Pervasive Computing Technologies to Monitor Vaccine Cold Chains in Developing Countries

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ABSTRACT

We have deployed a mobile phone-based temperature monitoring system in the national vaccine cold chain in Albania. This deployment was done in collaboration with the Albanian Ministry of Health, the World Health Organization, and PATH, our Seattle-based partner in this project. Our system covers the national vaccine storage facility, one district-level storage facility, and several local health centers. The monitoring devices are based on FoneAstra, a low-cost sensing system we developed for a range of applications. FoneAstra uses the cellular network to send summarized sensor data via SMS messages, a medium that is familiar and available in many developing nations. When the data arrives at a central server it is stored in a database and accessible to supervisors through a dashboard viewable with a web browser. We describe how our system has helped diagnose problems in the vaccine cold chain (in one case, within several hours of first being deployed). Practicality and scalability are points of our system and we discuss these in comparison to the current state of the art in cold chain monitoring.

Categories and Subject Descriptors

H.4.2 [**Information System Applications**]: *logistics*.

General Terms

Management, Measurement, Design.

Keywords

Sensor systems, SMS, remote monitoring.

INTRODUCTION

Using Information and Communication Technologies (ICT) to help under-served populations has been of much interest in the research community in recent years. Building effective technology solutions for such communities poses a unique set of challenges and constraints. For instance, it is often not practical to deploy systems that are expensive or rely on availability of reliable infrastructure (e.g. uninterrupted electricity, high-speed IP networks, 3G cellular networks etc). We believe that Pervasive Computing technologies can effectively address some of these challenges because systems are often built using low-cost and low-energy (or power-harvesting) embedded systems and sensors. Additionally, these systems often present alternate forms of user interactions like tangible or audio-based interfaces, as opposed to the traditional text-based interfaces. These alternate interfaces can be especially useful if users are semi or illiterate [12]. In this article we present a system built using Pervasive Computing technologies that is being used to monitor the temperature-controlled storage for national vaccine distribution (the vaccine cold chain). This work focuses on a specific application but the system can be generalized to be applicable to other domains as well; for instance, blood cold chain monitoring and large scale environmental monitoring.

Vaccines need to be stored in a temperature-controlled environment (+2° to +8°C for most vaccines) until they are administered to patients [10]. Refrigeration requirements for vaccines are more stringent than many foods and pharmaceuticals since vaccines contain biological agents that are permanently damaged if frozen. Studies have shown that vaccine spoilage due to freezing is a more frequent (and serious) problem in cold chains than damage due to exposure to high temperatures [1, 4, 9]. High cost of vaccines, coupled with the fact that even short durations of exposure to temperatures outside the normal range can cause irreversible damage [1, 9] necessitate the need for having robust storage equipment as well as continuous temperature monitoring and reporting systems. The vaccine market segment in developing countries is estimated to be about $3 billion USD [8] of which 5% is wasted annually [7].

A typical vaccine cold chain is a hierarchical system with a national-level storage facility that distributes vaccines to state/district-level storage facilities. These regional facilities then distribute to their local health centers or health posts where vaccines are administered to patients. There are various stakeholders in this system. The supervisory staff at the storage facilities needs to ensure that the supply chain in their region is working efficiently. This includes logistics management and monitoring the operational efficiency of cold chain equipment. Store managers at these facilities are responsible for the day-to-day operations. This includes distributing vaccines to sub-regional levels, monitoring the temperature of storage equipment, troubleshooting problems such as power outages, equipment failures, etc. The health facility staff administers vaccines to patients and is responsible that vaccines are stored under safe conditions. These stakeholders have different roles and different information needs. Temperature monitoring is a critical aspect at all levels of the system.

Monitoring devices and reporting systems need to be simple, low-cost and scalable due to the countrywide scale of operation. A variety of monitoring devices are used for recording temperature. Thermometers provide the simplest and cheapest way to monitor temperature; however they lack some important features needed for cold chain monitoring. For instance, they only show the current temperature; information such as the daily max/min temperatures, deviations from the normal temperature range, etc. is not available. Products at the next level up in price and complexity provide these missing pieces of information, including persistent history over a period of time. These devices are quite effective and are widely used in cold chain management. However, these devices do not have communication interfaces in order to keep costs low. The capability to easily move data out of the monitoring device has potential to significantly improve cold chain management. For instance, alarm notifications can inform staff about problems in real-time. Remote monitoring can provide the data to several stakeholders simultaneously allowing for better supervision of operations.

More expensive alternatives do exist that provide many of these capabilities. However, because of their cost, installation and management complexities, they do not scale either economically or due to infrastructure and staffing requirements in many of the developing world contexts we have studied.

Our system contributes several capabilities that should greatly enhance the management of vaccine cold chains:

- Continuous monitoring rather than sampling of temperatures thus enabling maintenance of equipment;
- Use of SMS for data transfer as 2G cellular networks have the highest penetration in developing world contexts;
- Coarse location tracking for logistics management as well as sensor readings tagged with location;
- Two-way communication between sensors and administrative staff to report alarms and reconfigure system parameters; and
- Low-cost implementation using low-tier mobile phones rather than more expensive cellular modems.

SYSTEM OVERVIEW OF FONEASTRA

The system we designed is called FoneAstra and occupies a middle ground between existing solutions as it provides the capabilities of the more expensive systems at a very low-cost while using familiar components (low-tier mobile phones) and communication methods (SMS). It does not require Internet access, which is difficult in environments with transitory power supplies and only basic cellular service and phones. It is cost-effective to use low-tier mobile phones, which cost about $20 as communication modems as opposed to cellular modem modules (e.g. Telit modems), which cost over $60. Moreover, the phones' user interface is very helpful in troubleshooting system problems in the field. Specific examples include: low battery indicator, signal strength indicator, being able to test SMS sending and receiving capability etc. Based on our interactions with deployment partners in developing countries we have come to realize that the practical benefits of using mobile phones significantly outweigh the cost benefits.

FoneAstra is a small add-on board to a low-tier mobile phone (Figure 1). It includes an embedded microcontroller (based on ARM7) that communicates with the phone over its data port. The phone informs the FoneAstra processor whenever it receives an SMS message (or even a voice call). In turn, the FoneAstra board can request the phone to send an SMS message on its behalf. Coarse location tracking is possible because FoneAstra can query the current cellular tower-ID that the phone is associated to.

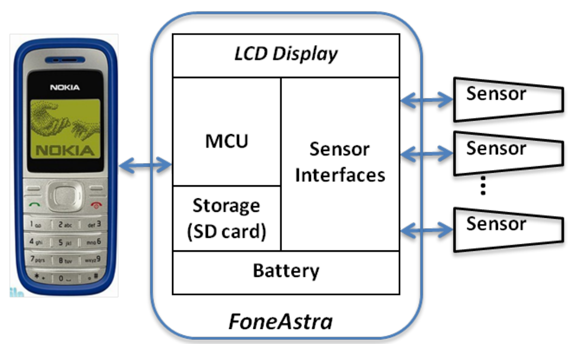

Figure 1: Block Diagram of the FoneAstra board. FoneAstra is a small add-on to a mobile phone that uses the phone as an SMS gateway to send sensor readings in one direction and also respond to commands that it receives. It consists of a small ARM7-based microcontroller, some local SD card storage, an optional LCD and battery, and standard sensor interfaces. It integrates with the phone through a serial line that connects to the phone's data port.

The ARM7 processor directly supports several I/O interfaces to which a variety of external sensors can be connected. For this application, we have experimented with temperature sensors, light sensors, and power-line monitors. However, there is no limit to the type of sensing that could be done. FoneAstra reads sensor values at a specified rate (that can be adjusted through SMS commands sent to the device), compresses the data (this is, of course, highly application-specific), and packs the result into an SMS message for the phone to send. Incoming SMS messages can be used to set parameters or request more fine-grain data from the on-board storage (which stores all sensor readings at the full sample rate).

The software elements of FoneAstra are built on top of FreeRTOS, an open-source, general-purpose embedded real-time operating system. The system is composed of a set of cooperative tasks that executing concurrently in the FreeRTOS runtime environment. Much of the application-specific logic is built into a task that is responsible for periodically sampling the on-board sensors. There is one task that listens for and processes incoming SMS messages. Another task controls the on-board LEDs.

The combination of the FoneAstra board, mobile phone, and sensors are packaged together as shown in Figure 2. Of course, the packaging is also application-specific. FoneAstra can be powered with its own battery or share the phone's battery. The phone and FoneAstra can run for up to two weeks (depending on rate of SMS messages and number of sensors) on a typical fully-charged phone battery. The expectation, of course, is that there will be a trickle of power available to keep the battery charged; this is the case when placing FoneAstras near refrigerators.

The FoneAstra board also supports an optional 2-line LCD if the application is required to display some data (e.g., the latest sensor readings) at the board itself.

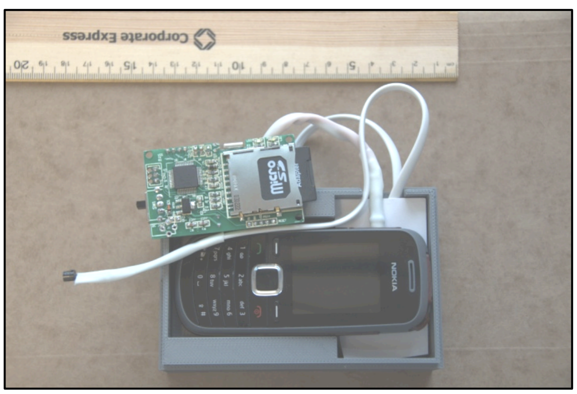

Figure 2: FoneAstra with a temperature sensor (at the end of the white cable used to place it appropriately within the cold-box) and connected to a Nokia 1661 mobile phone. The SD card is visible on the right side of the FoneAstra board. The ensemble is packaged in the gray box visible around the phone (the final dimensions are 12cm X 8cm X 5cm).

Figure 3 shows a schematic for a typical deployment of FoneAstras. Each location has a FoneAstra board and phone and a multitude of sensors. Of course, more than one device can be placed at a single facility if required. These all communicate through SMS messages over the cellular network to the headquarters where a server backs up data into a master database. A web interface provides visualization of this data through standard web protocols. Typically, the FoneAstras are programmed to send a periodic summary message as well as to send alarm messages if particular conditions are detected.

The server can send commands to the FoneAstras to adjust sampling rates, clear storage, change alert thresholds, or to request more data in addition to the summaries regularly sent. This level of control may be necessary to deal with dynamic situations and/or control SMS costs for a particular deployment. For example, it may be advantageous to have the FoneAstras send alarm messages only, while someone visiting each site weekly or monthly to read the SD card can collect logged data physically.

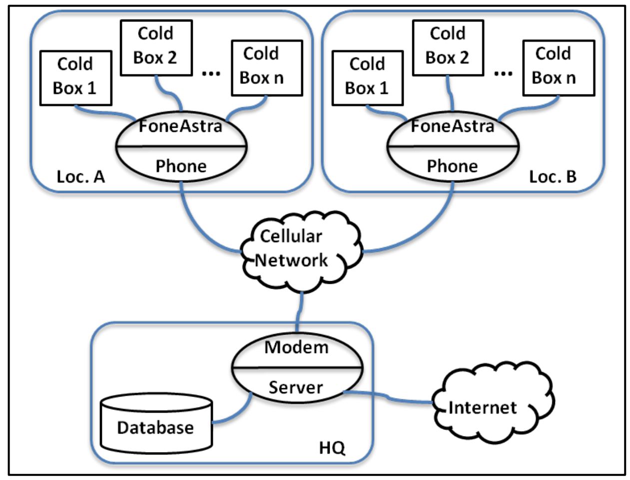

Figure 3: System Architecture of FoneAstra. Phones coupled with FoneAstra are deployed at vaccine storage facilities. Each FoneAstra can monitor several temperature sensors simultaneously. The phones communicate to a central server using SMS messages over the cellular network. The server receives the messages through its cellular modem, stores the data in a database, and permits users to browse the data through an Internet browser.

Figure 4 describes the format of an SMS message sent from FoneAstra and the details of a typical SMS report message from a facility where two cold-boxes are being monitored. Messages sent to FoneAstra are much simpler, for example, an SMS containing "@FAQ" is used to make a FoneAstra query for the current sensor values. This is made purposely short and simple so a human can send it easily from his or her own phone and receive a direct reply. Further details of the system including alternate architectural instantiations, power consumption and system cost are discussed in [2, 3].

The server component of the FoneAstra system is based on RapidSMS, an open source SMS gateway and Django, an open source Web application framework. We used a version of RapidSMS packaged by Inveneo, a San Francisco-based social enterprise that works with many NGOs, such as PATH, our partner in this project.

	Header				Data Payload Per Sensor			
Size (chars)	1	4	1	2	2	2	2 per data sample	
Field Name	Type	Seq. no	Retry count	No. of sensors	Sensor-id	No. of samples		

Typical message from FoneAstra:

```
1 0069 1 02
00 30
1V 1Z 1d 1h 1k 1o 1q 14 1D 1M
18 0u 1L 1G 11 0x 1I 1D 0y 1E
17 15 12 10 0/ 0z 0z 0x 0x 0v
01 30
1R 1R 1d 1G 1b 18 1Y 1M 1T 1e
1L 1d 19 1a 1D 1W 1O 1S 1e 1K
1c 1C 1b 19 1X 1N 1S 1e 1J 1c
```

Header specifies there are 2 sensors

ID for sensor 00 followed by 30 samples

ID for sensor 01 followed by 30 samples

Figure 4: Format of SMS messages sent from FoneAstra with an illustrative example (with extra spaces for readibility). Sensor values use 2 characters – the value is encoded in 6 bits of each of the 7-bit SMS ASCII characters as a 12-bit 2s-complement value.

DEPLOYMENT IN ALBANIA

In November 2010, we deployed the FoneAstra-based continuous monitoring system in Albania. The Albanian national-level vaccine storage facility is located in Tirana (the capital city), at the Institute of Public Health (IPH). The IPH has four cold rooms where vaccines are stored until they are transported to district-level storage facilities. The IPH supplies vaccines to 36 district-level stores once every four months. The district stores supply vaccines to their local health centers and health posts every month. While the exact number of health centers/facilities under each district is not fixed; Albania has a total of about 500 health centers and 1500 health posts across the country. The district stores have multiple, large refrigerators for storing vaccines, while the health centers and health posts typically have one standard refrigerator per facility.

We deployed six FoneAstras to monitor equipment at five different facilities. Our deployment covers the four cold rooms at the IPH, two refrigerators at Tirana's district-level store (called the Directorate of Public Health or DPH) and individual refrigerators at three health centers in the district. The cold rooms at the IPH are grouped into two pairs separated by an aisle. Two FoneAstras, with two temperature probes connected onto each device, are used to monitor these rooms. Figure 5 shows one pair of cold-rooms with the compressors for each room mounted on the wall next to their respective doors. A FoneAstra is mounted on a panel in the space between the two compressors. Temperature probes from each device are routed into the cold room through thermally insulated holes in the rooms' walls. An electric outlet is accessible to charge the battery of the phone coupled to FoneAstra.

The two refrigerators being monitored at the DPH are located in a room and are positioned next to each other; so only one FoneAstra is deployed at this facility. Since only one refrigerator is being monitored at each of the health centers, one FoneAstra with one temperature probe is deployed at these facilities. Figure 6 shows a FoneAstra mounted at the top of a refrigerator at one of the health centers. The inset is an interior view of the fridge and shows the tip of FoneAstra's temperature probe. A FridgeTag [6] temperature monitor and some vaccines stored in this fridge are also visible in this picture. We used this arrangement to compare the readings from the two devices.

The FoneAstra devices are configured to sample the temperature sensor(s) once every four minutes and send an SMS message to the server every two hours. These periodic SMS messages (referred to as routine reports) contain the temperature data aggregated over the two-hour reporting interval (30 samples per sensor). The compact messaging protocol is discussed in [2]. Alarm notifications are sent to the server as soon as an alarm condition is triggered. The local staff is able to remotely query the temperature of monitored equipment at any time by sending an SMS message to a FoneAstra with a predefined command. These configuration parameters (sampling interval and reporting interval) have been chosen because the cellular plan, which costs about 4 Euros per month, includes 500 SMS messages for each billing cycle. In this configuration each FoneAstra device generates 360 (or 372) routine reports per month. The remaining monthly quota of messages is used for responding to SMS queries sent into the device and sending alarm notifications.

Figure 5: FoneAstra deployed at IPH in Tirana, Albania. The FoneAstra box is placed between the two compressors for two cold rooms (note door handles on left and right). Wires from the board pass through thermally insulated holes in the walls of the cold rooms and lead to the sensors inside.

The server that is shared by all the FoneAstras deployed in the system is being hosted in Tirana itself. Users (i.e. cold chain supervisors) login to the server via the web interface to access information about the system and configure FoneAstra as needed. An example of the server's web interface is shown in Figure 7 (to improve readability, the figure is grouped with temperature graphs the end of the Results section). This screenshot shows detailed information for the FoneAstra deployed at the DPH (the phone number for this device has been hidden intentionally), which includes current temperature, alert status and configuration parameters like the temperature thresholds for alarms, reporting and alert frequencies. Parameters can be edited and changes result in an SMS message being sent to the device with the updated configuration parameters. The detailed temperature history can be viewed by clicking on the hyperlink of the respective sensors. Figure 8 - Figure 10 (discussed in the next section) show screenshots of temperature graphs obtained from a few sensors.

The system deployment was completed over a 12-day period in November 2010. The first author travelled to Albania to set up the deployment and the system has been running since then. Some basic training to troubleshoot common system problems was provided to the IPH staff during the initial 12-day period. There have been interruptions in operation due to issues that have arisen since then, but the IPH staff has been able to resolve these.

Figure 6: FoneAstra deployed at a health center. Note the box on the top back-right corner of the household fridge and the wire going down to the door and through the insulating lining. The inset shows the sensor hanging inside the fridge, just above a FridgeTag for comparing temperature readings from both devices.

RESULTS

In this section we discuss the results from our Albania deployment. All the graphs have been grouped into a single-column space at the end of this section.

Alarms

The WHO specifies the temperature and time thresholds for various alarm conditions [10]. Being able to precisely and successfully detect alarm conditions in the refrigeration equipment was amongst the early results we obtained from the system.

Within a few hours of deployment at one facility, our system reported negative temperatures (Figure 8). This particular equipment was known to have intermittent problems, but its severity got highlighted because the staff was now receiving near-real-time feedback from the equipment through FoneAstra and was able to view its detailed temperature profile. Based on this feedback, vaccines were moved out of this refrigerator while they experimented with the refrigerator's thermostat settings to control the situation. Staff was not able to fix the freezing issue and the refrigerator was replaced in early 2011.

The graph in Figure 8 also shows two time periods when FoneAstra experienced problems and went offline. These are around the November 7th and November 28th time frame, depicted by the straight line connecting two data points. In the first case, the connecting cable between FoneAstra and the phone had got disconnected so the server was not receiving any messages from this device. In the second case, the prepaid SIM card had run out of SMS credits. The staff was easily able to diagnose and resolve both of these issues on their own.

Detecting Power Interruptions

Figure 9 shows the temperature graph from one of the cold-rooms at the national store. The three temperature spikes shown in the graph are due to interruptions in the power supply for the cold-room. The huge temperature spike between November 9th and November 11th is because the cold-room was under maintenance and its door was left open in addition to the power interruption. This was actually a WHO high temperature alarm condition (temperature higher than +8°C for at least 10 hours), however FoneAstra was not configured to generate alarms at the time, hence an alarm does not show up on the graph. The other two spikes are due to shorter duration power failures at the facility.

Performance Profiling

Having a continuous monitoring system gives insights about the operational efficiency of equipment being used in the cold chain. Figure 10 shows the temperature profile of a newly installed fridge that was used as a baseline for performance comparison in the deployment. The inset shows the fridge's temperature curve over a 24-hour period. The uniformity in the temperature curve of this fridge indicates that this fridge is performing efficiently. If equipment generates alarms often, it is obviously a strong indicator of an underlying problem; however a lot can be inferred from the temperature profile beyond just the flagged alarms. For instance, the graph in Figure 8 has periods of time when the internal temperature was subzero but alarms were not generated by the fridge. This is indicative of a poorly performing compressor. Figure 11 shows the temperature profile of a fridge that generated a few high temperature alarms due to power failures. The high degree of variation in the temperature profile of this fridge indicates that it has poor performance. While we do not show a zoomed-in view of the temperature profile of the cold room at the IPH (Figure 9), a quick visual inspection of the graph shows the uniformity in the temperature profile (barring the situations when power was cut-off), indicative of its high operational efficiency.

In the future, it is our expectation that we might even be able to predict when a fridge is beginning to fail so that it can be serviced sooner rather than later. With an additional sensor we can easily detect when doors on cold boxes and fridges are opened and FoneAstra can pay particular attention to how the recovery to the set temperature point is accomplished. If a unit starts to show a curve with different characteristics, this will be an early indication that the equipment is experiencing a loss in efficiency and should be serviced.

Summary of Results

The results shown by our continuous monitoring system have been very encouraging (a fact endorsed by cold chain experts involved in this project). While the local cold chain staff was already aware of some of the problems diagnosed by our system; the near-real time reporting and flexible data visualization gives them a fine-grained and real-time view into their system. This makes them pro-active in diagnosing problems in the cold chain and enables them to intervene in a timely manner to resolve issues. The evidence of this was already strong in the two short weeks when the deployment started and has continued since. The reconfigurability built into the system empowers the staff further; for instance, they can remotely increase the sampling/reporting interval of poorly performing equipment, on-demand, to understand the problem better. Based on feedback from the FoneAstra system, the staff quickly identified poorly performing equipment and either replaced them or got them serviced.

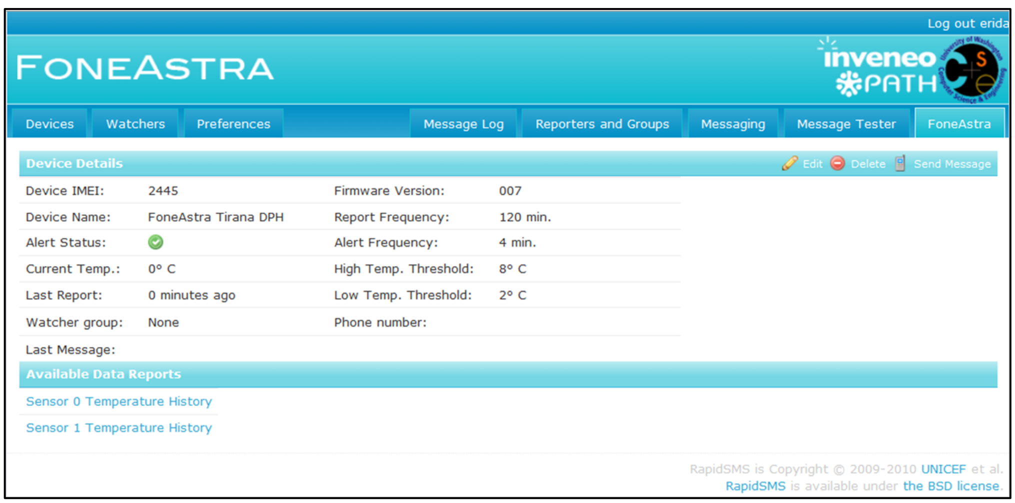

Figure 7: Detailed view of the FoneAstra deployed at the DPH. Information displayed includes system parameters like the SMS reporting frequency and temperature thresholds. The FoneAstra at this site has two sensors connected to it that are displayed as "Sensor 0" and "Sensor 1" on this web page.

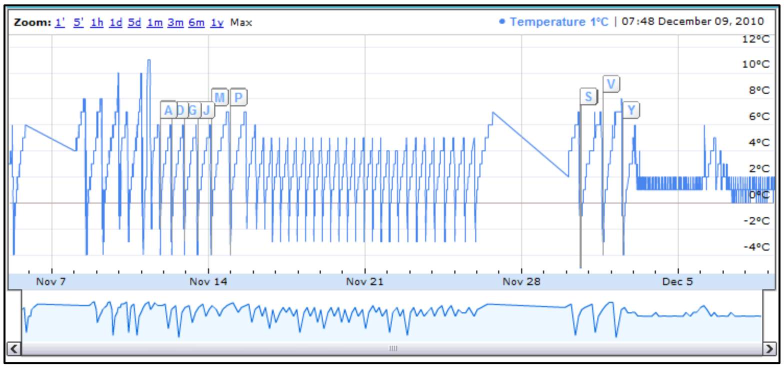

Figure 8: Freezing alarms (indicated by flags on the graph) reported for a fridge by FoneAstra. Variation in the temperature profile is due to the fact that facility staff was adjusting fridge settings to resolve the freezing issue based on the feedback available from this graph.

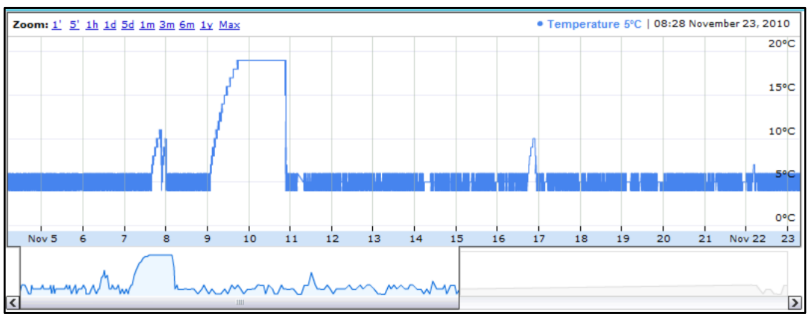

Figure 9: Temperature graph for a cold room at the IPH being monitored by FoneAstra. The three temperature spikes are due to power interruption for this cold room. The temperature drop in the first spike is because the generator was turned on for a brief period to control temperature during the power failure.

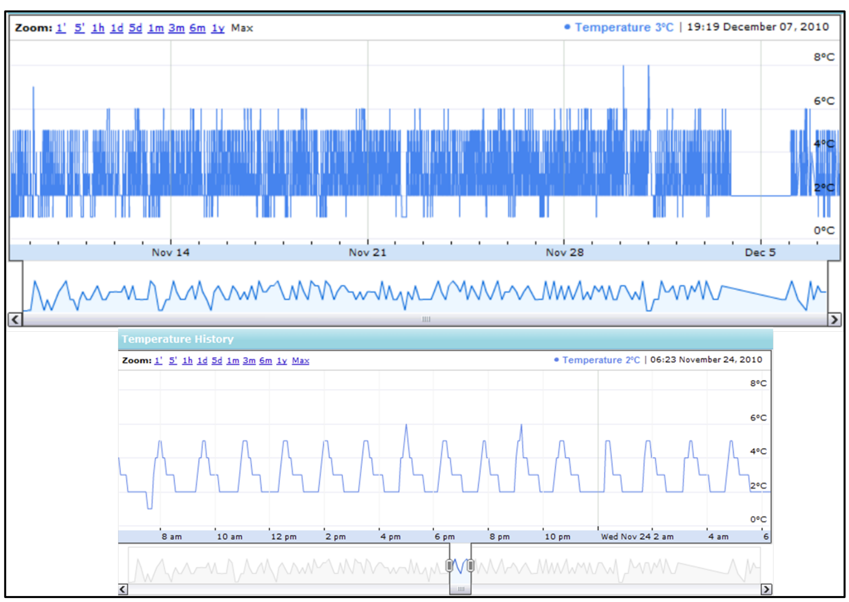

Figure 10: Temperature graph of a newly installed fridge. The uniformity in the temperature profile indicates high operational efficiency of this fridge. The inset shows a zoomed-in view of the temperature profile over a 24-hour period.

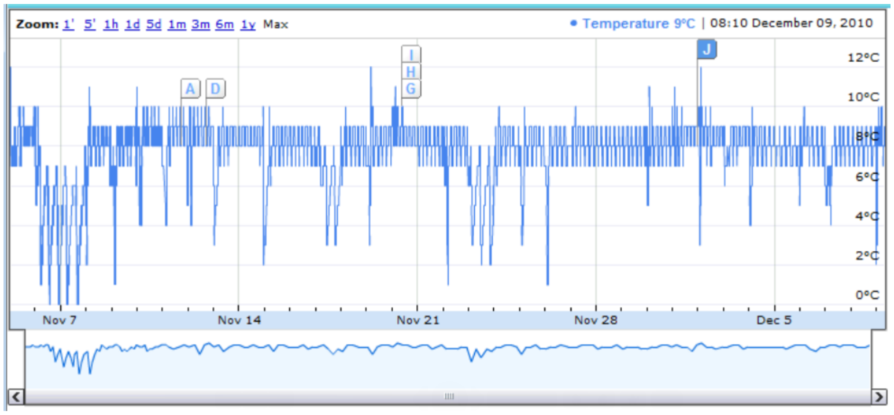

Figure 11: Temperature profile of a poorly performing fridge. The high degree of variation in the temperature profile indicates poor operational efficiency. Flags on the graph indicate high temperature alarms. At least two of these alarms occurred due to power failures over weekends when the facility was closed.

LESSONS LEARNED

Motivated by the positive results shown by the system deployed in Albania, we are now working on scaling the system up to cover the cold chain of the entire country. However, deploying a smaller system in Albania has given us a new perspective, which has helped evolve our thinking about the system.

Our low-cost solution seems appropriate for large-scale deployments but provides limited local feedback on the device via an LCD and LEDs. We have learned that a richer user interface is needed on monitoring devices used at facilities that store large volumes of vaccines (national level stores for instance). These are critical points in the cold chain and it is important even for local staff to be able to view temperature profiles of storage rooms. Since a computer connected to the Internet is not accessible to everyone at the facility, the monitoring device itself needs to be made more interactive. Higher cost of an enhanced device deployed at these locations, which are relatively few, is acceptable because of need to ensure safety of large volumes of expensive vaccines.

Rather than enhancing the I/O capabilities of FoneAstra, we are now working on building a smartphone-based temperature-monitoring device that will be used at critical locations in the system. Smartphones are especially attractive because their price continues to fall with increasing market penetration. In order to use smartphones for vaccine monitoring, we are currently working to connect temperature probes to them over a wired interface. To address varying needs at different levels of a cold chain, our next trial will have monitoring devices based on smartphones as well as low-tier phones.

Administering and maintaining the server in Tirana has been an issue that needs to be addressed. The cold chain staff is unable to do this because they are not IT administrators. At times the server machine goes offline and it becomes difficult even for us to access it remotely for troubleshooting. It is clear that a more scalable and sustainable solution is needed in the long run. The server is currently hosted in country because it acts as an SMS gateway, in addition to being a web server. In the next trial we will decouple these components to lower this deployment/administration barrier. Colleagues working in the ICTD space have had mixed experiences with 3rd party SMS gateway service providers in developing countries. So rather than follow the same approach, we are planning to use an Android-based Smartphone as the SMS gateway. In the new architecture, our web application will be hosted as a cloud service that communicates with FoneAstras deployed in the field via one or more in country Android gateway(s). We expect this to be an interim solution because few years down the road, as cellular data on 2.5G, 3G and 4G networks become more pervasive; in country SMS gateways might not be needed.

The deployment has also given a new perspective to cold chain supervisors and researchers. The FoneAstra-based continuous monitoring system begins to make a distinction between data meant for different stakeholders in the system. For instance: supervisors are most concerned about the long-term temperature history of equipment, while store managers and health workers are most concerned about the short-term operational conditions (e.g. current temperature, daily max/min, alarm status etc). Compared to the current state of the art, our system generates a lot of data; so channeling this data to appropriate stakeholders in a timely manner becomes an important aspect of the system. We realized during the initial few days of the deployment that this will need to be given more thought and incorporated into future systems that get deployed.

CONCLUSION AND FUTURE WORK

In this paper, we have discussed the FoneAstra-based continuous monitoring system deployed in Albania to monitor the national-level vaccine cold chain. The deployment covers the national vaccine storage facility, one district-level storage facility and three health centers within this district. The system has enabled the cold chain staff to diagnose critical problems in equipment used to store vaccines. Easy access to detailed temperature profiles of equipment in real-time gives cold-chain staff a much closer and quicker view into the system. This significantly improves their effectiveness in managing the cold chain.

Low-cost of our system significantly lowers the barrier for large-scale deployments. Experience gained from the deployment in Albania has helped us differentiate between monitoring requirements at different levels of a cold chain. Based on that, we are now building a more interactive, smart phone-based monitoring device that will be used at critical points in system. We expect to do a larger deployment in 2012 that will leverage both smart phones as well as low-tier phones for cold chain monitoring. We will also experiment with a new server architecture in which the web application, hosted as a cloud service, will communicate with monitoring devices via one or more in country Android-based SMS gateway(s).

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