, in which an emergency packet containing the values of "0,0,0,0,0" was received and decoded by the Node-Red process flow, before being redirected away from writing to the database and instead forming an emergency message that could then be pushed to the Pushsafer API. The Pushsafer API had been configured with all group member's cellphones prior to the demonstration with minimal hassle. Once all devices had been registered to the API, they could all be assigned to a group within Pushsafer, allowing for all to be notified of a LoRaware emergency message simultaneously with one singular call to the API from Node-Red.

Figure 23 Pushsafer API Node in Node-Red Flow (Left), and Pushsafer Configuration & Admin Page (Right)

10. Tool Requirements

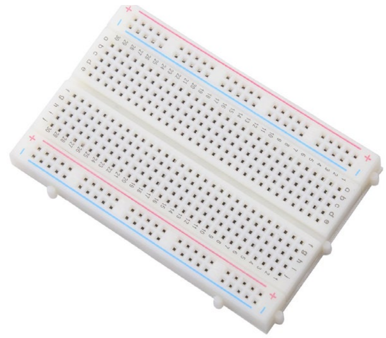
This project made use of various inexpensive hardware and open source software tools to design, manufacture and assemble the various components of the LoRaware system. The following lists are meant to highlight that the manufacture of this developmental system is achievable at minor cost to the participants including the manufacture of non-commercial items.

10.1 Hardware

This project did not require the use of complex or expensive tooling to prepare, assemble and test the LoRaware components. The following comprises a list of mechanical, electric and electronic tools used throughout the project's development and testing.

- Multimeter
- Soldering station
- Soldering lead
- Tip tinner/flux
- Pliers
- 3D printer
- Bread board
- Jumper wires
- Magnifying lens
- Laser Thermometer

- Tweezers
- Oximeter/Heart Rate monitor


10.2 Software

The project required use of software design tools for the circuit schematic, PCB, and the LoRaware Wireless Device enclosure case.

The PCB was designed using EasyEDA. EasyEDA is an Electronic Design Automation Software (EDA), also known as an Electronic Computer Aided Design (ECAD), that is web-based with an extensive database of both that commercially available and user-defined electronic components used in the LoRaware Wireless Device. Both can be accessed for free with a user account. EasyEDA enabled the project team to select the components, create the circuitry schematic diagrams and the electronic components architectural arrangement within the circuit board design the connecting circuitry and physical features necessary for structural assembly. The tool allows for multi-layered PCB designs and the creation of a manufacture-ready specification blueprint (EasyEDA, N.D.).

The use of EasyEDA was instrumental in defining the overall layout of the LoRaware wireless device circuitry, as well as the primary means of expressing the schematics corresponding to each of the printed circuit boards required in the full wireless device assembly.

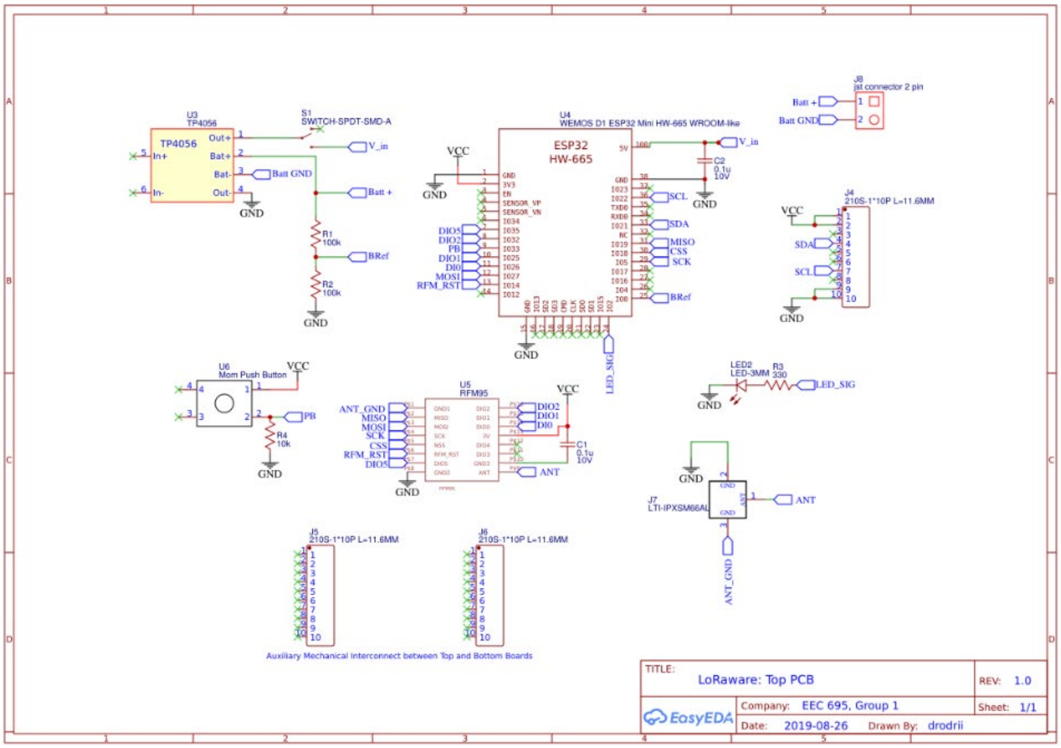


Figure 24 LoRaware Wireless Sensor Device - Top PCB

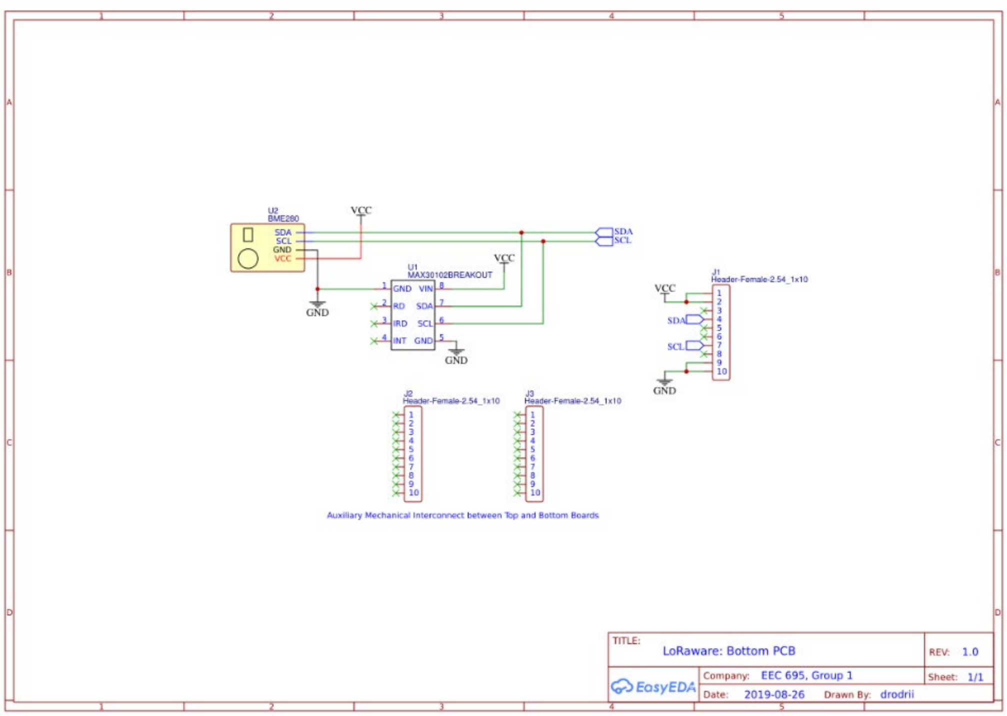


Figure 25 LoRaware Wireless Sensor Device - Bottom PCB

For the LoRaware Wireless Device enclosure case design, the team used Fusion 360. The tool enables the design of the case structure and displays the final 3D design in a rotatable isometric view (Autodesk, N.D.) The application was also able to generate 3D mesh files that could later be imported into a 3rd party gcode slicing application, which takes two-dimensional slices of the exported mesh and converts them into a set of toolpath commands for a 3D printer to follow in order to produce the model.

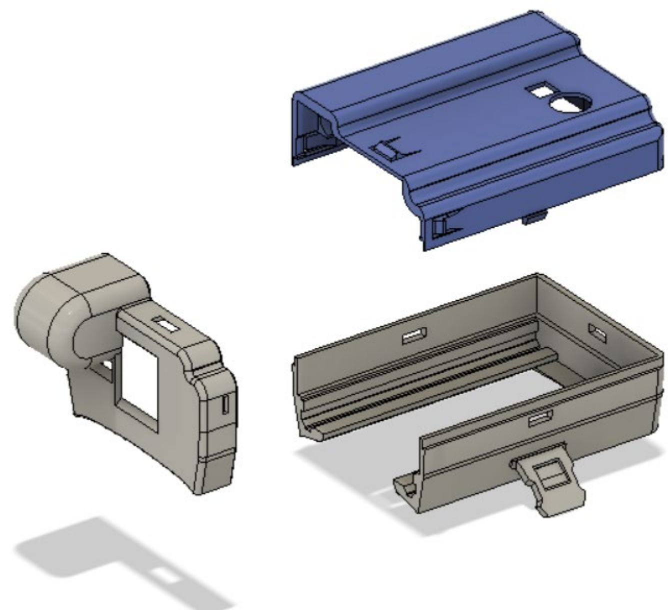


Figure 26 Exploded View of LoRaware Wireless Device Enclosure Assembly

11. Project Management

"Project management objectives are the successful development of the project's procedures of initiation, planning, execution, regulation and closure as well as the guidance of the project team's operations towards achieving all the agreed upon goals within the set scope, time, quality and budget standards." To successfully execute this project, the team had to plan and schedule the effort through a thorough assessment of the academic and project requirements. The project team was able to leverage available equipment and make use of resources available at low or no cost. In the same manner, a project schedule was created to provide team members with a reference of the timeline for accomplishing the tasks that would bring the project to a successful completion.

11.1 Project Cost Estimation

Projects costs were estimated separately for labor and materials. Both are illustrated in the following two tables, with the entire estimated project cost shown at the bottom of the second table

Table 1 Materials Cost Estimation

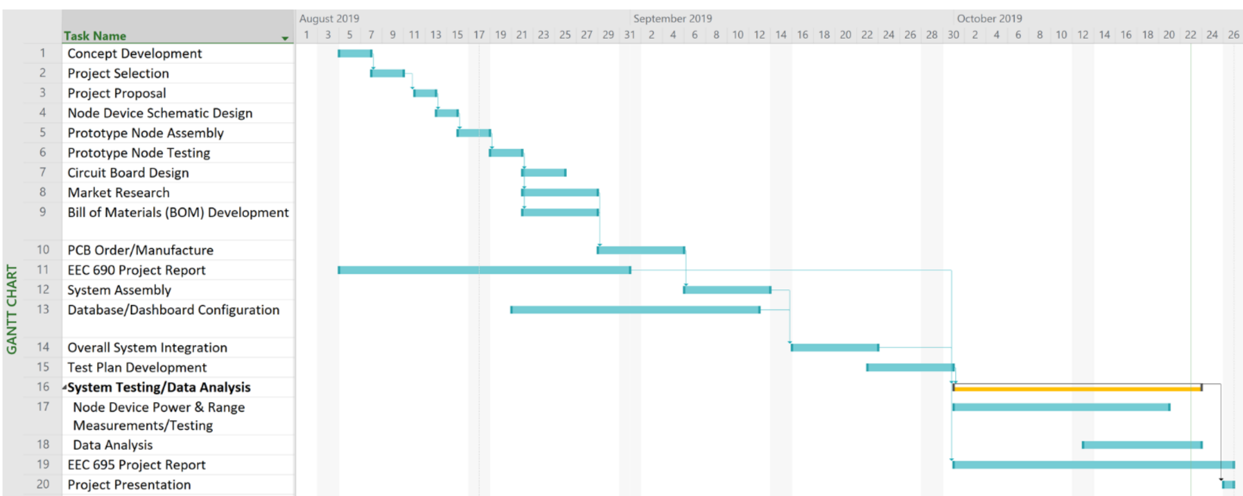
MATERIALS	Unit Cost	# Units	Total Cost
MatchX LoRa Gateway	$ 450.00	1	$ 450.00
RFM95 LoRa Module	$ 20.00	4	$ 80.00
TP4056 Li-Ion Charge Protection IC	$ 1.20	4	$ 4.80
2000 mAh Lithium Polymer Battery	$ 10.00	4	$ 40.00
ESP32 – Microcontroller	$ 10.00	4	$ 40.00
MAX30102 HRT/O2LT Sensor	$ 8.00	4	$ 32.00
BME208 Temperature/Pressure Sensor	$ 2.00	4	$ 8.00
Raspberry Pi 3B+	$ 30.00	1	$ 30.00
LoRa 915 MHz Antenna	$ 10.00	4	$ 8.00
IPX ULF Connector	$ 0.60	4	$ 2.40
PCB's manufactured by JLC PCB	$ 2.00	5	$ 10.00
TOTAL MATERIAL	**$ 537.80**		**$ 705.20**

Table 2 Labor and Total Project Cost Estimation

LABOR	Cost/Hour	# Hours	Total Cost
Design	$ 20.00	80	$ 1,600.00
Prototype Manufacture	$ 20.00	20	$ 400.00
Testing	$ 20.00	20	$ 400.00
TOTAL LABOR			**$ 2,400.00**
TOTAL PROJECT COST			**$ 3,106.20**

11.2 Project Schedule

The project schedule was established through a distribution of expected effort bounded by the time constraints imposed by NU requirements. Project selection, design and implementation had to be completed in a 3-month period that began in August 2019 and ended in October 2019, when all project deliverables were due. With these considerations in mind, the Figure below illustrates the main efforts associated with the completion of this project.



12. System Assembly

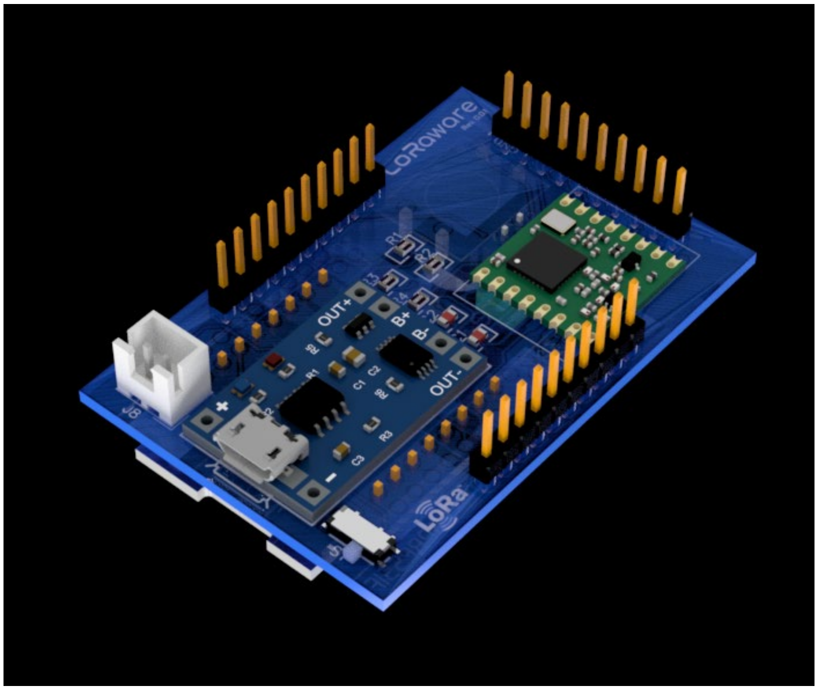


Figure 27 Rending of populated underside of Top PCB

System assembly was performed in stages. Initially system components were connected on a breadboard to test projected system design and capabilities. This led to the circuitry design that resulted in the manufacture of the two system PCBs. Selected components had to be soldered prior to the mechanical assembly of the wireless devices. Once the initial set was assembled it had to be tested for fit and function to ensure the structural design was capable of supporting the components for further testing.

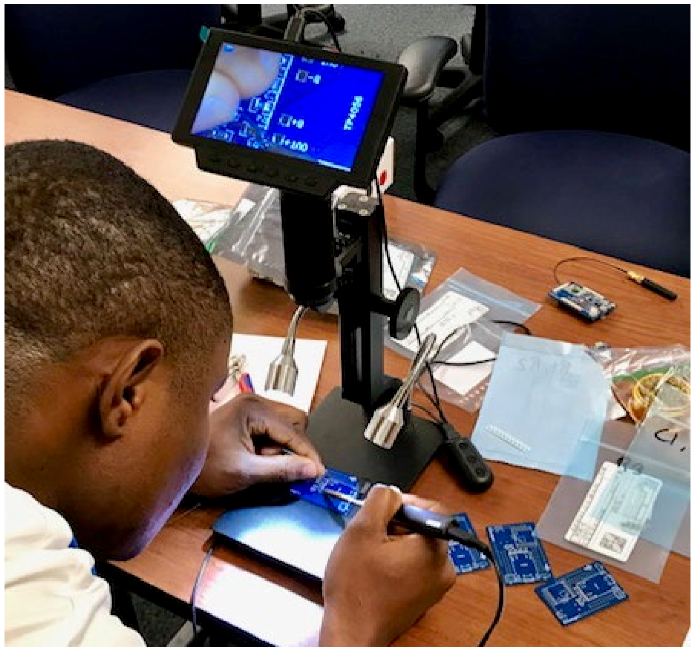


Figure 28 Soldering 0805 SMT Resistors and Capacitors to LoRaware Wireless Device Top PCBs

Figure 29 Rendering of Assembled LoRaware Wireless Device Electronics in Bottom-half of Enclosure

13. Testing

LoRaware system testing was performed on an incremental basis as components were acquired and became available. Initial component testing was performed by using a breadboard to test basic connections and component functions. As each element was integrated into a breadboard, it was tested as part of the whole assembly. This methodology progressively expanded to include all design features encapsulated in the LoRaware network. Once all the components were acquired and assembled as a complete system component, a more extensive testing process begun by with a single wireless device test of features through hardwire connections and wireless connections. This, again, included measurements from each sensor Sensor. This testing was not sufficiently extensive to define calibration values that would be required to bring the system to its design capability; however, the results were indicative that calibration was required for all sensors. The following describes the testing plan requirements and the data to collected at each stage.

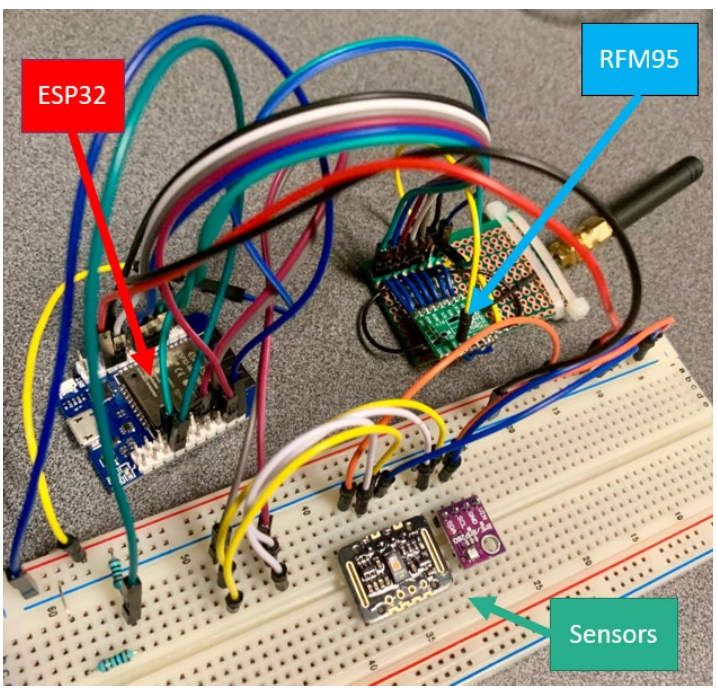


Figure 30 LoRa Proof of Concept Testing (Point-to-Point Configuration with Receiving Node)

13.1 Static and Dynamic Node Testing

This phase required that each of the LoRaware Wireless Devices, a.k.a. node, component elements is tested for function and performance against a pre-determined standard. Sensor sets were tested under two sets of conditions: one is static, and the other dynamic.

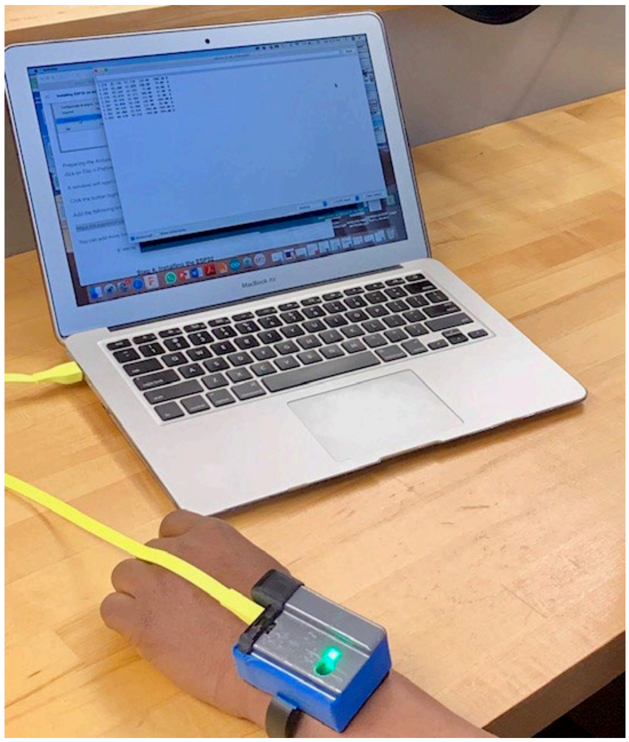


Figure 31 LoRaware Static Testing Setup with COM Port Debugging

Static testing consisted of the collection of data from a single node with a hard wire connection to the management console. This test was designed to collect system generated information under steady-state conditions to determine differences between node data and data obtained from more reliable measurement devices. Any differences found between both sets of data would be indicative of a requirement to adjust the node's output to more closely reflect values produced by calibrated instruments.

Dynamic testing was designed to collect data from more than one sensor simultaneously two achieve two objectives. The first objective was to prove the system was capable of networking wirelessly at a distance with more than one sensor. The second objective was to ensure that each sensor set was capable of providing node information through a range of values.

To change the reading values, the stages started with a stationary test, this was then followed by a slow climb through a set of stairs, medium speed climb and a fast climb. At the end of each dynamic stage, values would be collected from the node and the calibrated devices and compared for performance.

13.1.1 Temperature Sensor

The temperature sensor measured temperatures at the location where the sensor contacts the skin on the user's wrist. This measurement shall be annotated and compared against the core temperature of each test subject and repeated no less than n-times (n=26). The core temperature shall be measured with a different body temperature calibrated measuring device nearly simultaneous. Both measurements shall be recorded for dynamic software adjustments of the temperature sensor data measured during continuous operation.

13.1.2 Pulse Rate Sensor

The pulse rate sensor shall be measured and the value compared against the pulse rate measured by a calibrated pulse rate measuring device at least 10 time per test subject and at least 3 subjects. Both measurements shall be recorded for adjustment to the software that must account for variations during actual operation.

13.1.3 Humidity Sensor

The humidity sensor was not part of the original functional design, but given that it was integral to the temperature sensor Sensor, then it can be tested to determine if it can provide some measure of hydration based on the ambient humidity at skin level versus humidity of ambient air versus wearer hydration. Since this requires more complex and less available calibrated instruments, it may not be entirely possible to test this feature. However, if it is possible, then a successful set of measurements has the potential to allow inferences about the sensor wearer hydration base on humidity measured at skin level.

13.1.4 Transceiver Functionality

This test checked the node's ability to concatenate measured data in a uniform, orderly, and concise packet, append the packet into a buffer array, and wirelessly transmit and receive data from the Gateway. Transmitted data includes battery power level, temperature, humidity, oxygen saturation and heart rate. Each set of measurements was transmitted at 15-second intervals and displayed in the management console. The sensor set received commands to select the parameters to be transmitted and the frequency of transmission.

13.1.5 Power Consumption

This test is intended to determine how long will the battery last in a sensor set in a full operation condition. The and compare the result to the expected value. The power consumption based on the collective power draw of the combined set of node components that include all sensors, the node processor and the node transceiver.

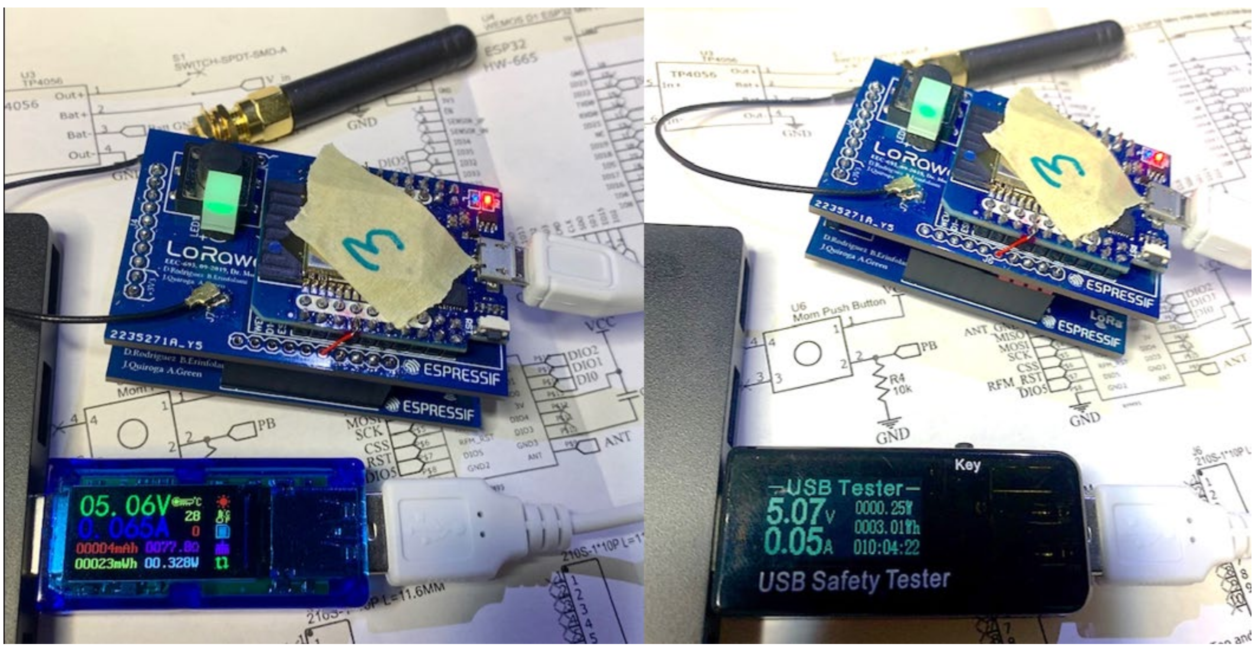


Figure 32 LoRaware Wireless Device Testing Setup, (Left) Blue USB Power Meter, (Right) Black USB Power Meter

The procedure employed in testing the power consumption of the LoRaware wireless devices involved the use of two separate USB Power Meters. These power meters display various power consumption-related metrics on their OLED displays, such as the input voltage, the instantaneous current draw, the energy usage in amp-hours, and the overall power in watts.

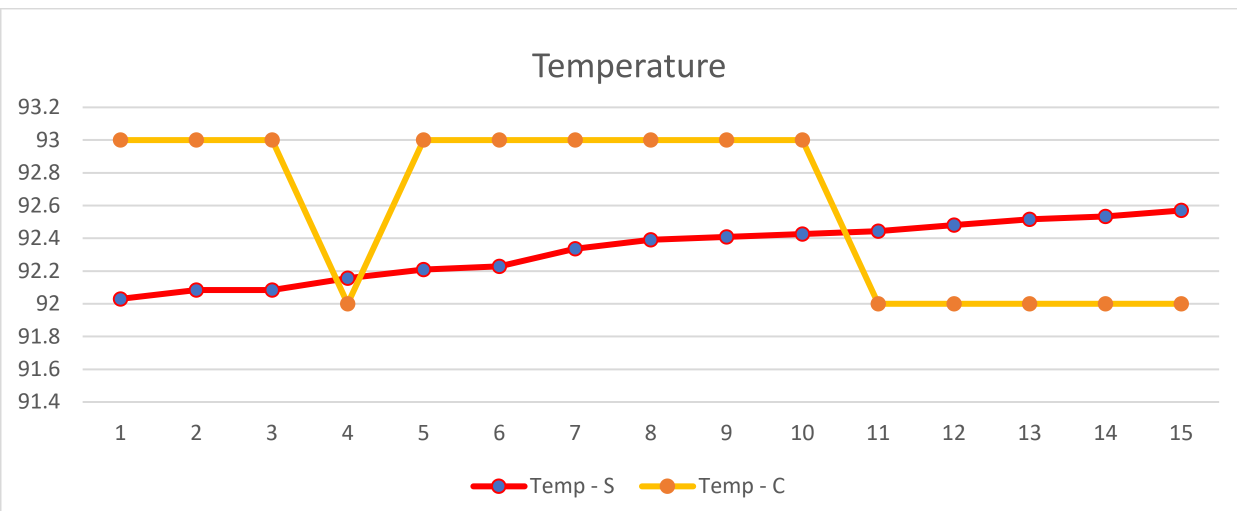
The decision to use two separate USB Power Meters from two different manufacturers was to objectively verify that if there were any considerable improvements to power consumption observed on one meter, the results could then be replicated on the other meter used within testing.

The testing procedure would be performed in a static environment, in which the LoRaware wireless device would be powered via its micro USB port and perform its normal set of firmware instructions of taking all sensor measurements, performing conversions and calculations, concatenating measured values into a LoRaWAN packet, and finally transmitting its data to the MatchX Gateway, before repeating. The testing procedure was individually performed on each of the four LoRaware wireless devices, for each of the USB power meters. The measurements of current draw and the power consumption from the USB power meters were then recorded in a spreadsheet. Calculations could later be applied to these measured values in order to determine the duration of battery life for each LoRaware wireless device.

14. Test Results & Analysis

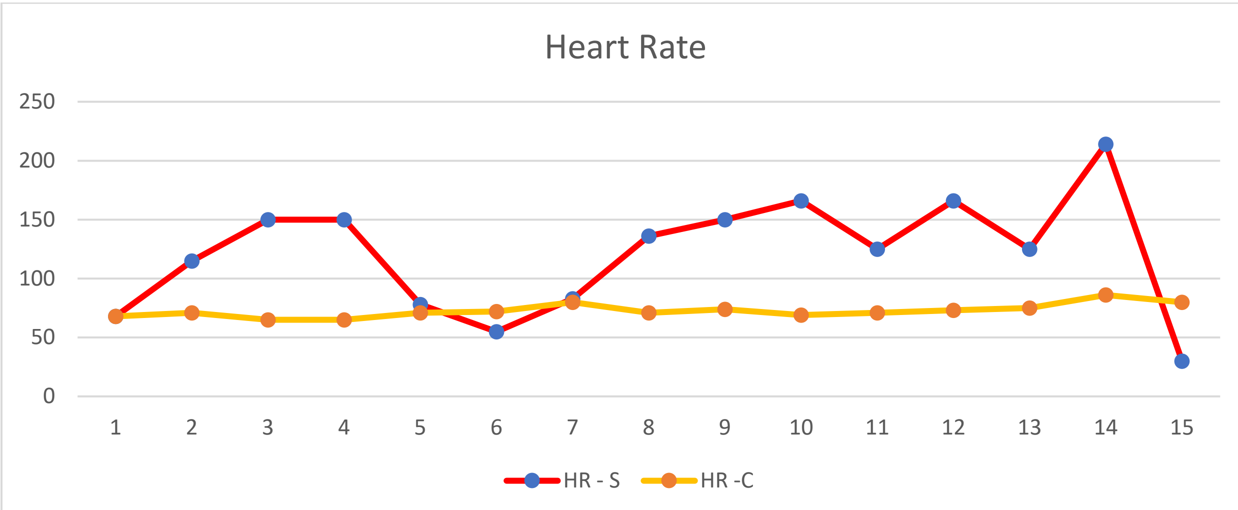
14.1 Static Testing of Sensor Measurements

The following figures illustrate the results of the static testing:

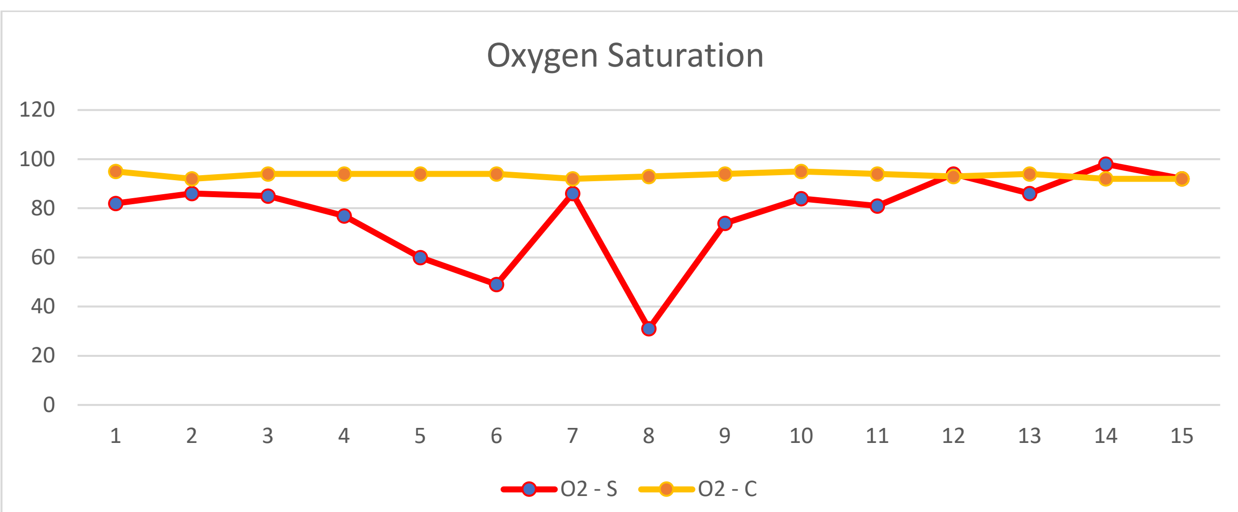


The yellow line in the figure above represents the calibrated measurements (Temp-C) while the red line represents the sensor set (node) measurements (Temp-S). Due to the lower resolution of the calibrated measuring device the line display only two possible values, 92^0 F or 93^0 F. Simultaneously, the node measurements begin at 92^0 F and progressively increase toward

93^0 F with greater resolution than the calibrated readings. This particular test indicates that the device does not need to be calibrated. The increasing slope of the node readings indicates that the sensor was not reading temperatures at steady state.



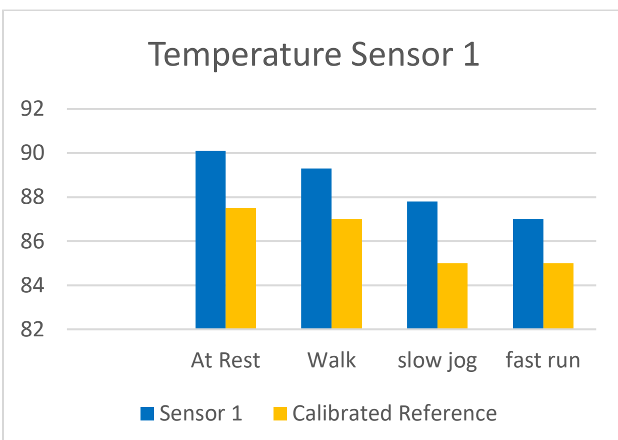
As in the previous figure, the yellow line represents the calibrated device measured values while the red line represents the node measured values. In this set of results, the calibrated measured heart rate is steady, as would be expected in a static condition. The node measurements, however, vary significantly from end to end. This is could be indicative that the sensor was not in full contact throughout the test, or that the sensor was malfunctioning. In either case, more tests are required and should include a few more nodes.

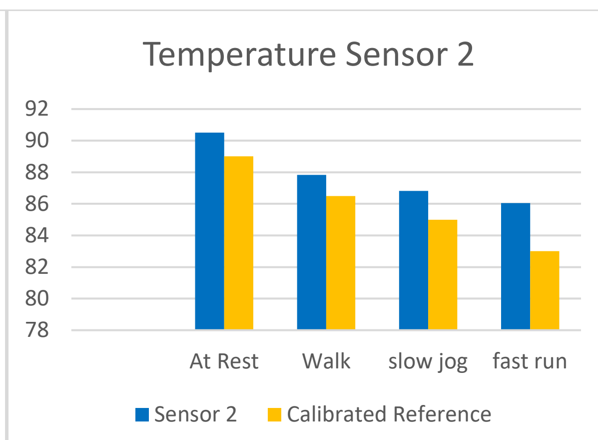


In this graph, the same color convention was used to illustrate measured vs. calibrated oxygen values as in the previous two graphs. As in the previous graph, the measured calibrated values display a steady-state condition while the sensor set measurement show significant variability. Although the node measurements vary, they show some stability on both ends of the collected data range. These results seem to indicate that the sensor set may not have been in good contact with the test subject and indicate that further testing is required.

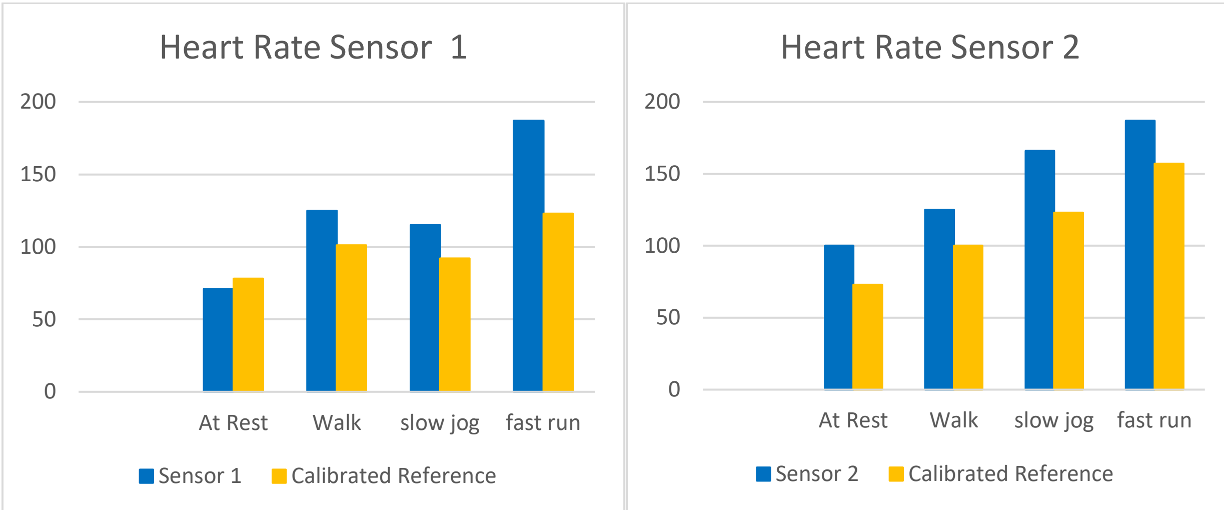
14.2 Dynamic Testing of Sensor Measurements

As previously explained, dynamic testing was designed to demonstrate if the sensor design would operate normally through a variety of conditions. The following graphs depict the results of the various conditions in the design of this test while simultaneously testing the viability of multi-sensor networking. Each of the graphs in this section represents one sensor's measurements against the calibrated device measurements, with both graphs displaying data for the same parameter.

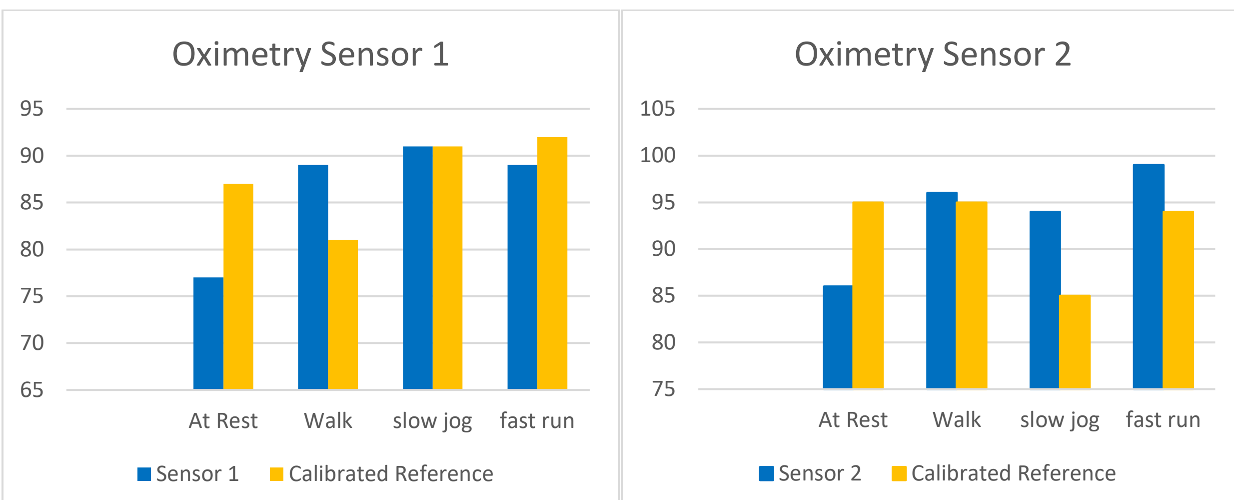




In the graph above, the results indicate that temperature measurements for both nodes are consistent. In both cases , skin temperature decreases with an increase in activity. This decrease in temperature could be explained by the body's own cooling effect during exercise, which is more evident at skin level due to convective cooling. The calibrated measure values also show consistency with a decrease in temperature that decreases in parallel with the sensor set.



The dynamic test results for heart rate measurements depicted in the graph above display similar results as in the Temperature results. As expected, the heart rate increases with greater activity. Likewise, the, calibrated measurement rise nearly in parallel. Both of these two measurements are indicative that calibration would likely help match the result from both types of measuring devices.



The dynamic oxygen saturation testing results displayed above show great variation from both nodes. These variations appear to be similar to those found during static testing. Furthermore, both nodes results are similarly inconsistent. One thing to keep in mind is that each measure was observed once for each condition. This indicates that to obtain more consistent results, testing needs to be performed foe longer periods at each level of activity.

14.3 Power Consumption Test

The duration of Battery Life was able to be determined by dividing the 2000 mAh rated capacity of our 1S 2000 mAh Lithium Polymer Batteries by the recorded values of Current Draw in mA to yield a value representing the total number of hours that the batteries could support the continuous operation of the LoRaware wireless devices.

$$[Duration\ of\ Battery\ Life]\ (h) = \left[\frac{C_{battery}\ (mAh)}{I_{device}\ (mA)}\right] = \left[\frac{2000\ (mAh)}{I_{device}\ (mA)}\right]$$

The power test was measured across all four sensor sets to determine the actual expected battery life and compare it to the target value. The tests were completed using two different meters; with the results displayed in the tables below:

USB Power Meter 1 (Blue)			
Device	**Current Draw (mA)**	**Power (W)**	**Battery Life (hrs.)**
LoRaware_1	66.0	0.333	30.30
LoRaware_2	63.0	0.319	31.75
LoRaware_3	60.0	0.303	33.33
LoRaware_4	58.0	0.298	34.48
Average Battery Life (hrs.):			32.47
Average Percent Improvement (%):			102.91

USB Power Meter 2 (Black)			
Device	**Current Draw (mA)**	**Power (W)**	**Battery Life (hrs.)**
LoRaware_1	50.0	0.253	40.0
LoRaware_2	50.0	0.253	40.0
LoRaware_3	50.0	0.253	40.0
LoRaware_4	40.0	0.202	50.0
Average Battery Life (hrs.):			42.5
Average Percent Improvement (%):			165.6

Overall Average Battery Life (hrs.)	37.48
Overall Average Percent Improvement (%)	134.27

To reiterate, the duration of Battery life was calculated using the maximum amp-hours (2000 mAh) divided by the current draw. The minimum value was 32.47 hours and the maximum 42.5 with the overall average amounting to 37.48 hours. This represents a 137% longer battery life than that currently available within the market.

15. Conclusion

The project team achieved the National University MSEE program objectives through the design, development and testing of the LoRaware Optimized Wireless Patient Monitoring System as a modern wireless sensor network. In this process, the project team successfully addressed all aspects of the project's requirements while exercised various aspects of the disciplines that comprise the MSEE curriculum. The LoRaware Wireless Patient Monitoring System proved that it is an effective proof-of-concept design that can be further tested and developed.

To find CAD Models, Schematics, PCB Files, and other resources used in the LoRaware Project, please visit our Github Page: https://github.com/DavidRodrii/LoRaware-Project

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16. Appendix

Lithium Polymer Battery Voltages and Capacity (Tabulated)

Li-Po Battery Voltage Chart						
Capacity %	Cell Count					
	1S	2S	3S	4S	5S	6S
100	4.2	8.4	12.6	16.8	21	25.2
95	4.15	8.3	12.45	16.6	20.75	24.9
90	4.11	8.22	12.33	16.45	20.56	24.67
85	4.08	8.16	12.25	16.33	20.41	24.49
80	4.02	8.05	12.07	16.09	20.11	24.14
75	3.98	7.97	11.95	15.93	19.92	23.9
70	3.95	7.91	11.86	15.81	19.77	23.72
65	3.91	7.83	11.74	15.66	19.57	23.48
60	3.87	7.75	11.62	15.5	19.37	23.25
55	3.85	7.71	11.56	15.42	19.27	23.13
50	3.84	7.67	11.51	15.34	19.18	23.01
45	3.82	7.63	11.45	15.26	19.08	22.89
40	3.8	7.59	11.39	15.18	18.98	22.77
35	3.79	7.57	11.36	15.14	18.93	22.72
30	3.77	7.53	11.3	15.06	18.83	22.6
25	3.75	7.49	11.24	14.99	18.73	22.48
20	3.73	7.45	11.18	14.91	18.63	22.36
15	3.71	7.41	11.12	14.83	18.54	22.24
10	3.69	7.37	11.06	14.75	18.44	22.12
5	3.61	7.22	10.83	14.43	18.04	21.65
0	3.27	6.55	9.82	13.09	16.37	19.64
y = Battery Voltage (V)						
x = Battery Capacity (%)						
x = (y - 3.5952) / 0.0055						
y = 0.0055*x + 3.5952						

LoRaware Wireless Device – Arduino C++ Firmware for the ESP32

```
/**
 *  LoRaware Rev.6
 *      Author: David Rodriguez
 *      September 2019
 *
 *  For US915MHz, Requires
 *  Beelan LoRaWAN Library: https://github.com/BeelanMX/Beelan-LoRaWAN
 *
 *  Other Required Libraries
 *  ESP32_AnalogWrite: https://github.com/ERROPiX/ESP32_AnalogWrite
 *  Sparkfun_MAX3010x_Sensor_Library:
https://github.com/sparkfun/SparkFun_MAX3010x_Sensor_Library
 *  Adafruit_BME280_Library:
https://github.com/adafruit/Adafruit_BME280_Library
 *
 *  LoRaware Device #1
 */
#include <lorawan.h>
#include <SPI.h>
#include <Wire.h>
#include "MAX30105.h"
#include <Adafruit_Sensor.h>
#include <Adafruit_BME280.h>
#include "heartRate.h"
#include "spo2_algorithm.h"
#include <analogWrite.h>
Adafruit_BME280 bme;
MAX30105 particleSensor;
uint32_t irBuffer[100]; //infrared LED sensor data
uint32_t redBuffer[100];  //red LED sensor data
int32_t bufferLength; //data length
int32_t spo2; //SPO2 value
int8_t validSPO2; //indicator to show if the SPO2 calculation is valid
int32_t heartRate; //heart rate value
int8_t validHeartRate; //indicator to show if the heart rate calculation is
valid
byte pulseLED = 34; //Must be on PWM pin
byte readLED = 2; //Blinks with each data read
byte battPin = 0; //Battery Voltage Pin
byte button = 33; //Push Button Pin
//ABP Credentials - FOR Device: LoRaware_1
const char *devAddr = "aff30559";
const char *nwkSKey = "f4720873994fabe280806161ca753a6f";
const char *appSKey = "13c4a1b5ec7c7aee7cbb90e2bbce9f71";
#define MAX_BRIGHTNESS 255
#define SS 18
#define MISO 19
#define MOSI 27
#define SCK 5
unsigned long previousMillis = 0;  // will store last time message sent
int countHR = 0; // MAX30102 HR Error Counter
```

```
int countO2 = 0; // MAX30102 HR Error Counter
int wearState = 0; // Default Wear State Enabled
int dbgState = 0; // Default Debugging Disabled
char myStr[50];
char myStrCB[26];
char myStrVB[26];
char myStrT[26];
char myStrH[26];
char myStrHR[26];
char myStrO2[26];
char payload[255];
char emergencyPayload[255];
char outStr[255];
byte recvStatus = 0;
bool eState = false;
const sRFM_pins RFM_pins = {
  .CS = 18,
  .RST = 14,
  .DIO0 = 26,
  .DIO1 = 25,
  .DIO2 = 32,
  .DIO5 = 35,
};

void LEDbreathe() {
  // Breathes Green LED with Sinusoidal PWM Function
  for (int i = 0; i < 360; i++) {
    analogWrite(readLED, (sin(i * 0.0174533) + 1) * (127/16));
    delay(6);
} // End of void LEDbreathe()

void LoRaware_norm() {
  // LoRaware Normal Operation
  LEDbreathe();
  particleSensor.wakeUp();
  bufferLength = 100; //buffer length of 100 stores 4 seconds of samples
running at 25 sps
  for (byte i = 0 ; i < bufferLength ; i++)
  {
    while (particleSensor.available() == false) //do we have new data?
      particleSensor.check(); //Check the sensor for new data

    if (eState == true) {
      break;
    }
    else {
     redBuffer[i] = particleSensor.getRed();
     irBuffer[i] = particleSensor.getIR();
     particleSensor.nextSample();
    }
  }
  maxim_heart_rate_and_oxygen_saturation(irBuffer, bufferLength, redBuffer,
&spo2, &validSPO2, &heartRate, &validHeartRate);
  float measuredvbat = analogRead(battPin);
```

```
  float battV;
  battV = (((measuredvbat)*(2.1) / (4096)))*2;
  dtostrf(battV,6, 3, myStrVB);
  dtostrf((bme.readTemperature()*(1.8) + 32),6, 3, myStrT);
  dtostrf(bme.readHumidity(),6, 3, myStrH);
  dtostrf(heartRate,6, 2, myStrHR);
  dtostrf(spo2,6, 2, myStrO2);
  String str;
  str = (String(myStrVB) +","+ String(myStrT) +","+ String(myStrH) +","+
String(myStrHR) +","+ String(myStrO2));
  unsigned int str_len = 37;
  str.toCharArray(payload,str_len);
  Serial.println(payload);
  // LoRaWAN Data Send Uplink to Gateway
  lora.sendUplink(payload, strlen(payload), 0); // 0 = LoRaWAN UNCONFIRMED
Message Type
  analogWrite(readLED,0);
  particleSensor.shutDown();
  delay(5000);
  recvStatus = lora.readData(outStr);
  if(recvStatus) {
  }
  // Check Lora RX
  lora.update();
  particleSensor.wakeUp();
} // End of void LoRaware_norm()

void emergencyPush() {
  analogWrite(readLED,250);
  static unsigned long last_interrupt_time = 0;
  unsigned long interrupt_time = millis();
  // Disregard Interrupts faster than 200 ms
  if (interrupt_time - last_interrupt_time > 200){
    eState = !eState;
  }
  last_interrupt_time = interrupt_time;
} // End of void emergencyPush()

void sendEmergencyLoRa() {
  analogWrite(readLED,250);
  // LoRaWAN Emergency Message Payload
  particleSensor.shutDown();
  analogWrite(readLED,250);
  delay(300);
  String emergencyStr;
  emergencyStr = (String(0) +","+ String(0) +","+ String(0) +","+ String(0)
+","+ String(0));
  Serial.println("Sending Emergency msg");
  unsigned int str_len = 37;
  emergencyStr.toCharArray(emergencyPayload,str_len);
  Serial.println(emergencyPayload);
  delay(100);
  // LoRaWAN Data Send Uplink to Gateway
```

```
  lora.sendUplink(emergencyPayload, strlen(emergencyPayload), 0); // 0 =
LoRaWAN UNCONFIRMED Message Type
  // Check Lora RX
  lora.update();
  eState = !eState;
  analogWrite(readLED,0);
} // End of void sendEmergencyLoRa()

void setup() {
  Serial.begin(115200);
  pinMode(pulseLED, OUTPUT);
  pinMode(readLED, OUTPUT);
  pinMode(battPin, INPUT);
  pinMode(button, INPUT_PULLUP);
  attachInterrupt(digitalPinToInterrupt(button), emergencyPush, HIGH); //
Button Pin as Interrupt Pin
  if (!particleSensor.begin(Wire, I2C_SPEED_FAST)) //Use default I2C port,
400kHz speed
  {
    Serial.println("MAX30105 was not found. Please check wiring/power. ");
    while (1);
  }
  if (!bme.begin(0x76)) {
    Serial.println("Could not find a valid BME280 sensor, check wiring!");
    while (1);
  }
  SPI.begin(SCK,MISO,MOSI,SS);
  if(!lora.init()){
    Serial.println("RFM95 not detected");
    delay(5000);
    yield();
    return;
  }
  // LoRaWAN Class
  lora.setDeviceClass(CLASS_A);
  // Data Rate
  lora.setDataRate(SF8BW125);
  // Channel Set to Random
  lora.setChannel(MULTI);
  // ABP Key and DevAddress
  lora.setNwkSKey(nwkSKey);
  lora.setAppSKey(appSKey);
  lora.setDevAddr(devAddr);
  byte ledBrightness = 45; //Options: 0=Off to 255=50mA
  byte sampleAverage = 16; //Options: 1, 2, 4, 8, 16, 32
  byte ledMode = 2; //Options: 1 = Red only, 2 = Red + IR, 3 = Red + IR +
Green
  byte sampleRate = 400; //Options: 50, 100, 200, 400, 800, 1000, 1600, 3200
  int pulseWidth = 118; //Options: 69, 118, 215, 411
  int adcRange = 8192; //Options: 2048, 4096, 8192, 16384
  particleSensor.setup(ledBrightness, sampleAverage, ledMode, sampleRate,
pulseWidth, adcRange); // MAX30102 Sensor Configuration
} // End of void setup
```

```
void loop() {
  start:
  if (eState == true) {
    sendEmergencyLoRa();
    goto start;
  }
  else {
    eState = false;
    //LEDbreathe();
    LoRaware_norm();
    goto start;
  }
} // End of void loop
```

Raspberry Pi Single-Board Computer Specifications:

- SoC: Broadcom BCM2837
- CPU: 4× ARM Cortex-A53, 1.2GHz
- GPU: Broadcom VideoCore IV
- RAM: 1GB LPDDR2 (900 MHz)
- Networking: 10/100 Ethernet, 2.4GHz 802.11n wireless
- Bluetooth: Bluetooth 4.1 Classic, Bluetooth Low Energy
- Storage: microSD
- GPIO: 40-pin header, populated
- Ports: HDMI, 3.5mm analogue audio-video jack, 4× USB 2.0, Ethernet, Camera Serial Interface (CSI), Display Serial Interface (DSI)

Espressif Systems ESP32 Specifications:

- RAM 520 KB
- CPU Tensilica Xtensa LX6 is a 32 bit dual-core (I.e. two internal processors) at 160/240 MHz i.e. the clock frequency can go up to 240MHz
- Input/output: I2C up to 2, PWM up to 8, 1 PCM, 12-bit SAR ADC up to 18 channels, DAC 8 bit up to 2 channels.

- Flash memory up to 64 Mbytes
- Input voltage 2.2 V – 3.6 V
- Operating current 80mA
- Temperature Range -40C to 125C
- 38 I/O Pins

RFM95 LoRa Transceiver Specifications:

- LoRaTM Modem
- 168 dB maximum link budget
- +20 dBm - 100 mW constant RF output vs. V supply
- +14 dBm high efficiency PA
- Programmable bit rates up to 300 kbps
- High sensitivity: Down to -148 dBm
- Low RX current of 10.3 mA, 200 nA register retention
- Fully integrated synthesizer with a resolution of 61 Hz
- FSK, GFSK, MSK, GMSK, LoRaTM and OOK modulation
- Built-in bit synchronizer for clock recovery
- Preamble detection
- 127 dB Dynamic Range RSSI
- Packet engine up to 256 bytes with CRC
- Built-in temperature sensor and low battery indicator

TP4056 Charge Protection Features:

- Overcharge protection - the module will safely charge your battery to 4.2V
- Overcurrent and short-circuit protection - the module will cut the output from the battery if the discharge rate exceeds 3A or if a short-circuit condition occurs
- Soft-start protection limits in-rush current
- Trickle charge (battery reconditioning) - if the voltage level of the connected battery is less than 2.9V, the module will use a trickle charge current of 130mA until the battery voltage reaches 2.9V, at which point the charge current will be linearly increased to the configured charge current.

I-PEX MHF ELECTRICAL RATINGS

Impedance	50 Ω					
Insulation Resistance	>= 500M Ω					
Contact Resistance	**Center Contact**			**Outer Contact**		
	20 m ohms max.			10 m ohms max.		
Rated Voltage	AC 60V					
Withstand Voltage	AC 200V					
Frequency	Up to 3gHz			3gHz to 6gHz		
V.S.W.R.	1.3 Max			1.4 Max		
Coax Cable	1.13mm	1.32mm	RG-178	5.44dB/m	5.6dB/m	4.9dB/m

(Lighthorse Technologies, Inc., 2019)

MAX30102 Specifications:

- Integrated pulse oximetry and heart-rate monitor biosensor module MAX30102
- Size: 5.6 x 3.3 x 1.55mm
- Measures heart rate or pulse (in BPM)
- Measures O_2 concentration in the blood
- Ratio of oxygenated hemoglobin to total hemoglobin as %
- Can aid in detection of hypoxemia, deteriorating organ function and cardiac arrest.
- Internal LEDs (Red and Infrared)
- Photodetectors
- Optical elements
- Low-noise electronics with ambient light rejection
- Operates on 1.8V power supply and a separate 3.3V power supply for the internal LEDs
- Low power consumption (less than 1mW)
- Operating temperature between -40º C to 85º C