Development of a monitoring system and power management for an IoT based vaccine carrier

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Abstract. The development and implementation of automated system to monitor the temperature, humidity, and location of a vaccine carrier in real-time are presented in this paper. All the collected data are sent via SMS and also stored on an SD card to prevent the loss of any data. The weak power infrastructure is one of the challenges in the developing countries which brings into consideration the overall power management and power saving modes of the carrier. The monitoring system and vaccine carrier have been powered from the same source: by either using the vehicle battery or portable batteries. The current consumption of the individual components has been reduced up to 92% and the overall current consumption of the system has been reduced by 8%. Being able to monitor the vaccine storage conditions and the carrier location remotely in real-time, and maintaining low power consumption at the same time, would allow to reduce the vaccine wastage rates and can be very effective in increasing the vaccine outreach in developing and undeveloped countries.

1. Introduction

Vaccines, an assured way for disease immunizations, still remains unavailable to the mass population in a lot of developing countries. This unavailability of vaccines results in a yearly worldwide death toll of 2.5 million. Moreover, there are 19.4 million infants who are not receiving their regular immunizations [1]. On the other hand, vaccines are extremely temperature-sensitive where any discrepancy hampers the potency. Therefore, to ensure the viability of the vaccines, a management system named vaccine cold chain system is extensively adapted to maintain the optimum temperature of the vaccine carriers during transportation and storage.

World Health Organization (WHO), the governing body for global healthcare, sets the storage temperature range to be 2-8°C for most vaccines. They have specified procedures about the regular monitoring and reporting about the storage conditions. There are several WHO approved devices that are used to monitor the temperatures and to maintain the cold chain, such as vaccine vial monitors (VVM), temperature loggers and freeze indicators [2]. However, there are lack of availability of sensors and data loggers as well as well-trained people in the developing and undeveloped countries.
Another major concern for the transportation of vaccines in developing countries is the breach of the cold chain. The conventional vaccine carriers that are mostly used in developing countries, use ice packs and cool water packs to maintain the temperature of the vaccines. Usually, the functional period for such carriers is 3 to 18 hours for water packs and 18 to 50 hours for ice packs. The breach in the cold chain is most common during this transportation period since traveling to the most remote areas to reach the health centers can take anywhere between two to seven days [3]. The lack of transparency in the transportation process further makes it difficult to monitor the cold chain. According to the studies carried out in various developing and undeveloped countries mentioned in [4], some of the greatest challenges in maintaining the cold chain includes the lack of proper power supply in all parts of the countries and a lack of performance management of the cold chain. The data in the study indicates that almost 70% of the health facilities faces challenges in accessing sufficient power and even though there are occasional cold chain performance checks, no routine systems are in practice. These lead to the wastage of a large amount of the vaccines in the underdeveloped countries [4]. According to WHO, 50% vaccines are wasted globally every year because of these issues related to temperature control and vaccine transfer [5]. The breach of the cold chain is so severe in some cases that on average, 39.54% of vaccines are wasted at the session site and almost 25% of vaccines are wasted even before it can reach the children [6]. Besides, almost 30% of vaccines get lost in transportation even before reaching the health centers, and there is no accountability for such occurrences.

Numerous researches have been carried out till date to develop carriers and modules to prevent the breach of the cold chain. However, for a vaccine carrier to be efficiently used on field, a few basic characteristics needs to be present. These include, an efficient cooling system, continuous monitoring facilities with minimum delay, power saving features to provide sufficient battery backup in the field and portability of the carrier. From the various works done, the vaccine carriers reported in [7][8] do not use electrical cooling systems, rather these designs improved the existing ice pack carriers to prevent freezing. These carriers however do not have any monitoring features and also there still remains the problem regarding the ice packs not lasting beyond 50 hours, which means they are not suitable for travelling to the remote regions. The vaccine carrier reported in [9][10] on the other hand developed thermoelectric coolers with optimum power consumption, which are more efficient than the ice pack carriers, but these do not include any kind of monitoring facilities. The vaccine carriers in [11][12] have developed monitoring facilities for the carriers but these have limitations in the power saving features and the portability of the carrier. In [11], the monitored data from the carrier is sent to a remote server with the help of Bluetooth and Wi-Fi technologies which proved to be inefficient since it resulted in large delays in sending the data. Again, the carrier in [11] can be powered using a vehicle battery or a portable 12V battery, but the battery do not have a backup time large enough to allow it to be carried on foot to the distant areas. In [12], this same system as [11] was improved and along with sending the data to a server, SMS communication was also included. But the problem about the low backup time remained and in addition to it, the microcontroller needs to be connected to a computer to monitor the received data which hampers the portability of the carrier. The designs in [13]-[15] introduced the concept of a monitoring system for the vaccine cold chain using the traditional ice pack coolers, however, no further improvements have been reported. Also, although the carrier in [13] consumes less power, the battery chargers are always required to be plugged in with the main power supply with hinders portability.

Considering the limitations of the existing carriers, this research has designed and developed an IoT based vaccine carrier. In the proposed design, a thermoelectric module is used in the container to maintain the optimum temperature. The monitoring system monitors the temperature, humidity and location of the vaccine carrier and can also determine if the carrier has been opened in order to prevent the loss of vaccines during transportation. It also keeps the data stored onboard so that no data is lost due to bad network conditions. The carrier and monitoring module are designed using a single power source. It is possible to switch the power source between the vehicle battery and portable batteries which provides backup for 18.5 hours. In addition, the power consumption of the entire module during
the idle period is reduced to ensure longer hours of operation while still providing real-time monitoring.

The rest of the paper is organized as follows. In section II, the design and implementation of the proposed carrier is discussed. Performance evaluation of the proposed design is described in section III where experimental data are considered for analyses. Conclusion and future works are later discussed in section IV.

2. Design and Implementation
The design and implementation of the entire work can effectively be divided into two parts: the monitoring system and the power management. The basic diagrams can be seen in Figure 1.

2.1. Monitoring System
As shown in Fig. 1(a), the monitoring module for the vaccine carrier has been constructed using Arduino Uno as the core component. The system records the temperature and humidity inside the vaccine carrier at a definite regular interval. For temperature and humidity sensing, a Grove temperature and humidity sensor based on a digital DHT11 sensor has been used. The Grove temperature sensor is used in this case particularly because it provides more precise temperature and humidity measurements compared to other similar DHT11 based sensors and also has a larger measurement range. The other commonly available versions of DHT11 sensors have a temperature resolution of 1°C whereas the Grove sensor have the temperature resolution of 0.1°C and it also utilizes capacitive humidity measurement components providing a more accurate humidity reading [16][17]. Hence considering the importance of precise temperature and humidity measurements needed in this work, the Grove temperature sensor is most suitable. This sensor records the temperatures inside the vaccine carrier and the Arduino determines whether the temperature inside the carrier is within the optimum range. A light dependent resistor (LDR) is connected to the Arduino. The characteristics of the LDR of varying resistance with light exposure helps to determine if the carrier lid has been opened. A very simple and commonly available LDR model has been used in this work which inexpensive and very small in size, so that it can be easily integrated within cold chamber. A GSM_GPS_GPRS module based on SIM808 is connected to the Arduino which provides the location information of the carrier including the latitude, longitude and the date and time of the journey. This module further sends SMS notifications to the user at regular intervals with the temperature and location data. Another function of the GSM_GPS_GPRS module is to send the data to a server. An SD card module is connected to the system which stores all the sensed data in an external SD card, to ensure that the data is not completely lost even if no network is available for the data to be shared via SMS. The entire monitoring system is integrated with the vaccine carrier as a single unit. The temperature sensor and LDR are positioned inside the cooling chamber, while the microcontroller and GSM modules are placed outside the cooling chamber. All the components, however, are integrated with the overall structure of the carrier so that there are no moving parts.
2.2. Power Management

The power supply system is designed to utilize a single source to power the entire system as shown in Fig. 1(b). The supply system has been designed keeping in mind that at some point in the journey the vaccine carrier box will have to be carried on foot so, it must be portable and provide sufficient backup.

The power source of the system can either be the lithium polymer batteries or the vehicle battery using a cigar jack. Two buck converters are used to step down the voltage from 12 V to the necessary voltage level of the components of the monitoring module since the thermoelectric system of the vaccine carrier requires 12 V supply, whereas the control module and communication module require 5V and 9V, respectively.

For suitable battery selection, several factors such as cost, portability and maximum output capacity are considered. The most suitable battery to be used in this case, are lithium polymer batteries which are of lower weight and can provide a greater output capacity. Although the cost of lithium polymer batteries is greater than that of other batteries such as lead-acid batteries; but the capacity and portability are more important considerations in this case.

To calculate the current consumption of the Arduino and GSM module, it is necessary to know the “active mode” current \( I_{\text{active}} \) and “data transmission” current \( I_{\text{Data}} \) as well as the respective times to stay active \( T_{\text{active}} \) and for data transmission \( T_{\text{Data}} \) of these components. The average current consumption over an hour can be calculated using (1).

\[
I_{\text{Average}} = \left( (I_{\text{active}} \times T_{\text{active}}) + (I_{\text{Data}} \times T_{\text{Data}}) \right) / 3600
\]  

For the microcontroller-based control unit, observing the real time data transmission for one minute, indicated that 5 seconds are required for data transmission, and current consumption during this period is 25 mA along with the regular active mode current of 25 mA. In case of GSM_GPS_GPRS module, the data transmission duration is 8 seconds and current consumption during this period is 2 A including the 300 mA active mode current.

During transportation of the vaccines, data will be sent to the user at an interval of 15 minutes, which means 4 times in an hour. Considering that the temperature might reach the threshold values and it will be necessary to send the data more frequently, it is considered that data might be sent 8 times in an hour. The voltage and current requirements of the individual components are listed in Table 1. Among these, the power requirements of the thermoelectric module and cooling fans are predefined and fixed.

The power consumption of the microcontroller and communication units are calculated using (1).

| Components           | Voltage | Current  |
|----------------------|---------|----------|
| Thermoelectric cooling module | 12 V    | 6 A      |
| Cooling Fans         | 12 V    | 500 mA   |
| Microcontroller Unit | 5 V     | 25.27 mA |
| Communication Unit   | 9 V     | 330.22 mA|

The remaining components require small amount of power to function compared to these and are powered directly from the Arduino.

Considering the voltage and current requirements, the power supply of the system is 12 V and the total current requirement is 6.85 A. The batteries used in this work each can supply 12 V and 1.5 A. Hence,
the power supply of the system consists of five lithium polymer batteries connected in parallel to meet the current consumption requirements of the system. The capacity of each battery is 30 Ah. However, it is essential to drain lithium polymer batteries only up to 80% of the capacity to maintain the efficiency. So the usable capacity of the batteries ($C_{\text{usable}}$) can be calculated using (2).

$$C_{\text{usable}} = 80\% \text{ of normal capacity}$$  

This gives the capacity of each battery as 24 Ah and the total capacity of the system containing five batteries as 120 Ah.

An important feature of this design is to provide sufficient backup to the carrier to be able to carry it on foot to the most remote regions. The backup time of the system can be estimated using (3).

$$\text{Backup time} = \frac{\text{Battery capacity}}{I_{\text{Average}}}$$  

With an average current of 6.85 A, the vaccine carrier is designed to operate for 17.5 hours using the portable power supply system.

3. RESULTS AND DISCUSSION
To verify the performance of the system, the temperature and humidity are monitored using both vehicle battery and portable batteries. The accuracy of the location tracking is tested in a vehicle. The current consumption and duration are measured using digital multimeter and oscilloscope. For testing the accuracy of the monitoring system, a simpler prototype carrier model has been implemented as shown in Figure 2.

3.1. Temperature and Humidity Monitoring
To verify the functions of the monitoring module, an experimental setting is setup inside a room. Figure 3 shows the temperature and humidity data inside the carrier that are recorded at three different ambient temperatures (24°C, 23°C and 22°C) for 190 minutes each.
Since a thermoelectric cooling system has been used, the temperature inside the carrier reduces based on the ambient temperature. The lower the ambient temperature, the lower will be the temperature inside the cooling chamber, with 2°C being the lowest in this case. In case of humidity, naturally, there exists an inverse relationship between temperature and humidity, which is maintained inside the box as well.

3.2. Location Tracking and SMS Notifications

In order to verify the accuracy of the location tracking and sending of SMS to the user, an experimental setup is made inside a vehicle. The vaccine carrier is transported along a test route of around 31 km from Mohammadpur, Dhaka to Zinda Park, Narayanganj, Bangladesh. The GSM mode of the communication module has been used in this case to acquire the GSM location of the carrier while on a moving vehicle and each time the location is send via SMS to the user at an interval of 20 minutes along with the temperature and humidity reading. If the temperature values are at threshold (less than 3°C or greater than 7°C), the SMS notifications are sent at an interval of 2 minutes. There was no delay in receiving the SMS notifications even outside the city limits.

When the acquired latitude and longitude data is plotted on Google maps, the resulting route of travel can be viewed as in Figure 4. Using the GSM technology implies that the location that is acquired is the location of the nearest cell tower. Therefore, the exact location of the vehicle at every instance is not received, however the overall travel route can be traced accurately. Besides, if the carrier lid is opened at any instant, a separate text notification is sent along with the current location of the carrier.
3.3. Data Storage in SD Card

Since the carrier is to be transported to the most remote regions, it is possible that at any instance of the journey, there will be no available cellular network. That would result in permanent loss of data. In order to prevent this, all acquired data is saved on an external SD card.

3.4. Power Management

As explained in Section II-B, the battery backup acquired without any power saving features is 17.5 hours. In order to increase the battery backup time, the microcontroller and communication modules are kept in sleep mode and only activated when required. The current consumption \( (I_{\text{sleep}}) \) is significantly reduced during sleep time duration \( (T_{\text{sleep}}) \) and in this case, the average current of Arduino and GSM_GPS_GPRS module can be calculated using (4).

\[
I_{\text{Average, sleep}} = ((I_{\text{Active}} \times T_{\text{Active}}) + (I_{\text{Data}} \times T_{\text{Data}}) + (I_{\text{sleep}} \times T_{\text{sleep}})) / 3600 \tag{4}
\]

Table 2 shows the current consumption of Control Unit and Communication unit for all modes while also mentioning the duration of each mode in the span of a minute.

| Components                        | Mode         | Current | Duration |
|-----------------------------------|--------------|---------|----------|
| Microcontroller based control system | Sleep        | 15 mA   | 50 secs  |
|                                   | Active       | 25 mA   | 5 secs   |
|                                   | Data Transmission | 50 mA | 5 secs   |
| Communication Module              | Sleep        | 25 mA   | 50 secs  |
|                                   | Active       | 100 mA  | 10 secs  |
|                                   | Data Transmission | 500 mA | 0.015 secs |

Using (4) the average current consumption of the microcontroller in sleep modes can be calculated as 15.22 mA and the current consumption of communication module has been reduced to 26.35 mA. Thus, the total current requirement of the system is reduced to 6.54 A. As a result, the battery backup time can be increased to 18.5 hours. A comparison of the regular and sleep mode current consumption can be seen in Table 3.

| Components                        | Normal Mode | Sleep Mode |
|-----------------------------------|-------------|------------|
| Microcontroller based control system | 25.27 mA  | 15.22 mA   |
| Communication Module              | 330.22 mA  | 26.35 mA   |
| Overall (including thermoelectric cooler) | 6.85 A    | 6.54 A     |
Even though considerable reduction can be seen in the individual currents of the Control Unit and Communication modules, the overall current has not reduced to that extent because most of the current consumption in this case is by the thermoelectric cooling module.

3.5. Comparison

As mentioned in section I, several studies have been reported on improving the cold chain system of vaccines, however, very few of these studies involve a monitoring system or improved power supply methods. A comparison of the reported modules that include a monitoring system with this work is presented in Table 4.

Even though the monitoring system in [13], which use a traditional cold box for storage, has a low power consumption; the chargers need to be always plugged in with the main power supply. In addition, it has a significant delay in the communication system. The designs presented in [14] [15] do not show any significant improvement. In [11] and [12], thermoelectric modules are used to maintain optimum temperature; however, large amount of power is necessary to drive the monitoring module and the data communication system has significant delay.

| Table 4. Comparison of the current work with previous studies. |
|---------------------------------------------------------------|
| Power consumption | Data communication | Delay | Local storage |
| [13] 2010 | FoneAstra – 50 mA Mobile device – 5 mA | SMS and Server | 3-10 minutes | Yes |
| [14] 2014 | Not mentioned | Server/SMS based on availability | Significant delay due to poor connection | Yes |
| [15] 2014 | Not mentioned | SMS | Not mentioned | No |
| [11] 2018 | Thermoelectric module – 72 W GSM module - 7.5 W Arduino - 0.45 W | Server | Significant delay due to using Bluetooth and WI-FI | No |
| [12] 2019 | Thermoelectric module – 70 W GSM module - 7.5 W Arduino - 0.45 W | SMS and Server | No significant delay | No |
| This work | Thermoelectric module – 72 W GSM module - 0.23 W Arduino – 0.07 W | SMS and Server | 10 – 15 secs | Yes |

In this work, thermoelectric cooler has been used to maintain optimum temperature inside the carrier. This is more efficient than the cold boxes used in some of the previously mentioned studies, as cold boxes tend to freeze the vaccines, but the thermoelectric cooler does not normally reduce the temperature of the cooling chamber below freezing points. Compared to the previous studies, the overall power consumption of the monitoring module is also reduced significantly. This helps to extend the battery backup time which makes this carrier more suitable than the previous ones, to be carried to the remote regions on foot during the last stretches of the journey. Another factor which makes this carrier more suitable for use in the remote areas is its’ portability. All the previously developed monitoring systems required wired connections either to an external power source or to a computer which limits the portability of those carriers. The delays in the SMS communication has been also been reduced in this work. Moreover, unlike some of the reported vaccine carriers, a local storage has been added to the monitoring system which prevents any loss of data due to poor network
conditions. This to a large extent ensures that this carrier contains all the key features in order to ensure maximum efficiency while using in practical fields to transport and distribute vaccines. The power management can be further improved to power the carrier directly using AC power supply initially to bring down the temperature the optimum level and using the batteries only during the journey. The reduction of power consumption of the thermoelectric module is also a potential field for future work.

4. CONCLUSION
This paper presents the design and implementation of a monitoring system and power management for an IoT based vaccine carrier. The system automatically monitors temperature, humidity and location of the vaccine carrier and SMS notifications to the user as needed. This ensures the continuous monitoring of the cold chain so that the vaccines do not lose potency at any point during the journey to the remote locations. It also stores the data on an SD card, as a result even if a network connection is not available, the monitored data is not completely lost. It can be referred to whenever necessary to identify if the vaccines are suitable for use. The use of LDR to identify events of opening and closing of the carrier prevents the theft of vaccines and ensures that the carrier is not opened before reaching the destination. The system is powered using the vehicle battery during the journey and can be powered using portable lithium ion batteries if carried on feet. The overall power consumption has been reduced by 8% and the individual consumptions has been reduced by up to 92%. This reduced power consumption of the module ensures enough backup to carry the vaccines to the most remote areas. As a result of these different features of the carrier, it will be possible to carry the vaccines safely to the most remote areas and ensure that people and specially children everywhere can have access to the essential vaccines. In future, a central monitoring system can be designed to consistently receive data on temperature, humidity and location from all the carriers and monitor the whole operation of cold chain.

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