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Internet of Things Remote Monitoring Solution for Efficient Storage and Delivery of Temperature-Sensitive Vaccines in Rwanda

A dissertation submitted in partial fulfillment of the requirements for the award of

MASTERS OF SCIENCE DEGREE IN INTERNET OF THINGS-EMBEDDED COMPUTING SYSTEMS

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Declaration

We, **KALISA Jean Bosco** and **TUYISENGE Jean Claude**, declare that the content of this research thesis report is our own work intended to serve as a part of the fulfillment of the requirements for the award of Master's degree in Internet of Things/ Embedded Computing Systems.

To the best of our knowledge, we hereby declare that this work is unique and has in no way been provided or submitted for any educational award, educational e-book, or some other motive on this or other university or higher learning institution. The section of references lists other guides or materials that had been used in this thesis record.

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Certificate

This is to certify that this submitted research thesis report is a record of the original work done by **Mr. KALISA Jean Bosco** (**REF.NO: 220014146),** and **Mr. TUYISENGE Jean Claude** (**REF.NO: 220014128**), MSc. Internet of Things –Embedded Computing systems (IoT-ECS) Students at the University of Rwanda/ College of Science and Technology/ African Center of Excellence in Internet of Things. Certified further, that according to the best of my knowledge; the work reported here doesn't form a part of any other research work.

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Dedication

To my wife INGABIRE Sylvie; my daughter UWASE KALISA Celine; my two sons SHYAKA KALISA Edwin and MUGISHA KALISA Elliott; my mother, sisters and all my in-laws, I dedicate this thesis report.

KALISA Jean Bosco.

To Almighty God, my family members, Brothers, Sisters and dear friends, I dedicate this thesis report.

TUYISENGE Jean Claude.

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Abstract

Pandemics such as COVID-19 pandemic cause a significant loss of human life around the world, and they constitute a very big challenge to public health. Lack of efficient and well-monitored vaccination systems leads to people's death and impact the economy of individuals and of the country in general. Some vaccines are temperature-sensitive, therefore, storing and delivering the vaccination to rural remote area in suboptimal conditions reduces their efficacy or even spoil the vaccine. Currently, monitoring of these vaccines is done manually and this is unreliable, making it impossible to know if their effectiveness has deteriorated by the time they are injected in individuals. This research project has been conducted with the objective of developing an Internet of Things Remote Monitoring Solution (IoT RMS) to provide a real-time monitoring of storage and delivery of these temperature-sensitive vaccines together with the ability to alert whenever there is an issue. Although some vaccines can be kept under $2^{o}C$, our system will only serve for vaccines kept between 2 and 8 degree Celsius which is the WHO recommended range. The methodology used consists of gathering information about the currently used cold chain systems, the types of systems used, their problems, and the needs in locally produced monitoring product. Questionnaires and One-on-one interviews with people directly linked with vaccine cold chain have been conducted to quickly map concepts and develop the cold chain IoT RMS product. The results obtained showed that 100% of all respondents manually record vaccine temperatures on daily basis, they 100% store vaccines into refrigerators, only 50% were aware of the ($2\text{-}8^{o}C$) WHO recommended temperature range for vaccines storage. 60% of vaccine stores have standby generators for automatic power backup in case of power outages. There is no any remote monitoring tool used for all vaccine stores as well as for vaccine delivery process. Sensors, Microcontroller Units, wireless communication technology and user interface have been connected together and configured to produce a prototype of an IoT RMS system. Test results proved that the designed system will be a suitable solution to the existing cold chain challenges and the data obtained compared to the data from existing system present high accuracy. To maintain efficient and accurate cold chain systems the research thesis recommends that cold chain technicians should be continuously trained, standby generators should be installed and regularly maintained, IoT RMS solution should be adopted.

Keywords: Cold chain, IoT RMS, COVID-19, Vaccine Storage, Vaccine Delivery, Web App.

Acronyms and Abbreviations

ACEIoT	:	African Center of Excellence in Internet of Things
API	:	Application Programmable Interface
CCE	:	Cold Chain Equipment
CCT	:	Cold Chain Technicians
CHUB	:	Centre Hospitalière Universitaire de Butare
CST	:	College of Science and Technology
DHT	:	Digital Humidity and Temperature
DVS	:	District Vaccine Store
EVM	:	Effective Vaccine Management
Fig.	:	Figure
FT2	:	Fridge Tag2
GPS	:	Global Positioning System
GSM	:	Global System for Mobile Communications
RMS	:	Internet of Things Remote Monitoring Solution
IoT	:	Internet of Things
LCD	:	Liquid Crystal Display
MoH	:	Ministry of Healthy
MySQL	:	My Structured Query Language
NVS	:	National Vaccine Store
PHP	:	Hypertext Preprocessor
RMS	:	Remote Monitoring Solution
RVS	:	Regional Vaccine Store
SMS	:	Short Message Service
UR	:	University of Rwanda
Web App	:	Website Application
WHO	:	World Health Organization

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Chapter 1: General Introduction

1.1 Background and Motivation

Vaccination is among the most effective strategies for preventing diseases. However, its success depends on a well-managed cold chain that keeps vaccines within the World Health Organization 2 to 8 degrees Celsius recommended range from the time they are made to when they are administered, ensuring product quality and effectiveness [1]. Internet of thing (IoT) remote monitoring solution for efficient storage and delivery of temperature sensitive vaccines is crucial for better cold chain monitoring in different environments to monitor the storage of vaccines in cold rooms once imported, and to monitor the movements of vaccines once they leave the cold rooms and get delivered to health centers for use.

More than 5.6 million children died before reaching the age of five in 2016, the majority of them from preventable causes [2]. Immunization is largely regarded as one of the most successful public health initiatives, but global immunization rates have remained steady for several years at 85 percent [3][4]. Increased vaccination coverage rates, according to the World Health Organization, might prevent an additional 1.5 million deaths per year [5]. To attain the high vaccination coverage rates, proper cold chain management is necessary to keep vaccine quality [5].

Within this context health and economic crises created by the COVID-19 pandemic will only be fully resolved with the discovery and global dissemination of an effective vaccine. It is essential not only for the health and well-being of the populations of developing countries that nearly every individual there receives a vaccine, but also to the rest of the globe, in order to prevent small pockets of unvaccinated people beginning new outbreaks of the disease. Keeping consistent cold chains throughout the vaccine delivery system is a complex, but crucial, process that requires precise, temperature-controlled environments to store, manage and transport vaccines. A limited temperature range (often between 2-8ºC) must be maintained from the time vaccines are manufactured until they are delivered to the beneficiary [6].

Variation of temperature in vaccine supply chains are rather prevalent for industrialized as well as Third world nations, according to a number of studies. In low-income nations, It has been found that 37% of vaccines are subjected to temperatures that are outside of the acceptable range, making this an important issue to address [7][8]. Monitoring techniques have been shown to be unsatisfactory in existing research, resulting in vaccines being exposed to temperature extremes [8]. According to a study conducted in Cameroon's North West Region, about 76 percent of health centers assessed had a working thermometer for their vaccine storage facility, and 20% of those had abnormal temperatures when data was collected. [8].

The Fridge-tag 2 (FT2), a continuous temperature monitoring logger, is used to manually track and record the faults identified in the evaluation, as well as the temperatures of cold chain equipment at facilities and sub-country stores. The FT2 has a history of issues relating to users' lack of understanding of how to use it, how to read and interpret FT2 results, and how to respond to temperature excursions. [8][4]. The majority of people in low-income nations, like Rwanda, are not adequately taught to use these devices, and the cold chain system is frequently inefficient and under-monitored. As a result, over 39.54 percent of vaccines are thrown away at the session sites [4]. Furthermore, vaccines are typically transported in refrigerated boxes with ice packs and cold water packs. Vaccines frequently freeze below the required temperature range, leaving them useless and potentially dangerous. Vaccines are also lost or stolen throughout the trip to the health clinics due to a lack of accountability. All of these factors create a loss of over 30% of vaccines in delivery [9].

To address the above challenges for maintaining a cold chain, we propose a modern healthcare IoT platform with remote monitoring along with sensors for cold chain monitoring of vaccines, for real-time recording and reporting.

This project has the potential to transform the lives of people both in Rwanda and the wider region, by substantially increasing the resilience of fragile healthcare systems, saving limited financial resources, providing access to life-saving treatments, and building essential infrastructure for the response to the COVID-19 pandemic and other deadly diseases.

1.2 Problem Statement

Vaccines are temperature-sensitive substances that should be kept and transported at specific temperatures. They are all affected by heat, some by freezing, and others by light. Temperatures above or below the recommended ranges reduce the efficacy and safety of vaccines. Vaccines are often transported and stored in suboptimal conditions, creating breaks in the cold chain and limiting vaccine effectiveness. Because of handling and storage problems, vaccine wastage and revaccination can cost a lot of money. Errors can also lead to the loss of patient trust when repeat doses are required.

Maintaining equipment at the temperature range stipulated by the WHO (2-8^{o}C) is not always obeyed, as per evaluations of efficient vaccination management undertaken in several countries [6]. Many countries also lack temperature monitoring equipment for vaccine storage and refrigeration. It has also been found that cold chain processes focus on preserving vaccines against heat disruption, thus putting them at danger of exposure to freezing temperatures. As a result, vaccine unintentional freezing became a commonly overlooked problem worldwide. The possibility of freezing temperatures to occur in storage and transportation has been discovered to be a worldwide issue for both resource-rich and resource-limited environments.

Vaccine control is manual and inconsistent; and it is difficult to know if a vaccine's effectiveness has been impaired by the time it reaches the patient, resulting in senseless deaths and wasted medical expenses.

1.3 Aims and Objectives

1.3.1 Aims

1. To gain a thorough understanding of the current cold chain monitoring tools' challenges as they relate to the adoption and use of a possible IoT RMS product.
2. To ensure that vaccines efficacy is maintained and that vaccines are not thrown away in fixed stores or in delivery because of heat or extreme cold.
3. To guarantee that cold chain devices meets established requirements and that any problems are quickly identified and corrected.
4. To help cold chain technicians and managers remotely access data on cold chain performance.

1.3.2 Objectives of the Study

General Objective

The ultimate objective is to develop a cold chain Internet of Things Remote Monitoring Solution (IoT RMS) to ensure vaccines' efficacy by the time they are injected in individuals.

Specific Objectives

As this project consists of two parts namely the vaccine storage IoT RMS system and the vaccine delivery IoT RMS system our specific objectives are also separated respectively.

Although we worked as a team to achieve the general objective of this project, everyone had his own specific objectives to achieve. Mr. Jean Claude TUYISENGE focused on the specific objectives set on vaccine storage IoT RMS System while Mr. KALISA Jean Bosco focused on the specific objectives set on vaccine delivery IoT RMS System.

Specific Objectives on vaccine storage IoT RMS System

1. To collect data that support the design of the vaccine storage IoT RMS system.
2. To develop a prototype of vaccine storage IoT RMS System that responds to challenges identified during the data collection phase.
3. To test the developed prototype to ensure its accuracy and effectiveness.

Specific Objectives on vaccine delivery IoT RMS System

1. To collect data on how the process of vaccine delivery is currently done in order to identify the challenges.
2. To use sensors, microcontroller unit and communications technologies for temperature recording and vaccines location tracking during transportation.
3. To develop a web application based user interface for system performance remote monitoring and to provide an SMS notification to end users whenever the vaccine temperature goes above or below the recommended range.
4. To test the developed prototype to make sure it responds to the identified challenges.

1.4 Hypothesis

With the help of IoT as a new emerging technology, It is possible to develop a viable solution to the current cold chain challenges, Increase vaccines efficacy by the time they reach end users, avoid vaccines wastage hence save lives and enormous amount of money.

1.5 Scope of the Study

This research was conducted to design and develop a prototype of an IoT remote monitoring solution for efficient storage and delivery of temperature-sensitive vaccine in Rwanda. The system is able to record vaccines temperature inside refrigerators, send the recorded values to an online platform for remote monitoring, track the location of vaccines during transportation and notify end users whenever the temperature goes above or below the WHO recommended range.

1.6 Significance of the Study

The develop system will be used in monitoring the temperature-sensitive vaccines in Rwanda. It will help to identify breaks in vaccine cold chain where by different sensitive parameters must be monitored in real time and alert responsible persons whenever the cold chain breaks.

This system will provide a better cold chain monitoring in two environments in Rwanda; to monitor the storage of vaccines in cold rooms once imported, and to monitor the movement of vaccines once they leave the cold rooms and get delivered to health centers for use. It addresses not only the monitoring of storage and transportation environments in real-time through the development of innovative cold chain

IoT RMS, but also the ability to alert if there are issues, sending alert messages to key stakeholders who could immediately pinpoint and manage breaks in the cold chain, saving precious vaccines from spoiling.

1.7 Organization of the Study

There are five chapters in this thesis report. The first chapter deals with general introduction about the project. The second chapter gives a brief description about the previous related research and the gaps identified. The third chapter describes different methodology approaches used to carry out the research. The fourth chapter provides details about the system design and prototyping. The fifth chapter discusses the simulation results obtained and their analysis. The conclusion and recommendations to the country and future studies are discussed in the last chapter.

Chapter 2: Literature Review

This chapter discusses a brief analysis of related researches. This includes the problem investigated by the previous researchers, proposed technical solution, methodology approach used, and results found. Eventually, the gaps in the previous similar and related research were identified and these provide the justification and motivation for undertaking the current research.

Vaccines have saved millions of lives and avoided countless cases of disease over the years. Smallpox, mumps, tetanus, and rotavirus were all common infectious diseases in the past, as were polio, measles, diphtheria, pertussis (whooping cough), rubella (German measles), smallpox, mumps, tetanus, and rotavirus [5].

Despite this, one out of every five children in the world remains unprotected by even the most basic vaccines. Furthermore, due to a lack of vaccination, nearly 20 million individuals are at danger of experiencing avoidable diseases. Consequently, every year, almost 1.5 million children die from diseases that might be prevented if all children were vaccinated [10].

However, the production and transportations of vaccines, is most important for preventing the different disease all over the world. Through this, maintaining an unbroken cold chain for temperature-sensitive vaccines is a vital component of resilient healthcare infrastructure—never more so than in the midst of a global pandemic such as COVID-19; a health crisis that is not only straining healthcare systems, but has destabilized the economy, with disproportionate impacts on vulnerable rural communities. While a vaccine has been touted as the only solution that will allow societies and economies to resume "normal" activities, We believe that the objective should not be a return to normal; rather, this crisis should be taken as an opportunity to increase baseline health and well-being by transforming the healthcare value chain with IoT RMS.

Over the years, many research projects have been undertaken to develop online web and mobile-based applications that can aid in increasing vaccine coverage and controlling the cold chain. The majority of mobile applications developed are primarily responsible for collecting data on vaccine coverage in hard-to-reach parts of third world nations and for monitoring vaccine administration [11][12][13].

Nevertheless, all those previous studies have demonstrated, adequate vaccine coverage in these remote regions can only be assured if the vaccine supply system's cold chain is working properly. While these tools can accurately analyze vaccine outreach rates, they do little to boost coverage rates.

According to a previous WHO report [14] Two alarm-based temperature monitoring systems have been implemented at national immunization storage facilities in Sudan and Iran. These systems provide for continuous cold-store temperature monitoring at their respective sites. The systems, however, do not go beyond specific facilities, making it impossible to monitor the entire vaccination cold-chain.

National Vaccine Stores Temperature Recording System Khartoum, Sudan [14], To monitor the temperature, the system was developed with one temperature sensor (gas type) installed in each cold/freezer room. The sensor measures the cold/freezer rooms' internal temperature. A transmitter is linked to those sensors on the roof of each cold room and delivers a wireless signal to the hub, which is then connected to the computer for recording and saving the data. Outside the cold room, an extra sensor was mounted to record the store's ambient temperature [14], It also features an arming system that sends a warning to the staff phone and the extended Programme on Immunization Manager (EPI) when the temperature rises above 10 degrees Celsius and falls below 0 degrees Celsius. In Iran [14], In 2005, a local company, Sardzasaz, designed, manufactured, and installed an autonomous temperature recording system. The company is also in charge of system maintenance and has had a contract with the Ministry of Health and Medical Education for the past five years. The same company deployed similar devices in a few other provincial vaccine outlets [14]. These systems, on the other hand, are only acceptable for use in vaccine cool rooms and refrigerators at delivery sites. Those aren't designed for use during vaccine delivery, where cold chain breaches are most prevalent.

Using common mobile phones to provide remote monitoring of vaccination cold-chains [15] , is a low-cost, energy-efficient device for tracking the temperature and location of vaccines across the country. FoneAstra is a programmable platform based on a low-cost microcontroller that enhances the capabilities of low-tier cell phones commonly used in developing countries. FoneAstra comes with a digital temperature sensor as well as a vaccine cold-box for keeping vaccinations in a controlled environment. The temperature of the cold-box is continuously monitored by FoneAstra, which aggregates information over time. It sends periodic SMS messages with routine temperature updates or instant alerts if it detects abnormal temperature conditions using the mobile phone to which it is connected. It also allows for the tracking of vaccines in transit using cell tower-IDs from mobile phones. This system is an online-based application with the basic limitation that it does not include the function of allocating separate IDs to large numbers of vaccines that are sent out together on different trips, and it also does not have the ability to identify which vaccine delivery trip the definite data is being sent from, limiting its use to a single trip at a time.

In Kenya, Remote Temperature Monitoring and Data use teams [1], was carried out and implemented in Isilio, Kajiado, and Nairobi to see if employing remote temperature monitoring (RTM) devices, as well as a structured problem-solving and action-oriented strategy to data utilization, will help with vaccine management. Over 50 vaccine fridges were built across 18 sub-country vaccine storage and 18 high-volume health facilities as part of the system. When the temperature went above or below the vaccine's recommended temperature range, the system devices delivered an SMS alert to the employees. Following that, it collected and recorded continuous data before uploading it to the ColdTrace dashboard. However, this approach does not allow for remote monitoring of vaccines while they are being transported.

In the World Health Organization (WHO) Management Handbook[6], The Department of Immunization, Vaccines, and Biologicals has released a document developed by the Expanded Programme on Immunization that explains how to monitor temperatures in the vaccine supply chain. Among the methods described are the use of an electronics freeze indicator, which is a small device that is placed with freeze-sensitive vaccines during transport. It has a visual display that shows whether or not it has been subjected to cold temperatures

The vaccine manufacturer included an electronic shipping indicator, which is a single-use temperature monitoring device, with international or in-country vaccine delivery. It contains visual warnings set to indicate the vaccine's heat and/or frost sensitivity thresholds and maintains track of temperatures at regular intervals. A computer that consistently records temperatures in cold rooms, freezer rooms, refrigerators, and freezers utilizing several sensors is known as a programmed electronic temperature and event logger system.

A temperature sensor that is permanently put in cold areas, freezer rooms, refrigerators, and freezers is an integrated digital thermometer. Temperature sensors monitor the temperature in real time, which is digitally reflected outside the room or in the refrigerator/freezer. Temperature threshold indicator is another device that uses a chemical indicator to identify whether a vaccination has been irreversibly exposed to temperatures above or below a pre-determined limit. All of the preceding technology, however, presents the lack of a cold chain that can be remotely monitored throughout shipment. As a result, the constraints of existing works will be taken into account when designing this system.

Mercy Lutukai, E. Bunde, B. Hatch, et al, completed a study called Using Data to Keep Vaccines Cold. In 36 research sites across Kenya, a pilot study utilizing Remote Temperature Monitoring (RTM) technology and data use teams was deployed. They discovered that combining RTM technology with a structured data review procedure by a management team is an effective way to improve cold chain outcomes. [4].

Chunga Chimwemwe conducted a research on the factors that contribute to non-adherence to temperature ranges at district vaccine stores (DVS) in Malawi, in order to contribute to the reduction in vaccine wastage due to temperature excursions. This study was sequential mixed method design where qualitative and quantitative data were collected. The study sample size was 67 cold chain technicians and 101 refrigerators. It was observed that, 13 (46%) districts were found to have at least one refrigerator operated at temperatures above $8^{o}C$ for a period of more than 10 hours and $-0.5^{o}C$ and below for an hour or more. Lack of power back up, maintenance tools and fuel were the major challenges which were revealed [16].

In Jimma Zone, Oromia Regional State, Ethiopia, D. Feyisa conducted research on Cold Chain Maintenance and Vaccine Stock Management Practices at Public Health Centers Providing Child Immunization Services. The majority of cold chain handlers had little knowledge, and a considerable number had poor cold chain preservation practices. In public health centers, cold chain maintenance was insufficient, necessitating careful measures to provide proper vaccine cold chain management at immunization delivery points [17].

E. Ogboghodo, V. Omuemu1, O. Odijie, et al, conducted research on health care workers' cold chain management techniques in basic health care institutions in Southern Nigeria. This research used a descriptive cross-sectional study design. Registered nurses, auxiliary nurses, and community health extension workers in primary health care institutions in Benin City, Edo State, made up the research population. Over two-thirds of the 314 respondents (73.9%) have good cold chain management practices. All stakeholders should guarantee that they work together to create favorable circumstances that will improve the practice of health care providers [18].

Bogale, H. Adam Amhare, et al, investigated the factors that influence vaccine cold chain management at public health institutions in Ethiopia's Amhara region's east Gojam zone. According to their findings, health personnel who work in cold chain management have a knowledge gap. To solve this issue, there is an immediate need to strengthen cold chain management knowledge and practice through improved supervision and training at various levels of the health care system [19].

In Ghana's Sekyere Central District, Asamoah, A. Ebu Enyan, et al, conducted research on Cold Chain Management by Healthcare Providers. Despite the fact that the majority of the participants had a positive attitude toward cold chain management, there was a weak link between them. This means that good information may not always impact good cold chain management attitudes, and vice versa. The amount of support for cold chain management methods provided by facilities was insufficient [20].

Chapter 3: Research Methodology

3.1. Overview

Different approaches have been used to conduct this research activity. In general, the technological IoT RMS solution has been developed using a human-centered design (HCD) approach, which integrated the needs of the people directly linked with cold chain monitoring. This technique is a design thinking approach that assisted in the development of a viable IoT RMS product that is able to respond to local challenges such as limited connectivity, intermittent power outages, and user interaction patterns. The steps and methods mentioned below were used in this research project.

3.2 Preliminary review and analysis of technical and design needs

In this phase we gathered data from cold chain technicians through questionnaires. The IoT remote monitoring solution was designed based on the needs and technical requirements identified after a deep analysis on the data collected at this stage. Conducting this research helped us to get enough information on how the existing cold chain systems are used, their challenges and the improvement they need.

3.2.1 Research design

This study focused on collecting quantitative data. Questions were prepared and revised to make sure they are good enough to help us get the data we needed from cold chain technicians on the equipment they use to store vaccines, the temperature monitoring techniques, the approach used to ensure that vaccines are not affected during transportation and different challenges they face in their daily responsibilities.

Since the research questionnaires were anonymous, respondents were free to answer at the best of their knowledge and experiences. This helped us to get more details we needed and we are sure the presented data give the true situation of the existing cold system and its monitoring approach.

3.2.2 Location of the study

District vaccine stores were the study areas. Each district vaccine store was situated at district Hospital. District vaccine stores were taken care by at least 2 cold chain technicians. Every district vaccine store had 2 to 5 refrigerators depending of the population size of the district.

3.2.3 Target and study population

The study had two categories of study population. The first category of study population was cold chain technicians. Cold chain technicians are permanent employees at district vaccine stores. Each Vaccine store had at least two cold chain technicians. In total there were 70 cold chain technicians who were situated at district vaccine stores visited. The second target population was vaccine refrigerators in all district vaccine stores visited. Each district vaccine store had at least two refrigerators. In total there were 85 vaccine storing refrigerators at district vaccine stores.

3.2.4 Sample size

Only 20 cold chain technicians and 25 refrigerators were considered as sample during data collection. The choice of such a sample depended on the challenges faced in this data collection phase mainly caused by financial constraints. We therefore chose to collect data at nearest places hence the sample size couldn't be big enough.

3.2.5 Data analysis

Nine (9) different questions were set to evaluate the respondents' knowledge on vaccine storage standards, cold chain monitoring tools and vaccines storage equipment. Each question was given an option to answer with Yes or No and a space to give more details if any. Answers obtained showed that 100% of all respondents manually record vaccine temperatures on daily basis, they 100% store vaccines into refrigerators, Only 50% were aware of the (2-8ºC) WHO recommended temperature range for vaccines storage, All of the district stores we visited were lacking a proper system for ensuring that vaccines are kept in the acceptable range of temperature. Only cold boxes are used during vaccines transportation which do not have any means of temperature monitoring. 60% of vaccine stores have standby generators for automatic power backup in case of power outages. There is no any remote monitoring tool used for all vaccine stores as well as for vaccine delivery process. Excel packages for descriptive statistics were used for data analysis. We also found that the refrigerators used for vaccines storage have built-in thermometers with a display that provides the readings of the current temperature and cold chain technicians must keep reading on the display to note any possible unexpected temperature change.

Table 3.1: Questions asked and percentage of respondents who replied with "Yes"

S/N	Question Asked	Number respondents who replied "Yes"	Number respondents who replied "No"	Percentage (%) of those who replied with "Yes"
1	Do you use refrigerators to store vaccines?	20/20	0/20	100
2	Do you keep records of vaccine temperatures on daily basis?	20/20	0/20	100
3	Are you aware of the WHO recommended temperature range for vaccines storage?	10/20	10/20	50
4	Do you sometimes experience power outages in your vaccine stores?	20/20	0/20	100
5	Do you have standby generators for backup in case of power outage?	12/20	8/20	60
6	Has power outage once affected stored vaccines?	5/20	15/20	25
7	Do you have any Remote monitoring system to vaccines storage and delivery?	0/20	20/20	0
8	Is vaccines temperature sometimes affected during transportation?	20/20	0/20	100

9	Do you think using an IoT RMS solution can be a right way to address cold chain problems?	20/20	0/20	100

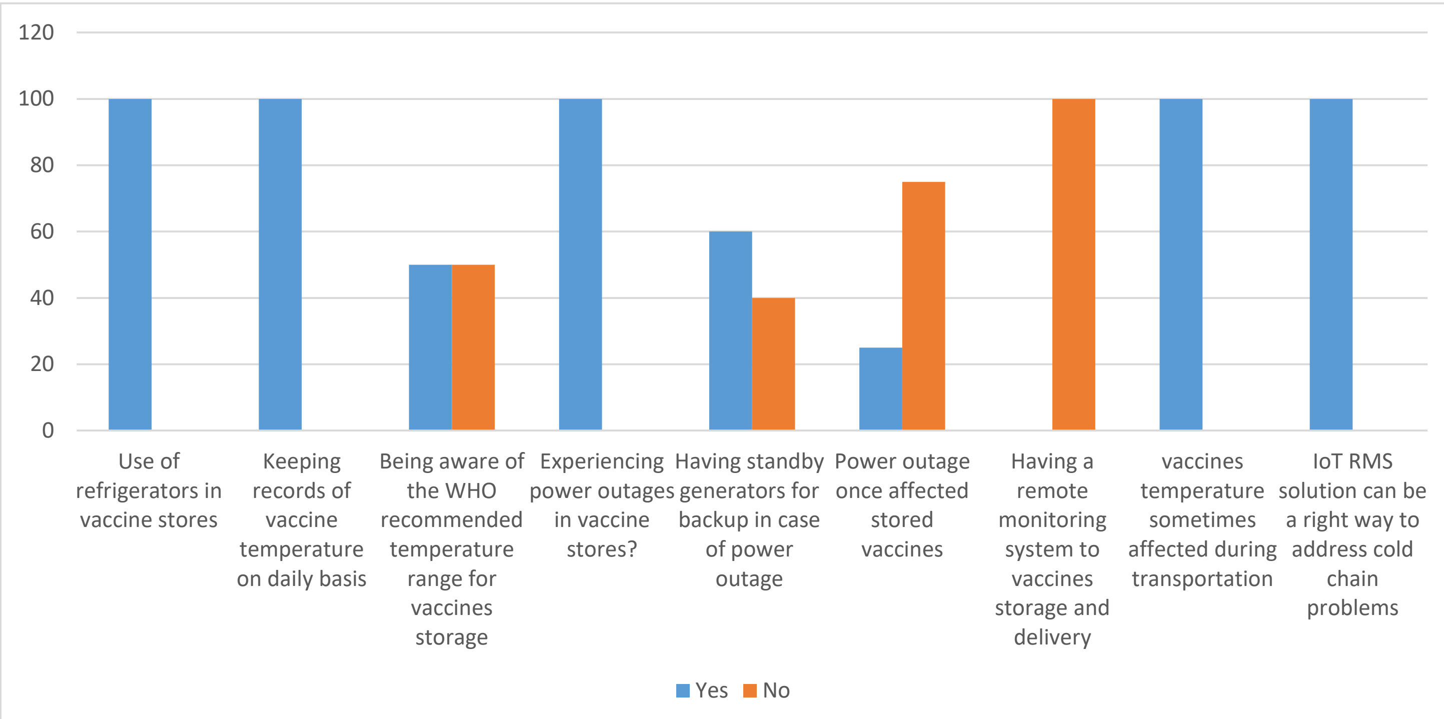

Figure 3.1: Data Analysis chart

3.3 Design and development of the prototype system

Following the identification and assessment of cold chain technicians' needs, we began the design and development of a prototype system, in which both physical and logical components required for the smooth operation of the entire system were modelled, simulated, and evaluated in order to produce a complete cold chain IoT remote monitoring solution.

3.4 Testing the developed cold chain IoT remote monitoring solution for a period of time

The developed IoT RMS solution was tested in a controlled environment, to determine the system accuracy, power management, and connectivity over a given period of time. Data were gathered, including comparison tests to determine the accuracy and durability of various types of sensors to be used in the final IoT RMS product.

Chapter 4: System Design and Prototyping

4.1 Introduction

The prototype design of this research project comprises different hardware and software components, however this chapter provides a description on the architecture of the system prototyped throughout this project. It gives the details about the system development and implementation prototypes on both system delivery and vaccines storage in different selected location. The Internet of Things Remote Monitoring Solution prototype architecture used contains five subsystems. These include sensing part, wireless communication subsystem, user interface and database subsystem. The following paragraphs describe the block diagram of prototype design model.

4.2 Prototype Design model

Our prototype design model consists of two separate parts as per the specific objectives of this project, the remote monitoring solution in vaccine storage refrigerators and remote monitoring solution in vaccine delivery. Different sensor nodes were used although they all collect data and post them in the same database for accurate and better monitoring from one place. The Figure 4.1 shown below, illustrates the block diagram of the IoT Remote Monitoring Solution in storage location, which is the first part of this project.

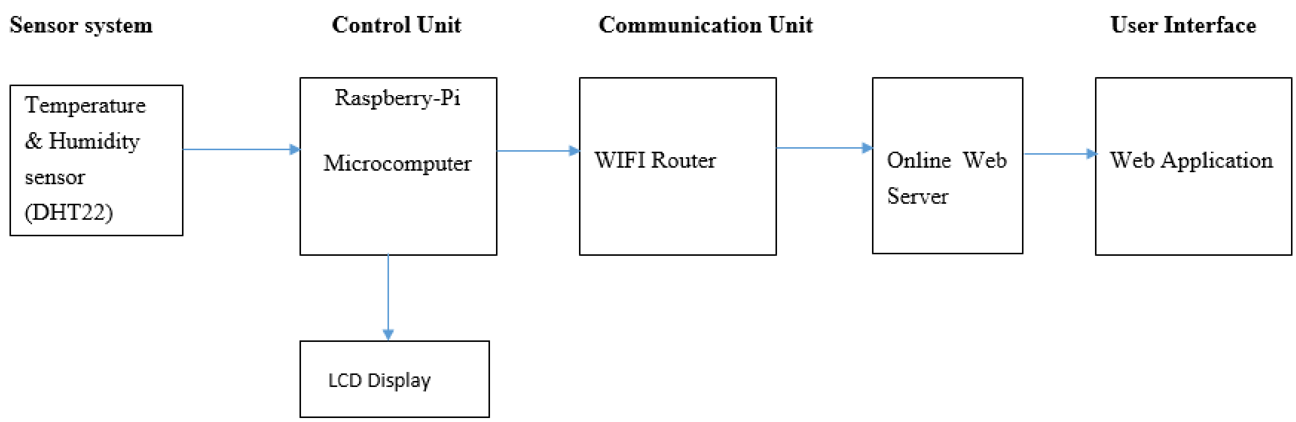

Figure 4.1: Vaccines Storage Remote Monitoring System.

The block diagram shown above explain different phases from collecting temperature to the data visualization point which is web application, the DHT22 sensor was used to capture the temperature and humidity, the control unit for process the data, Wi-Fi router for sending data to server and the user interface web application that allow the user to view and monitor those collected temperature. The Liquid crystal display (LCD) is mounted to the refrigerator to display the temperature value on the field. The second parts is the block diagram that represents IoT Remote Monitoring Solution in vaccine delivery from the country stores to referral and district hospital in Rwanda.

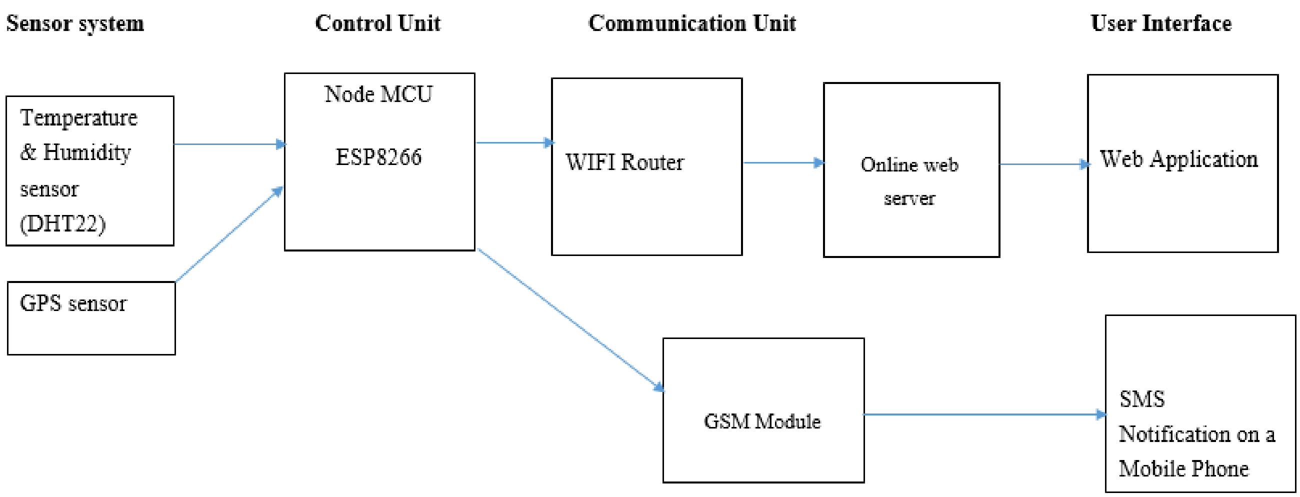

Figure 4.2: Vaccines Storage Remote Monitoring System.

The IoT remote monitoring solution on delivery as indicated in the above figure is composed by temperature and humidity sensors to sense temperature inside the cold box in vehicles, the NodeMCU for processing, Global Positioning System (GPS) sensor was used for easy track of vehicles during vaccine delivery. The geographical coordinate was sent to the mobile phones via Global System for Mobile communication (GSM) to responsible person when there is a change in prescribed temperature, while collected temperature was sent to online database via Wi-Fi router and is going to be monitored on web application using computer and smart phones. The following paragraph presents the details on each subsystem shown in the block diagram.

4.2 Sensing subsystem.

The main focus of this IoT Remote Monitoring Solution for efficient storage and delivery of temperature-sensitive vaccines is the real time monitoring of Temperature in vaccine stores. Vaccines are mostly kept in refrigerator and freezers inside the storage room and cold boxes used in transportation. The sensors used are the temperature sensor in vaccine storage and GPS sensor for sending geographical coordinates during vaccine delivery. The following figure illustrate temperature and humidity sensor, GPS sensor connected to microcontroller.

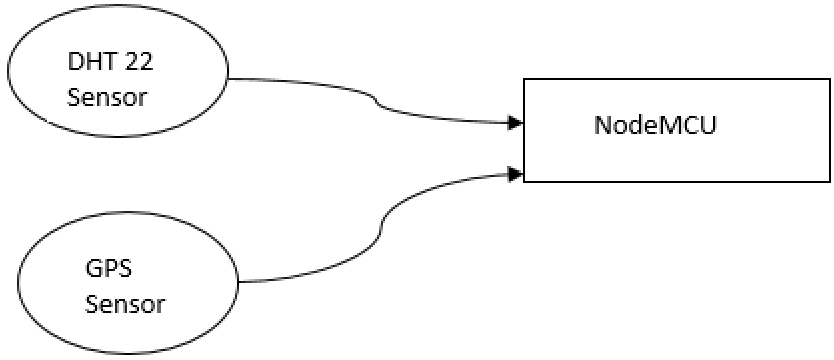

Figure 4.3: The sensing part

A sensor is an electronic device, module, machine, or subsystem that detects events or changes in its surroundings and transmits the data to other electronics, most commonly a computer processor. Sensors are always used in combination with other electronic devices. For our system prototype the Digital Temperature and Humidity sensor (DHT22) have been used to measure daily temperature inside the refrigerators and cold boxes. The temperature-humidity and GPS sensor used during system prototyping are shown in the figures below.

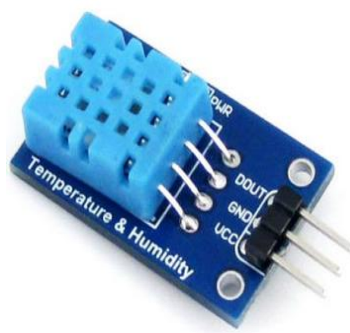

Figure 4.4: The temperature and humidity sensor

Figure 4.5: The GPS sensor

For collecting the sensed temperature during vaccines delivery, DHT22 and GPS sensor were directly interfaced with microcontroller (NodeMCU ESP8266). As seen in Figure 4.6, the ESP8266 Wi-Fi Module is a self-contained SOC with an integrated TCP/IP protocol stack that allows any microcontroller to connect to a Wi-Fi network. The ESP8266 may either host an application or offload all Wi-Fi networking functionality to a separate application processor. This board was designed with platform IO, a cross-platform, and cross-architecture, multi-framework professional Integrated Development Environment (IDE) tool for embedded system and software engineers that write embedded programs. By utilizing Platform to provide a universal IDE interface, hardware programming may be done in a more developer-friendly manner.

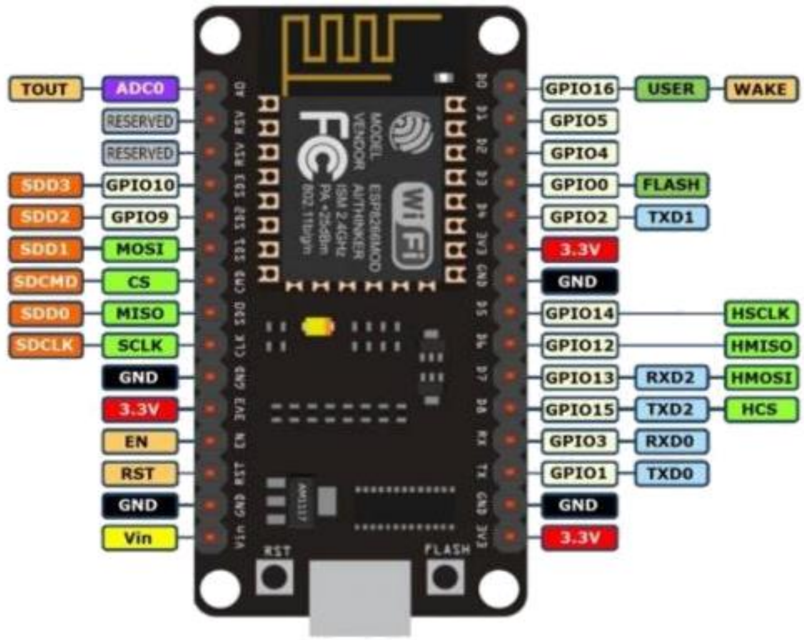

Figure 4.6: The Node MCU ESP8266

As this project complies also the vaccine storage monitoring, in Figure 8, the DHT22 sensor is also connected with the Raspberry Pi 3 for temperature collection in the storage facility. The Raspberry Pi is a low-cost, credit-card-sized computer that connects to a computer monitor or TV and utilizes a conventional keyboard and mouse. It can interface with the outside world and has been used in a variety of digital creative projects. The Raspberry Pi 3 model B+ is the most recent addition to the Raspberry Pi 3 family, with a 64-bit quad-core processor running at 1.4GHz, dual-band 2.4GHz and 5GHz wireless LAN, Bluetooth 4.2/BLE, faster Ethernet, and PoE functionality through a separate PoE HAT [21]. Its processing speed, allowed it to be used and its capabilities to quick communication with web applications rendered the pi to be used in this project. This board was programmed by using python programming.

Figure 4.7: Raspberry pi 3 Model B+

4.3 Wireless Communication System

Any IoT technology allows the end users to access the data collected from field and real-time monitoring, from any place by using different types of wireless or wired communication protocols. After collecting data from different site, the data were sent to the developed cloud platform by using Hypertext Transfer protocol (HTTP) using POST method and these are illustrated in figure 9. HTTP is a standard application protocol that serves as a client-server request-response protocol.

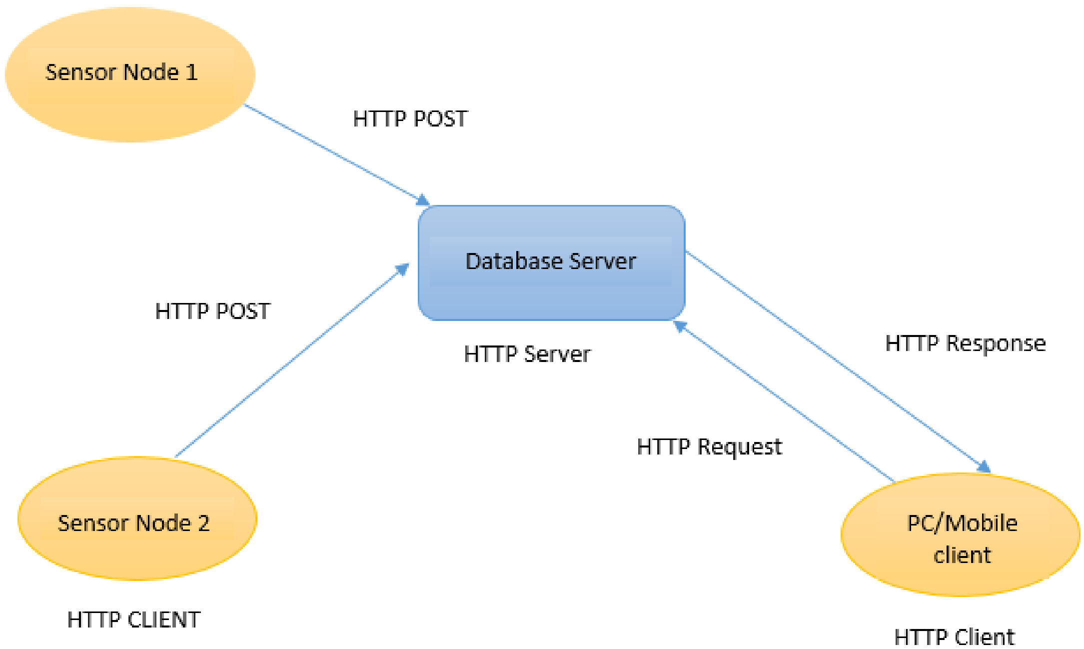

Figure 4.8: HTTP Communication Protocol

During the system prototype implementation the temperature data from DHT Sensor connected to nodeMCU and raspberry pi 3 Model that forms sensor node from different stations are using the HTTP client and sent the data to cloud database server which uses HTTP response and request to communicate with the web clients.

Hypertext Preprocessor (PHP), a widely used open source general-purpose scripting language that is especially suited for online development and can be incorporated into Hypertext Markup Language HTML, is used to obtain the data stored in the database.

The data from many sites is shown on the dashboard developed in Hypertext markup language (HTML), and cascading style sheets were utilized to produce dynamic effects within web browsers using JavaScript, which is an object oriented computer language. The HTTP client aids in the transmission of HTTP requests and the receipt of HTTP responses from the HTTP server. The connectivity between sensor nodes and the web application is depicted in Figure 4.9.

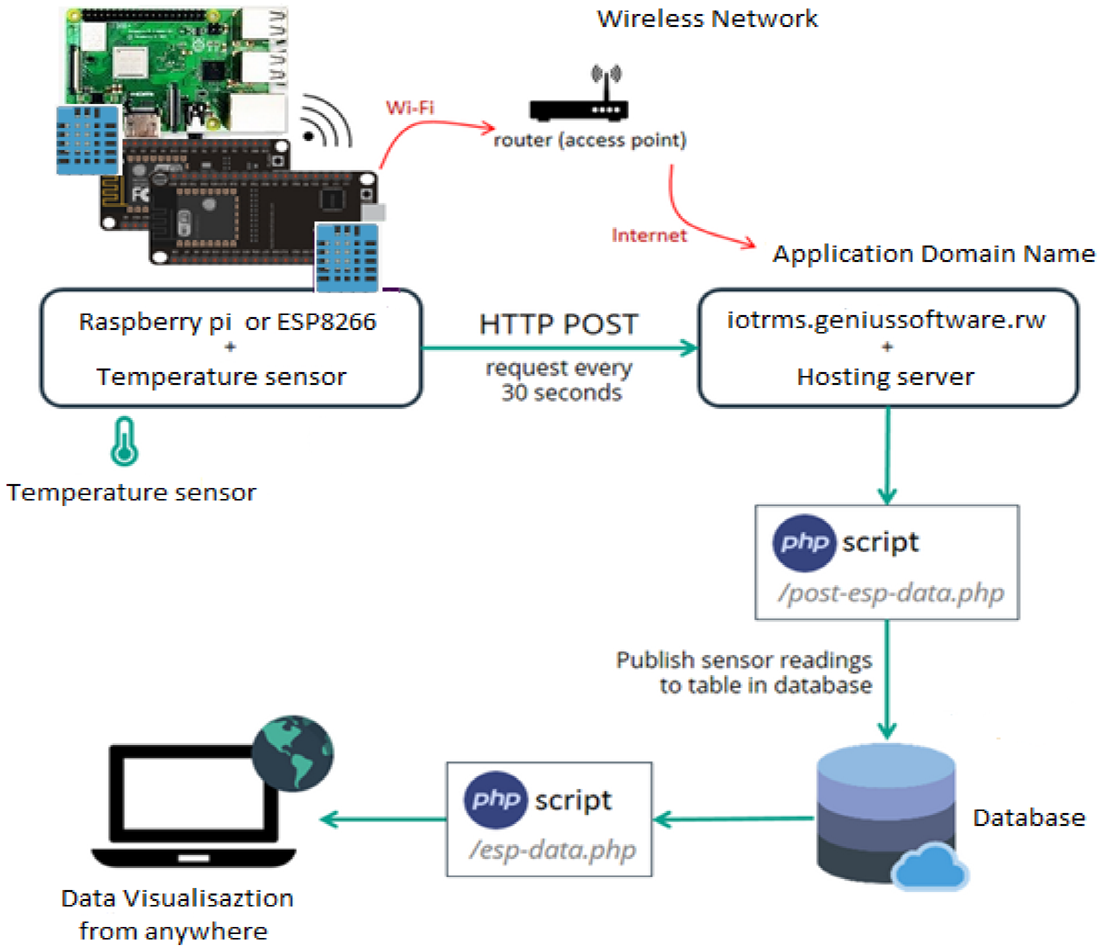

Figure 4.9: Wireless Communication and Web Application

Since this project is dealing with the temperature remote monitoring from different vaccine stores and during vaccine delivery, having your own domain name and hosted account that allow you to access sensor readings from the raspberry pi 3 and ESP8266 is crucial. You can visualize the readings from anywhere in the country by accessing your hosting server with particular domain name over internet connection.

In addition to the vaccine delivery, the system sends SMS notification using GSM, to responsible person in cold chain and coordinates on temperature change. The figure 4.10 show the GSM connectivity between sensor node and mobile phone.

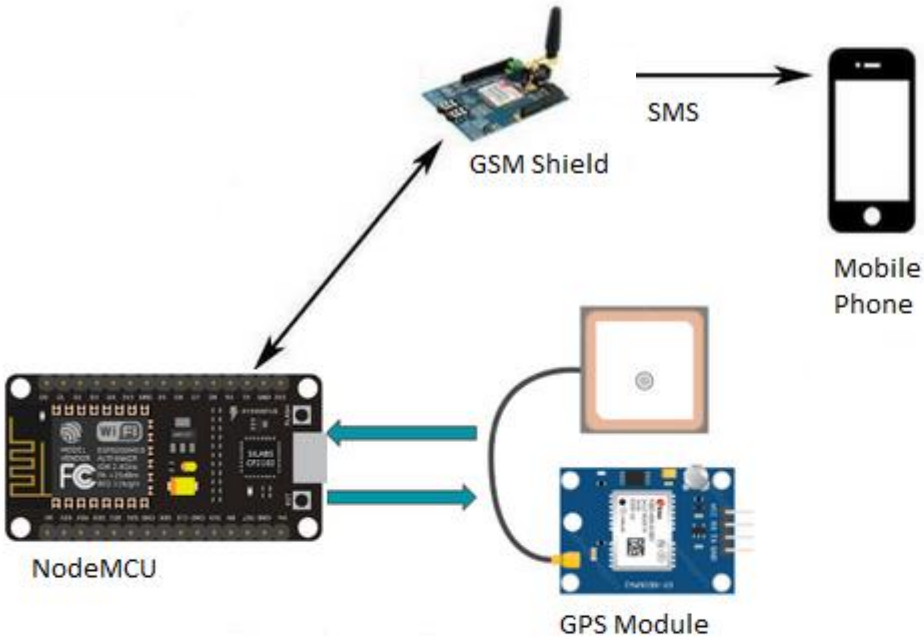

Figure 4.10: GSM Connectivity

4.4 User Interface subsystem

The dashboard was built using Hypertext Markup language and cascading style sheet web applications programming languages during the creation of the user interface for the IoT cloud application, through which the user may observe and monitor the temperature from various stations. This data are sent from different sensor nodes with their respective stations and they are stored to online server. With the use of PHP scripting language, the data were fetched from MySQL database and sent to the dashboard. The data storage and retrieval to dashboard are shown in the figure 4.11.

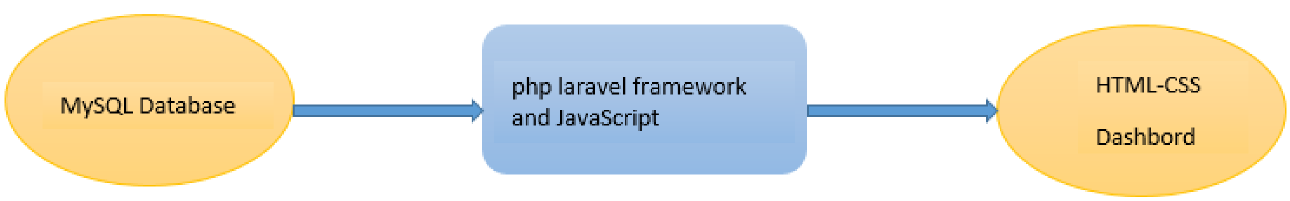

Figure 4.11: Building the user interface

The main dashboard of the internet of thing remote monitoring solution for both storage and delivery of temperature-sensitive vaccine in Rwanda in shown in figure 4.12. Its shows the main page where by each user when he/she open the domain name of the system can enter his/her credentials to login for managing or monitoring the temperature from a station, many stations or delivery routes.

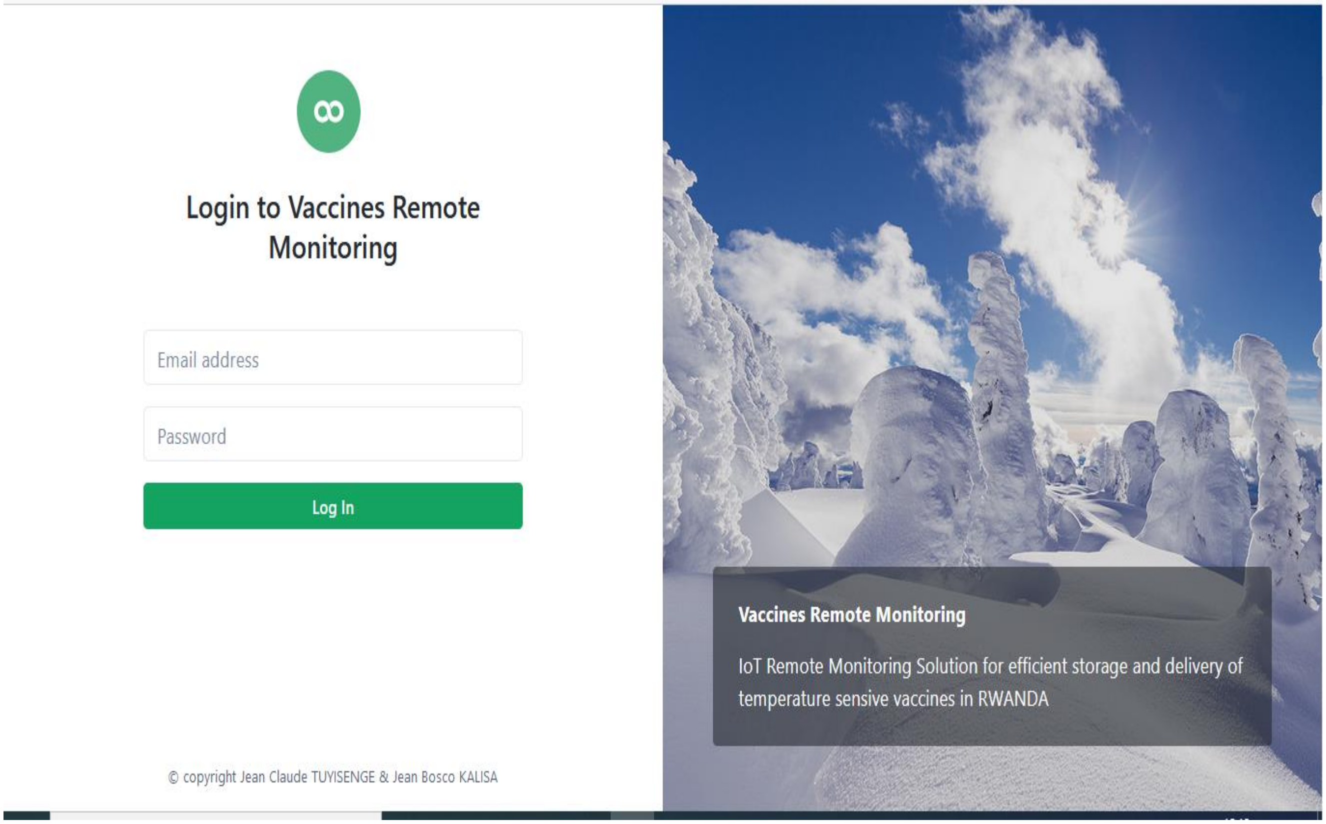

Figure 4.12: Login Screen for Remote Monitoring

The system consist of many different users as it comprises different stations, each single user have the ability to monitor the one assigned station which is really its vaccines storage room. As we stated in our scope, we are currently prototyping, deploying three sensor nodes, two for storage and other during transportation, but we can add many other devices as possible depends on the storage location. The super user also is presented and is able to monitor different location at time and he has also all the privilege of adding users with their respective vaccine storage stations. Figure 4.13 indicates admin dashboard.

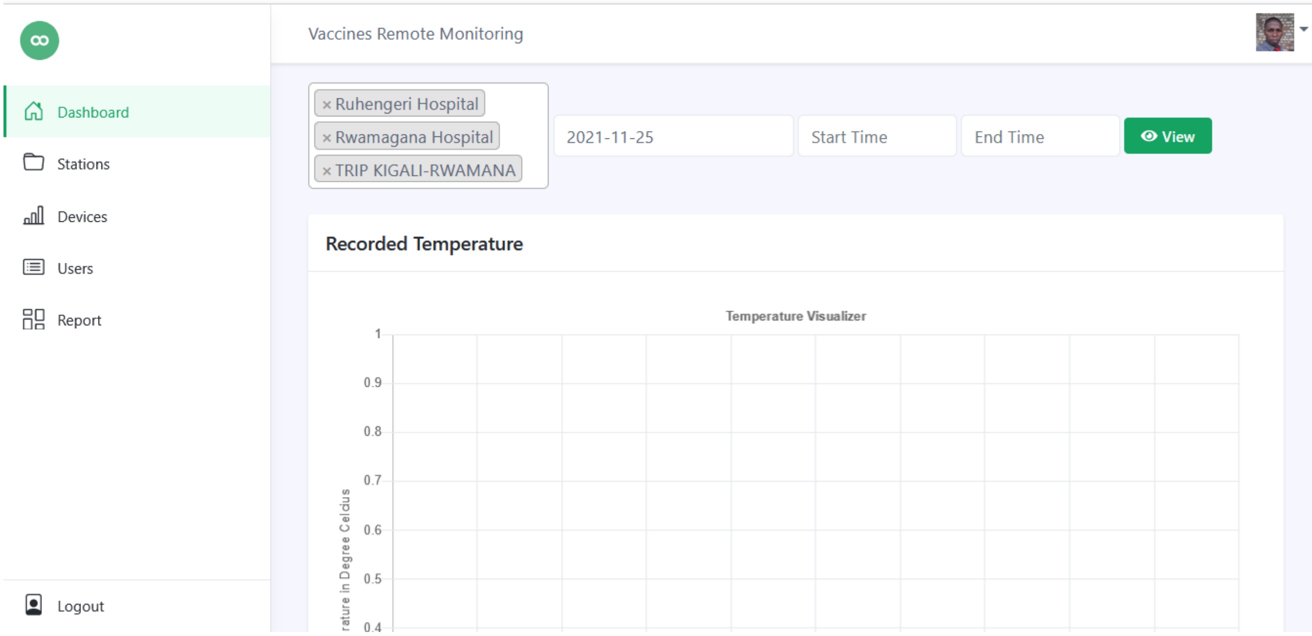

Figure 4.13: Admin Dashboard

The figure 4.15 shown below is the dashboard for site location and their associated sensor nodes. We mainly have 3 active devices from three different location: CHUB Butare, Ruhengeri Hospital, and Trip from Kigali-Rwamagana Hospital.

The devices from Rwamagana Hospital is not currently added by the admin of the system, when it is added and became active it will start posting data to online server and its temperature curves will start to indicate the temperature of refrigerators.

The moment the sensor node is not currently registered in the system the user will no longer see its sensed parameters from the site location. It is possible to remove the devices on the network when it is not in use. The active sensor node are identified by their given names respective to their site location. Last time to which they were connected, last recorded temperature and their last time of synchronization are shown in Figures 4.14.

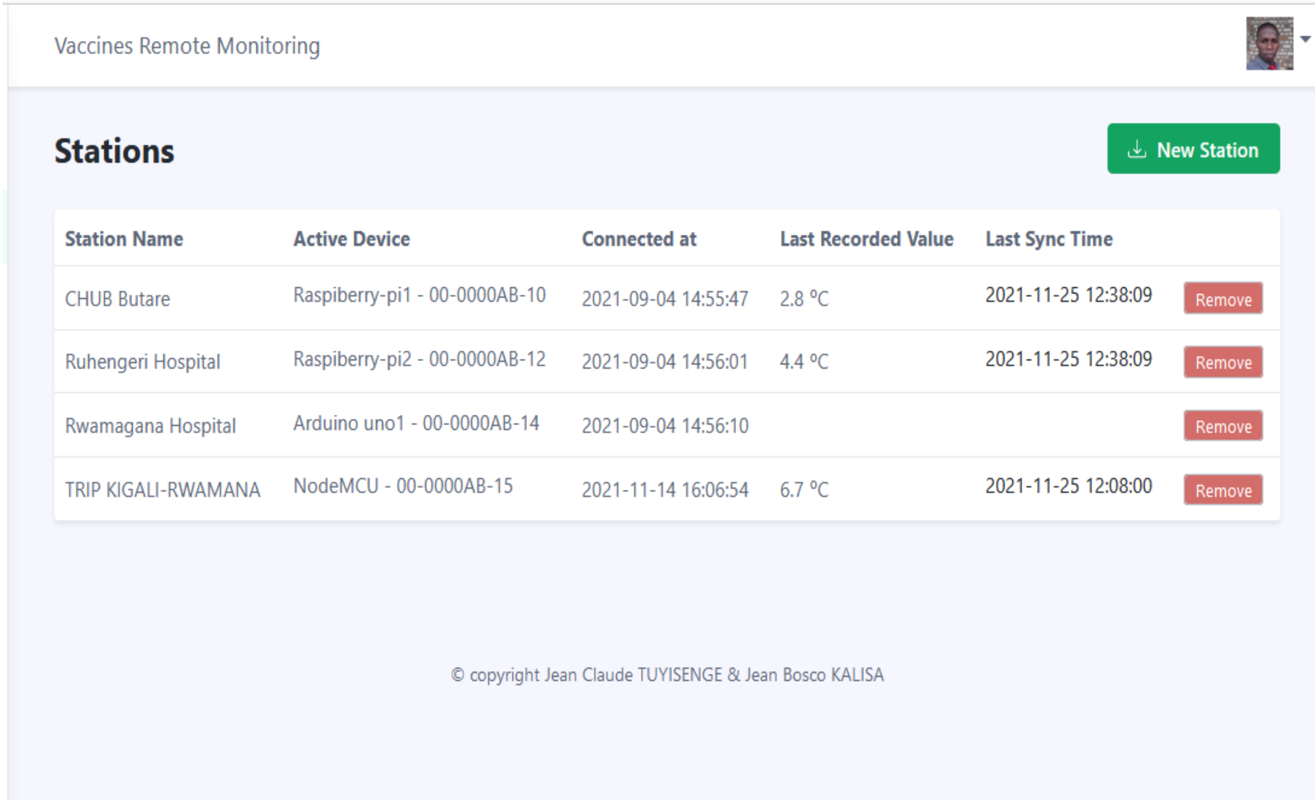

Figure 4.14: Dashboard for the site location

In the figure 4.15 below, the used sensor node are displayed and the administrator of the system can add other sensor node to the added location site, he can also disable the one that is not is use.

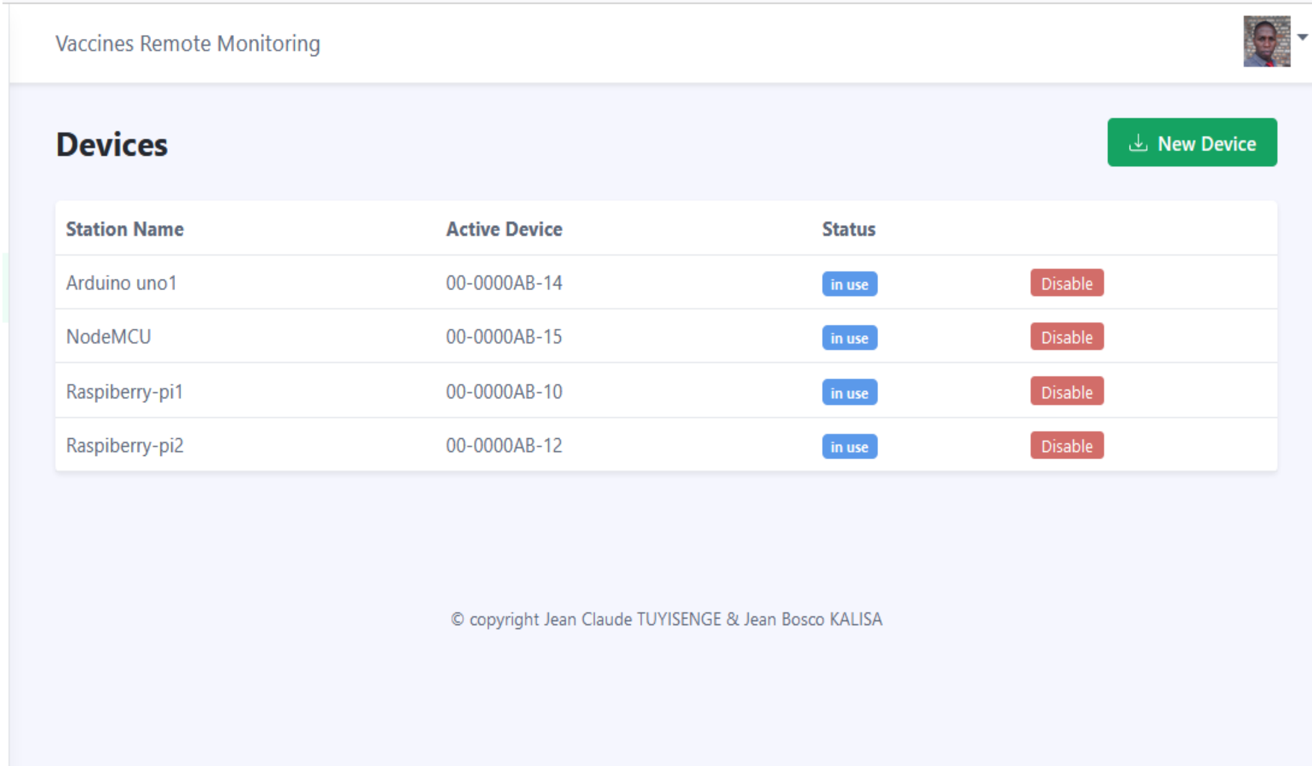

Figure 4.15: Used Sensor node

The Figure 4.16, shows the different users of the system with their different current location, the person in charge of vaccine at site location is the one who is responsible to monitor the temperature from storage room, their account are being managed by the overall admin of the system and he/she is responsible to add new vaccine monitor when there is new appointment and to disable the current one. Each site location user is only allowed to monitor his site.

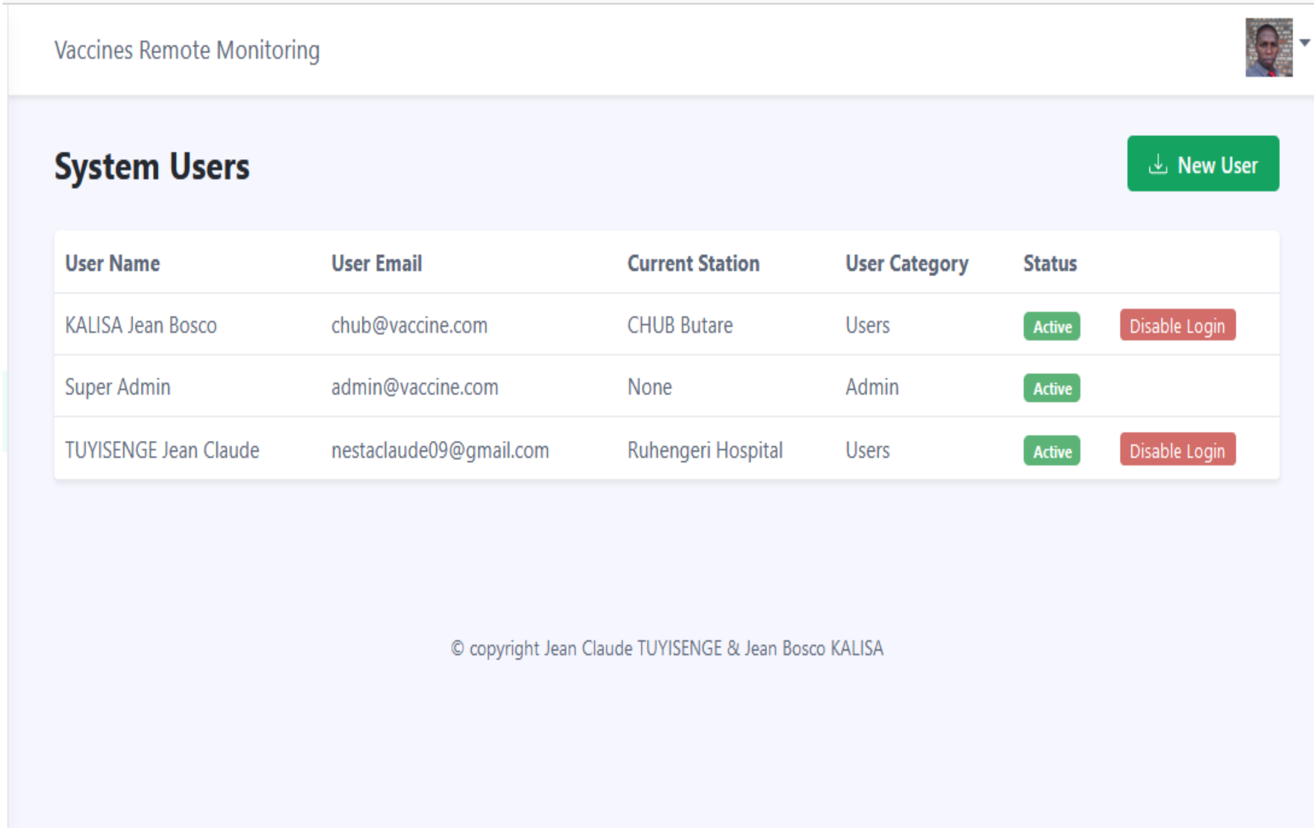

Figure 4.16: Users interface

4.5 Database subsystem

The management of temperature monitoring system from different location site requires online server with database for storing different data collected from various sensor nodes deployed at different site location. And it requires to be managed at site location and also the overall monitoring at national level, therefore the data are collected and stored in different tables that make a database. Below is database design indicating tables and their description in vaccine temperature monitoring system.

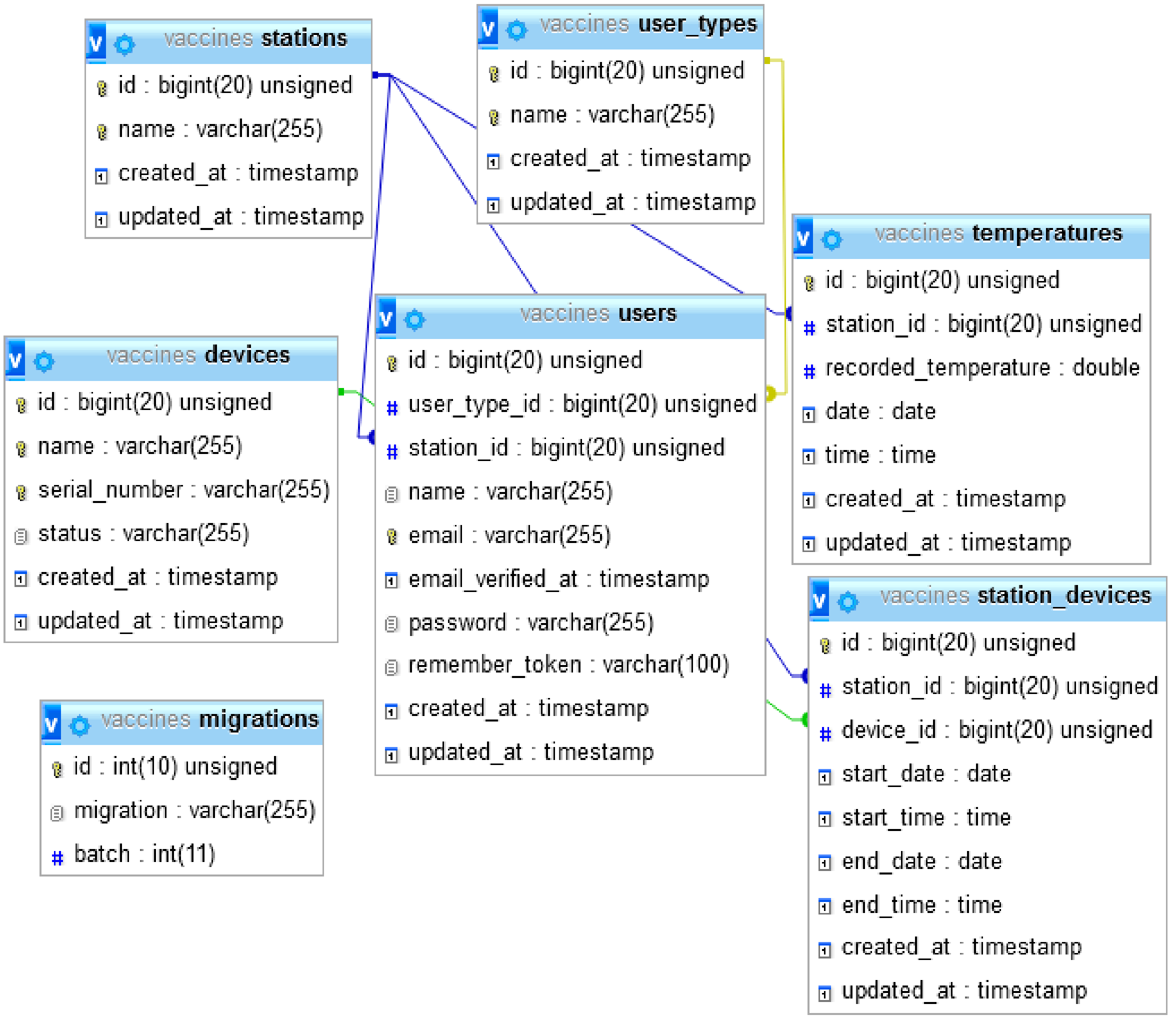

Figure 4.17: Database Design

IoT Remote Monitoring system is made of main tables, each tables stores particular information related to other information in another tables, those tables are: temperature table, station devices table, devices tables, station table and user tables. Temperature tables was used to store the recorded temperature from particular location indicated by station_id, the recorded date and time and the last update time which is time where by a sensor node post its updated temperature in database. The table 4.1 show different fields of the table.

Table 4.1: Table Temperature

id	station_id	recorded_temperature	date	time	created_at	updated_at
1	2	25	2021-09-04	15:40:00	2021-09-04 15:39:35	2021-09-04 15:39:35
2	2	45	2021-09-04	16:50:00	2021-09-04 16:51:17	2021-09-04 16:51:17
3	1	28	2021-09-04	16:55:00	2021-09-04 16:54:46	2021-09-04 16:56:53
4	1	27.6	2021-09-04	17:00:00	2021-09-04 17:01:06	2021-09-04 17:01:06
5	1	27.2	2021-09-04	17:15:00	2021-09-04 17:17:16	2021-09-04 17:17:16
6	1	27.9	2021-09-04	17:35:00	2021-09-04 17:35:00	2021-09-04 17:35:00
7	2	21	2021-09-04	19:30:00	2021-09-04 19:29:03	2021-09-04 19:29:03
8	3	26	2021-09-04	19:45:00	2021-09-04 19:46:01	2021-09-04 19:46:01
9	2	21	2021-10-25	14:30:00	2021-10-25 14:28:02	2021-10-25 14:28:02
10	2	21.5	2021-10-25	15:05:00	2021-10-25 15:06:43	2021-10-25 15:06:43

The following table in project design refers to devices, it was created to store the sensor nodes names and their serial number with the help of differentiating the sensor node location and the ones that have been used in the delivery, their given serial number will be with reference to sites location, their status to indicate whether they are in use or not in use so that the user can assign the sensor node to other site location.it shows the time added to a network and last updated information on online server. The table 4.2 describes its fields.

Table 4.2: Device Table

id	name	serial_number	status	created_at	updated_at
1	Raspiberry-pi1	00-0000AB-10	in use	2021-09-04 14:54:26	2021-09-04 14:55:47
2	Raspiberry-pi2	00-0000AB-12	in use	2021-09-04 14:54:54	2021-09-04 14:56:01
3	Arduino uno1	00-0000AB-14	in use	2021-09-04 14:55:20	2021-09-04 14:56:10

In Table 4.3 shows different site location of vaccine storage and the route during vaccine delivery, those four selected different locations, it stores site locations and the delivery trip, each location has the assigned sensor node to collect data at their respective site location.

Table 4.3: Vaccine site

id	name	created_at	updated_at
1	Rwamagana Hospital	2021-09-04 14:52:49	2021-09-04 14:52:49
2	Ruhengeri Hospital	2021-09-04 14:53:15	2021-09-04 14:53:15
3	CHUB Butare	2021-09-04 14:53:28	2021-09-04 14:53:28
4	KIGALI-RWAMANA	2021-09-21 18:08:07	2021-09-21 18:08:07

In the table 4.4: station device show the association of two tables linked by the primary key in table station and devices, as I have mentioned above every sensor nodes is associated to a particular site location, and each site location has only one device to which it have to collect temperature and post it in online sever for monitoring.

Table 4.4: Station Device

id	station_id	device_id	start_date	start_time	end_date	end_time	created_at	updated_at
1	3	1	2021-09-04	14:55:47	*NULL*	*NULL*	2021-09-04 14:55:47	2021-09-04 14:55:47
2	2	2	2021-09-04	14:56:01	*NULL*	*NULL*	2021-09-04 14:56:01	2021-09-04 14:56:01
3	1	3	2021-09-04	14:56:10	*NULL*	*NULL*	2021-09-04 14:56:10	2021-09-04 14:56:10

The last table 4.5 in database design is for storing the user of the IoT remote monitoring solution, it is normally subdivided into two categories: administrator of the system with overall privileges of accessing the system, other users are site location users responsible for controlling and monitoring the dairy record of the system.

Table 4.5: User Table

id	user_type_id	station_id	name	email	email_verified_at	password
1	1	NULL	Super Admin	admin@vaccine.com	2021-09-04 14:37:05	$2y$10$g8XXkMPljmy/J2l/kwoiqO41Y6x.
2	2	2	TUYISENGE Jean Claude	nestaclaude09@gmail.com	NULL	$2y$10$zQ0ljiFdjgZyWyfOCrmX8uOTkVr
3	2	3	KALISA Jean Bosco	chub@vaccine.com	NULL	$2y$10$ePTRml7sz69Zkzce94DBw.DJ0z

Chapter 5: Results and Analysis

5.1 Overview

The expected results of the IoT RMS solution for efficient storage and distribution of temperature-sensitive vaccines in Rwanda are provided and discussed in this chapter. It describes the results obtained from sensors to user interface of the system during prototype implementation and the graphs of temperature variations from different location where sensors are deployed. As we worked on both vaccine delivery and storage, we present the data from two different prototypes. The common result from both prototypes is the temperature which is monitored through a web application interface. The other result is an SMS notification from delivery monitoring system which is sent to the cold chain technician's mobile phone to show exactly the location of vaccines during transport and the change in temperature if any.

5.2 Vaccine delivery sensor node's output

The temperature vaccine monitoring prototype on delivery consists of temperature and humidity sensor with GPS sensor, all are connected on nodeMCU, by giving it the instructions to post the collected temperature, the results show that the temperature is recorded into database as the response from HTTP request.

The following Script on Figure 5.1, was used to check whether the controller is connected on wireless network and start posting the sensed data in database. A sensor node (client) uses components of a URL (Uniform Resource Locator), which contains the information needed to reach a server resource, the request is sent after 10 second.

```
if(WiFi.status()== WL_CONNECTED){
    WiFiClient client;
    String server_name="https://iotrms.geniussoftware.rw/api/00-0000AB-14/"
    HTTPClient http;
    http.begin(client,server_name);
    http.addHeader("Content-Type","application/x-www-form-urlencoded");
    String httprequest="data=all";
    int responsecode=http.POST(httprequest);
    Serial.println(server_name);
    Serial.print("Responsecode is: ");
    Serial.println(responsecode);
    http.end();
}
      delay(10000);

```

Figure 5.1: POST request Data to database

The results from the above request on the figure 5.1 is shown in the figure 5.2, showing the response code of 200. This code indicates that the request to send the temperature value has been recorded successfully into the database.

```
PROBLEMS    OUTPUT    TERMINAL    DEBUG CONSOLE

Responsecode is: 200
Current humidity = 64.00%  temperature = 24.80C
http://iotrms.geniussoftware.rw/api/00-0000AB-15/24.8/data
Responsecode is: 200
```

Figure 5.2: Response from Server

5.3 Vaccine storage sensor node's output

The DHT22 sensors connected to raspberry pi were used in vaccine storage temperature monitoring. The raspberry pi is programmed in python script as shown in the Figure 5.3. Most of Vaccine stores are connected to internet. This motivated us to use raspberry pi with its capability to connect easily to internet through either Wi-Fi or wired network infrastructures. Another important feature is its high processing speed and excellent interaction with the web application.

```python
import sys
import Adafruit_DHT
import time
import requests

while True:
    try:
        humidity, temperature = Adafruit_DHT.read_retry(11, 4)

#       URL = 'http://192.168.43.186:8000/api/00-0000AB-10/%s/data' % temperature
        #URL = 'http://10.10.0.13:8000/api/00-0000AB-10/%s/data' % temperature
        URL = 'https://iotrms.geniussoftware.rw/api/00-0000AB-10/%s/data' % temperature
        data = {'temp':temperature, 'serial_number':'00-0000AB-10'}

        #print ("Temp: %s C  Humidity: %s " % (temperature, humidity)
        print ("requested url %s " % URL);
        r = requests.post(url = URL, data = data)
        pastebin_url = r.text
        print("The API RESPONSE is:%s"%pastebin_url)
    except requests.exceptions.ConnectionError as err:
        print("Network issue found: Please check the network connection: ", err)
    time.sleep( (60*3) )

```

Figure 5.3: Python Script of Raspberry pi

The result of the script running in raspberry pi is shown in the figure 5.4, indicating how data collected are sent in database, for the storage the is set to be sent after 2 minutes for avoiding power consumption and overloading the server.

```
pi@raspberrypi:~ $ python~ test_temp.py
bash: python~: command not found
pi@raspberrypi:~ $ python3  test_temp.py
requested url https://iotrms.geniussoftware.rw/api/00-0000AB-10/26.0/data
The API RESPONSE is:{"success":true,"message":"Temperature recorded!"}
requested url https://iotrms.geniussoftware.rw/api/00-0000AB-10/26.0/data
The API RESPONSE is:{"success":true,"message":"Temperature recorded!"}
requested url https://iotrms.geniussoftware.rw/api/00-0000AB-10/26.0/data
The API RESPONSE is:{"success":true,"message":"Temperature recorded!"}
requested url https://iotrms.geniussoftware.rw/api/00-0000AB-10/29.0/data
The API RESPONSE is:{"success":true,"message":"Temperature recorded!"}
requested url https://iotrms.geniussoftware.rw/api/00-0000AB-10/27.0/data
The API RESPONSE is:{"success":true,"message":"Temperature recorded!"}
requested url https://iotrms.geniussoftware.rw/api/00-0000AB-10/26.0/data
The API RESPONSE is:{"success":true,"message":"Temperature recorded!"}
requested url https://iotrms.geniussoftware.rw/api/00-0000AB-10/25.0/data
The API RESPONSE is:{"success":true,"message":"Temperature recorded!"}
requested url https://iotrms.geniussoftware.rw/api/00-0000AB-10/25.0/data
The API RESPONSE is:{"success":true,"message":"Temperature recorded!"}
requested url https://iotrms.geniussoftware.rw/api/00-0000AB-10/26.0/data
The API RESPONSE is:{"success":true,"message":"Temperature recorded!"}
```

Figure 5.4: Raspberry posting data to database

5.4 Data visualization

During our prototype implementation, we assume the deployment of three sensor nodes on three different location, Rwamagana referral hospital, Ruhengeri referral hospital, CHUB Hospital for vaccine storage and one trips from Kigali to Rwamagana for vaccine delivery, The Data were collected from those different sensor devices and visualized on dashboard. The figures 5.5, 5.6 and 5.7 show the temperature collected in time intervals from CHUB, Ruhengeri Hospital and one round trip from Kigali to Rwamagana respectively. They have to be visualized by the cold chain technician from each site.

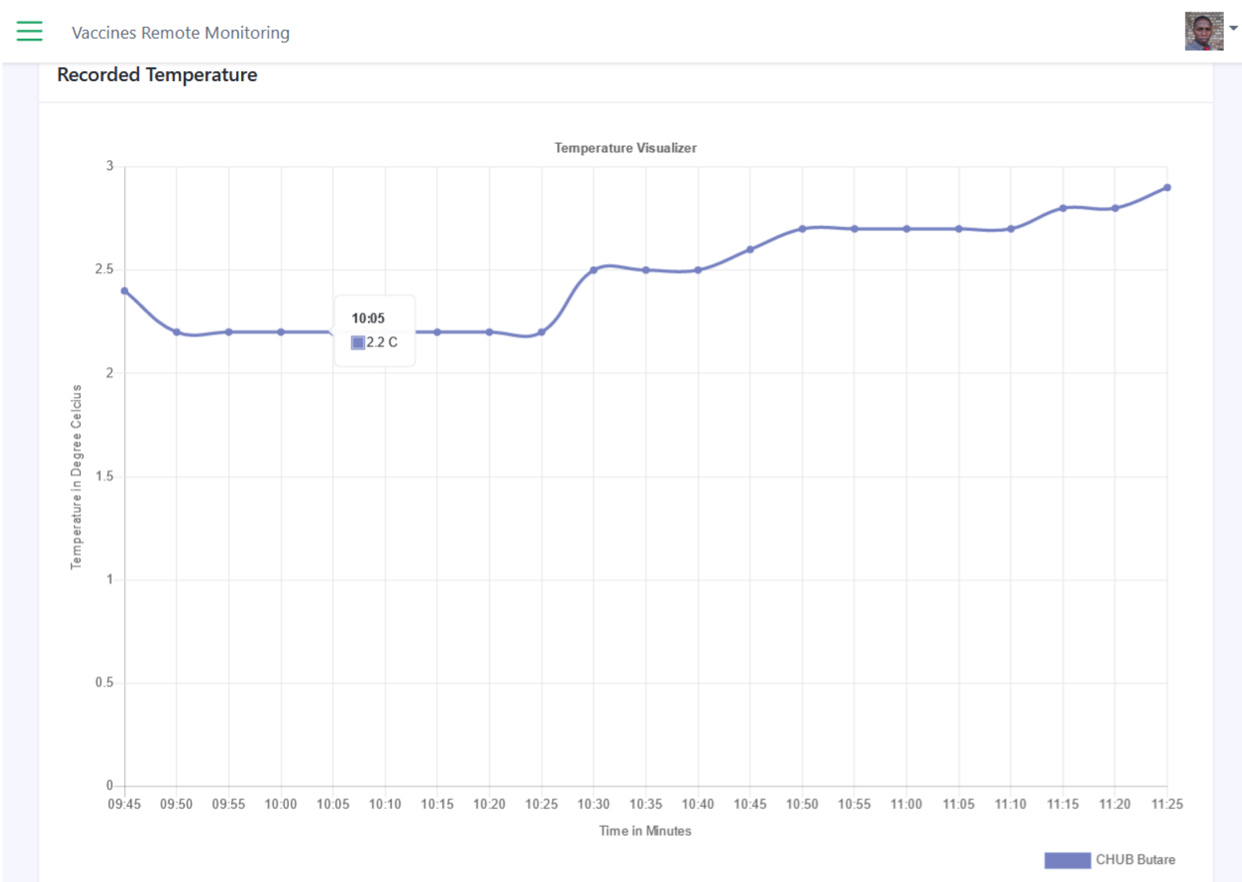

Figure 5.5: Temperature monitoring from CHUB

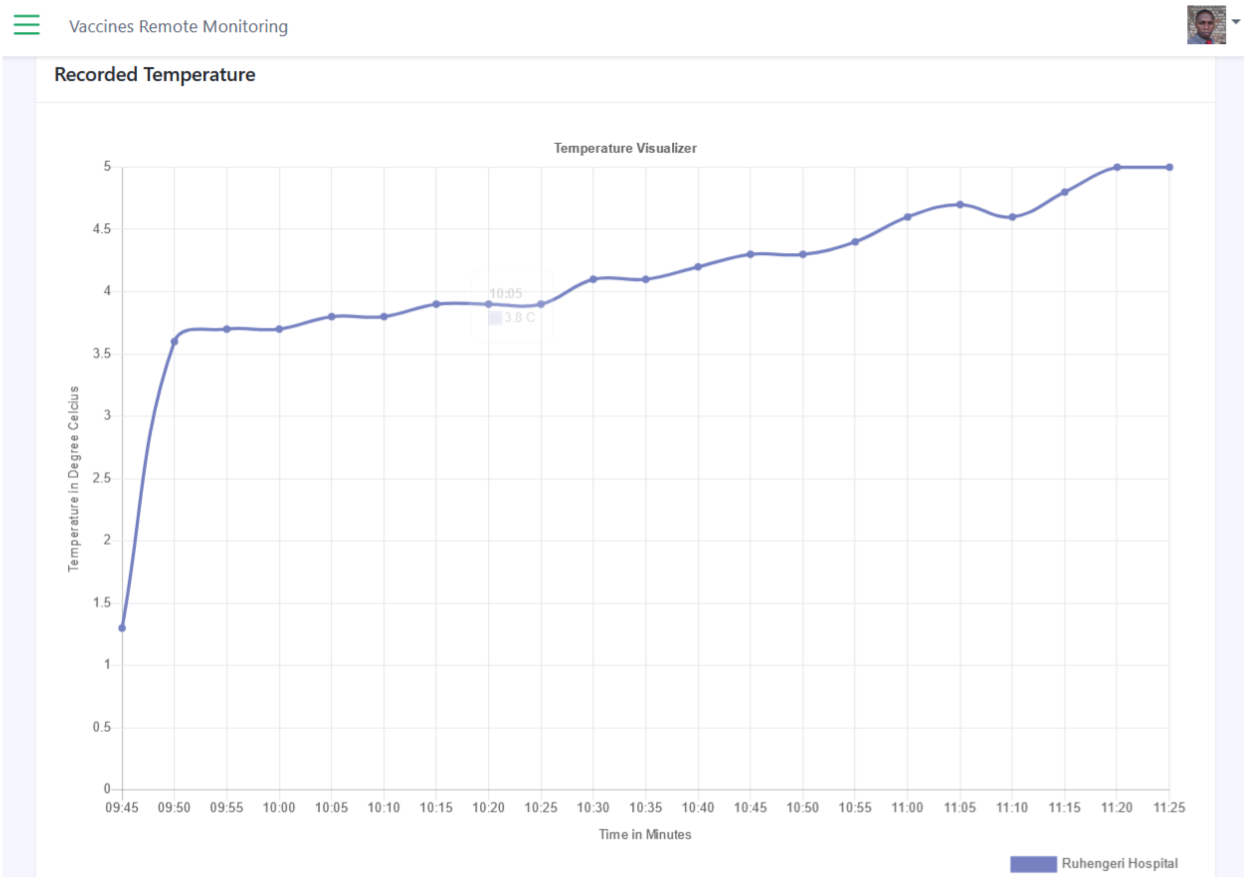

Figure 5.6: Temperature visualization from Ruhengeri Hospital

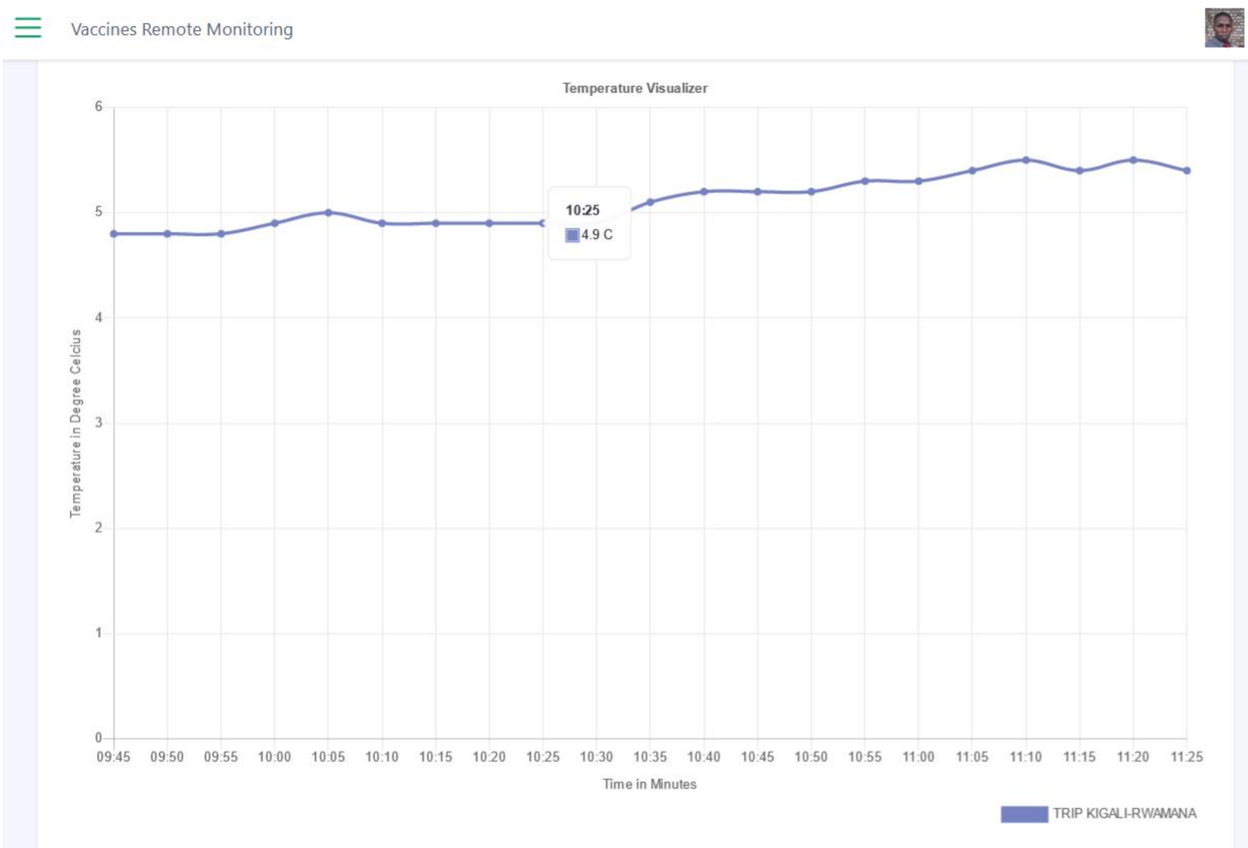

Figure 5.7: Temperature visualization from on vaccine delivery from Kigali to Rwamagana

The Figure 5.8 below represents the temperature data visualized from three different sites on a single dashboard. On the vertical axis temperature values in degrees Celsius are indicated while the horizontal axis indicates the times intervals to which the temperature was recorded. As it is observed on the graphs slight temperature decrease and increase from each site has not gone below or above the temperature range recommended by WHO.

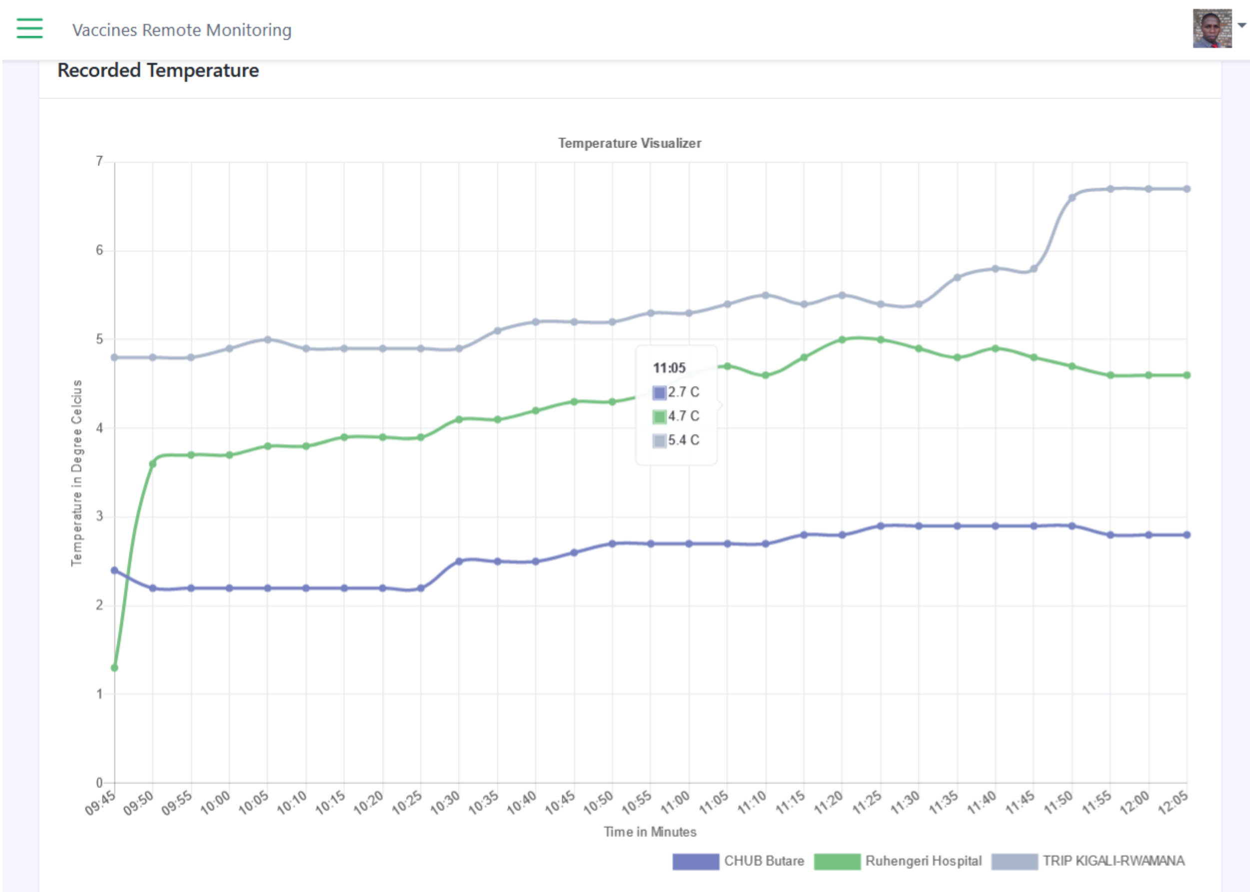

Figure 5.8: Temperature collected from different site location

5.5 SYSTEM ACCURACY ANALYSIS

5.5.1. Comparison

As discussed in the chapter two of this report, several studies have been conducted to address the challenges of vaccines cold chain. Although they can be used for monitoring vaccines temperature they have a relatively long delay to deliver data to the user interface. They also rely on a local storage which is a very big challenge for remote access of data. The table below provides a comparison of the existing cold chain monitoring systems to the designed system in this thesis project.

Table 5.1: comparison of the designed system to the previous works

Previous works	**Technology used**	**Data communication**	**Delay**	**Storage**
National Vaccine Stores Temperature Recording System Khartoum, Sudan [13].	Computer	Wireless connection	Not mentioned	local
Temperature Recording System in National Vaccine Stores Tehran, Iran [13].	Data logger	Wireless connection	Not mentioned	local
FoneAstra [14].	*microcontroller-based programmable device(Microcontroller type not specified)*	Netbook server, *GSM modem.*	3-10min	local
In Kenya, Remote Temperature Monitoring and Data use teams [1].	Microcontroller (not specified)	Server- SMS	10 min	online
In the World Health Organization (WHO) Management Handbook[6].	electronic shipping indicator, a programmed electronic temperature and event logger system, Temperature threshold indicator	Immediate reading	N/A	local

CURRENT WORK	Raspberry pi, Node MCU.	Server -SMS	5 Sec	Online

In this work, the online server has been used to store the collected temperature from the refrigerators, and this is more advantageous compared to the local storage, since it provides easy access on the data anywhere. The delay to post data to an online dashboard was reduced significantly to 5sec to enable the real time monitoring of vaccines temperature.

5.5.2. Data analysis

The accuracy of data generated by the designed system has been compared to three different data generated by the existing systems. As observed on the figures below, the data from other existing system present much fluctuations where some of them have gone above and below the WHO recommended range. This may be caused by malfunctioning of used equipment and sensors which need to be replaced or maintained. The data from the designed system lie between 2.5 and 4 degree Celsius which is a normal range for vaccine storage. According to the efficient of our designed system the data generated do not present much changes.

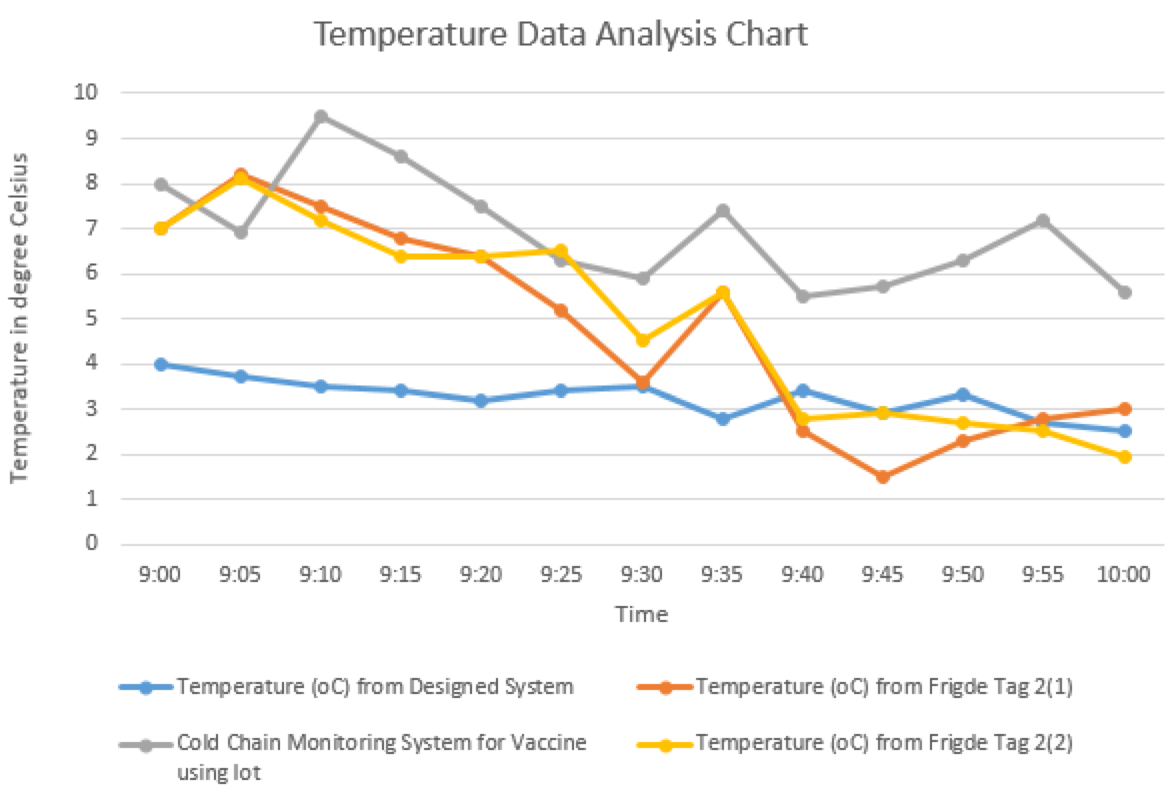

Figure 5.9: Data Analysis Chart

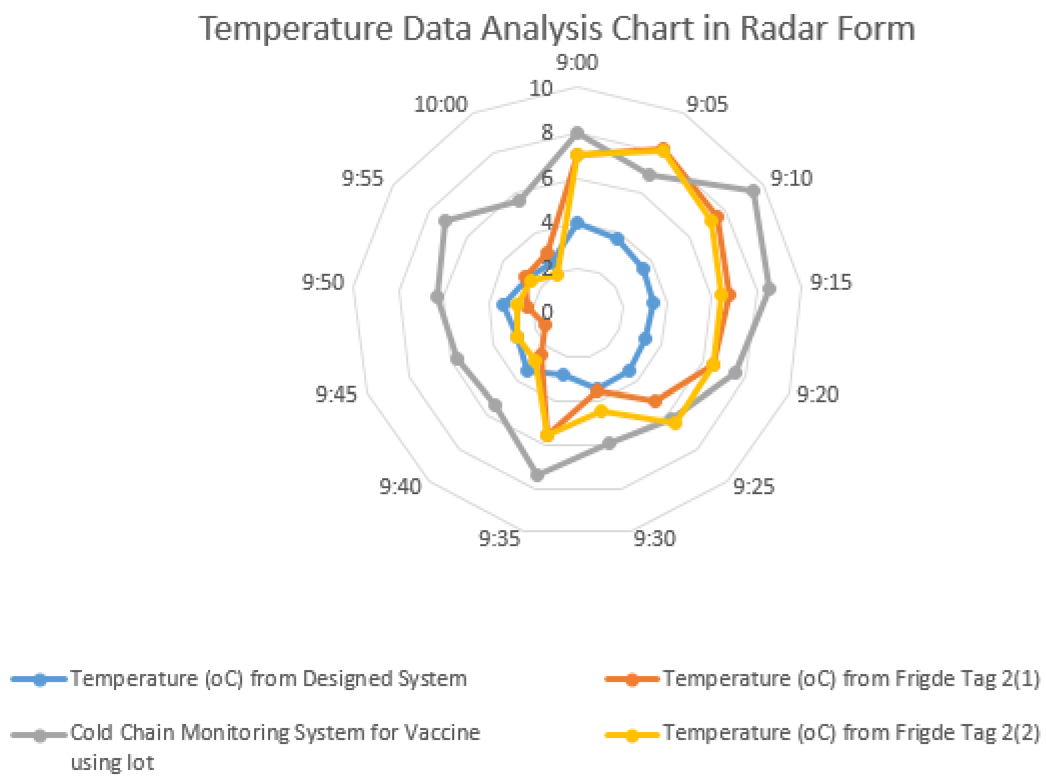

Figure 5.10: Data Analysis chart in Radar Form

For different site locations, the cold chain technicians can monitor different temperature data from any site location of their choice. Users can select one or more than one locations he/she want to observe either at real time or visualize it at selected time interval. The system allows users to generate the daily report on the temperature variations at a specified time interval.

The figure 5.9 below represents the report generated from the system between 9:45 AM and 15:25 PM on 25th November 2021 at Ruhengeri Hospital Vaccines Stores.

Temperature Recorded

Time	Recorded Temperature 2021-11-25
	Ruhengeri Hospital
09:45	1.3^{0}C
09:50	3.6^{0}C
09:55	3.7^{0}C
10:00	3.7^{0}C
10:05	3.8^{0}C
10:10	3.8^{0}C
10:15	3.9^{0}C
10:20	3.9^{0}C
10:25	3.9^{0}C
10:30	4.1^{0}C
10:35	4.1^{0}C
10:40	4.2^{0}C
10:45	4.3^{0}C
10:50	4.3^{0}C
10:55	4.4^{0}C
11:00	4.6^{0}C
11:05	4.7^{0}C
11:10	4.6^{0}C
11:15	4.8^{0}C
11:20	5^{0}C
11:25	5^{0}C
11:30	4.9^{0}C
11:35	4.8^{0}C
11:40	4.9^{0}C
11:45	4.8^{0}C

Figure 5.11: Temperature Data Report

Chapter 6: Conclusion and Recommendations

6.1 Conclusion

The findings of this research revealed that the existing cold chain monitoring approach has a number of drawbacks. These include the manual vaccine temperature recording, intermittent power outages and insufficient knowledge of cold chain monitoring technics. It is expected that the designed system will help to save a big number of vaccines which were wasted because it is able to collect vaccine temperatures, detect changes in temperature and alert users whenever the detected temperature goes above or below the WHO recommended range. A web application has been designed to help cold chain technicians view vaccine temperature data anytime and anywhere. In addition a GPS/GSM module has been added to send the notification to cold chain technicians in case of any temperature excursion during vaccine delivery.

6.2 Recommendations

The research thesis is recommending the following:

- Cold chain technicians' knowledge gap has to be address by continuous capacity building through trainings to enable them use the new technology to ensure cold chains are well monitored.
- Intermitted power outages constitute a big challenge too, availing standby generators and the use of renewable energy resources such as solar energy especially in rural areas can help mitigate this problem.
- Refrigerators should be fitted with remote monitoring systems since they lack WHO-recommended temperature monitoring devices, making it impossible to monitor temperatures on weekends and holidays.
- More efforts are needed to develop both infrastructural capacity and acquire adequate cold chain equipment in order to maintain a safe and efficient cold chain.
- Future researchers are recommended to scale up the project such as increase the sample size to get more data and possibly develop a mobile application to enhance the designed cold chain monitoring solution.

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Appendices

Appendix A: Introductory letters for data collection

UNIVERSITY of RWANDA

ACEIoT

Website: www.aceiot.ur.ac.rw
Mail: aceiot@ur.ac.rw

COLLEGE OF SCIENCE AND TECHNOLOGY

To: Director General of Rwamagana Hospital. **September 23th, 2021**

Eastern Province, Rwanda

Dear Sir/Madam,

Subject: Introductory letter for data collection, for ACEIoT Master's students,

Mr Kalisa Jean Bosco and **Tuyisenge Jean Claude**

This is to introduce **Mr Kalisa Jean Bosco** with reference number **220014146** and **Tuyisenge Jean Claude** with reference number **220014128**, master's students who are doing their research for master's thesis under the Africa Center of Excellence in Internet of Things (ACEIoT) established at the University of Rwanda (UR), College of Science and Technology (CST) in the program of Embedded Computing Systems (ECS).

Their research title is "**Internet of Things Remote Monitoring Solution for efficient storage and delivery of temperature-sensitive vaccines in Rwanda**." Th students need to collect data related to their thesis from the Hospital under your responsibility.

Your support with the needed information will be highly appreciated.

Dr Damien HANYURWIMFURA

Ag. Director, ACEIoT

College of Science and Technology

University of Rwanda

Tel: 0787394447

AFRICAN CENTER OF EXCELLENCE IN INTERNET OF THINGS
ACEIoT
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ACEIoT

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COLLEGE OF SCIENCE AND TECHNOLOGY

To the Director General of Ruhengeri Hospital. **September 23th, 2021**

North province, Rwanda

Dear Sir/Madam.

Subject: Introductory letter for data collection, for ACEIoT Master's students,

Mr Kalisa Jean Bosco and **Tuyisenge Jean Claude**

This is to introduce **Mr Kalisa Jean Bosco** with reference number **220014146** and **Tuyisenge Jean Claude** with reference number **220014128**, master's students who are doing their research for master's thesis under the Africa Center of Excellence in Internet of Things (ACEIoT) established at the University of Rwanda (UR), College of Science and Technology (CST) in the program of Embedded Computing Systems (ECS).

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UNIVERSITY of RWANDA

ACEIoT

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Mail: aceiot@ur.ac.rw

COLLEGE OF SCIENCE AND TECHNOLOGY

To: Director General of Muhima Hospital.

Kigali, Rwanda

September 23th, 2021

Dear Sir/Madam

Subject: Introductory letter for data collection, for ACEIoT Master's students,

Mr Kalisa Jean Bosco and **Tuyisenge Jean Claude**

This is to introduce **Mr Kalisa Jean Bosco** with reference number **220014146** and **Tuyisenge Jean Claude** with reference number **220014128**, master's students who are doing their research for master's thesis under the Africa Center of Excellence in Internet of Things (ACEIoT) established at the **University of Rwanda** (UR), College of Science and Technology (CST) in the program of Embedded Computing Systems (ECS).

Their research title is "**Internet of Things Remote Monitoring Solution for efficient storage and delivery of temperature-sensitive vaccines in Rwanda.**" The students need to collect data related to their thesis from the Hospital under your responsibility.

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Dr Damien HANYURWIMFURA

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Appendix B: Questionnaire used for data collection

UNIVERSITY of RWANDA

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MASTERS RESEARCH PROJECT

QUESTIONNAIRE FOR DATA COLLECTION

The purpose of this questionnaire is to gather preliminary information from cold chain technicians. With this information, an Internet of Things Remote Monitoring Solution will be designed and it will aid in preserving vaccine efficacy in the vaccine supply chain, as well as preventing vaccines from being thrown away owing to heat or freezing conditions in fixed storage facilities or during delivery.

Questionnaire Instructions:

Please take a moment to answer the following questions. Include any more information or descriptions in the comments section. Use N/A for Not Applicable (enter under Comments)

S/N	QUESTIONS	YES	NO	COMMENTS
1	Do you store vaccines in refrigerators? If NO, mention the other means you use in comments			
2	Do you keep records of vaccine temperatures on daily basis? If Yes, Use the space provided in 'Comments' to mention the minimum and the maximum temperatures recorded yesterday.			

3	Are you aware of the WHO recommended temperature range for vaccines storage? If yes mention it in Comments.			
4	Do you have a proper way to ensure that the recommended range is maintained? If yes describe it briefly in comments.			
5	Is vaccines temperature sometimes affected during transportation?			
6	Do you have means to ensure vaccines efficacy during their transportation? If yes, briefly describe it in comments and mention any challenges associated with it.			
7	Do you sometimes experience power outages in your vaccine stores? If Yes, how long does it take and how do you deal with such a challenge? Use the space provided in comments to answer to this question.			
8	Does power outage have the effect on vaccine stores? If YES, what are they? Use the space provided in comments to answer.			
9	Do you have any Remote monitoring system to vaccines storage and delivery? If Yes, Describe it briefly in comments and mention the communication technology used as well some challenges associated with it.			

Please use this space to provide any other information that can be helpful to this survey.

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Declaration – To the best of my knowledge, I declare that the above statements and information provided are accurate.

Signature………………………………………………………… Date…………………………………..