A NOVEL CELL PHONE BASED APPLICATION FOR TRACKING THE VACCINATION COVERAGE IN RURAL COMMUNITIES

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ABSTRACT

Millions of children born worldwide do not receive proper vaccination. Driven by the concern for the lives of such children, institutions and organizations around the world have emphasized the need to strengthen vaccination surveillance and monitoring in developing countries to prevent the spread of vaccine-preventable diseases. In this regard, we present a cell phone based application called Jeev to track the vaccination coverage of children in rural communities. Jeev synergistically combines the power of smartphones and the ubiquity of cellular infrastructure, Quick Response (QR) codes, and national identification cards. In this work we present the design of Jeev and highlight its unique features along with an extended evaluation of its performance. We plan to continue our investigation by pilot testing Jeev in a rural population to study its effectiveness and identify socio-cultural issues that may arise in a large-scale deployment.

APPROVAL PAGE

The faculty listed below, appointed by the Dean of the School of Computing and Engineering, have examined a thesis titled "A Novel Cell Phone Based Application for Tracking the Vaccination Coverage in Rural Communities", presented by Anas A. Katib, candidate for the Master of Science degree, and certify that in their opinion it is worthy of acceptance.

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CHAPTER 1

INTRODUCTION

Although cases of vaccine-preventable diseases appear to be decreasing in high-income economies such as the USA [30] and Canada [31], about 20% of the children born every year do not receive proper immunization during their first year of life [28]. Many organizations worldwide continue to contribute various kinds of support to overcome this tragedy. The WHO and UNICEF have developed the Global Immunization Vision and Strategy (GIVS) which is a ten-year-framework for countries to reach high immunization converge and lower mortality rates from vaccine-preventable diseases [33]. While the GIVS aims to achieve 90% vaccine coverage by 2015 and reduce the number of childhood deaths to 4.3 million, there are several constraints that must be overcome.

According to the World Health Organization (WHO) and the United Nations Children's Fund (UNICEF) [28], the health care systems are weak in middle-income economies. There is insufficient political and financial support. The healthcare facilities and the public services are inadequate in the remote and poor areas of these countries. There is a shortage of trained health workers who can deliver immunization to the population. In addition, due to the lack of knowledge about the importance of immunization in such communities, many children do not receive the required vaccines. Furthermore, the unexpected deaths and side effects create a fear of immunization among parents, thereby reducing the number of children who receive a full course of vaccines. Lastly, the monitoring infrastructure is weak and information systems are unacceptable.

UNICEF and WHO have emphasized the need to strengthen the immunization surveillance and monitoring in developing countries [28]. Immunization coverage information is useful to monitor the performance of immunization programs and improve the delivery of vaccines to the population [27]. In addition, immunization information systems (IISs) prove to be crucial in controlling infections during outbreaks [34]. On the other hand, the lack of immunization coverage information can lead to wastage of vaccines due to unnecessary revaccinations and poor forecasting of the vaccine demand [28], [10]. Furthermore, the use of paper records to track the immunization status of children leads to inconsistencies in the way information is recorded; immunization records may be lost or damaged [17], [2], [10].

While tracking the vaccination coverage of a population has become a global challenge in public health, little research has been done in this domain. In this work, we address the problem of tracking the vaccination coverage of children in hard-to-reach areas where cellular infrastructure is available. We present a low-cost cell phone application called Jeev that synergistically combines the power of smartphones and ubiquity of cellular infrastructure, Quick Response (QR) codes, and national identification cards to track the vaccination coverage in a population. Jeev is based on a client-server model: the data collected by the clients are synchronized at the server; the clients and server exchange small amounts of data using low-cost SMS text messaging (the transmitted data is always encrypted for security and privacy reasons). The clients and the server are all smartphone devices.

This thesis is based on the paper: "Jeev: A Low-Cost Cell Phone Application for Tracking the Vaccination Coverage of Children in Rural Communities", published in the proceedings of IEEE International Conference on Healthcare Informatics 2013 [32]. In this thesis we traverse more details regarding the design and the implementation of Jeev. In addition, we report a preliminary evaluation of Jeev using the National Immunization Survey datasets [4]. Although Jeev has not been deployed and studied in a rural community, we are planning to pilot test it in rural Haiti through the help of Maison de Naissance [14], which is a community health care facility in Torbeck, Haiti. The rest of this thesis is organized as follows.

Chapter 2 explores the background and the related work in this area. It starts by examining the current state of cellular infrastructure in middle-income economies such as Haiti and India. Next, it presents the reasoning behind the adoption of Quick Response (QR) codes in our proposed solution. After that, it provides the explanation for incorporating national identity cards in the design. Lastly, the chapter concludes by reviewing the related work and concepts to the issue of tracking vaccination coverage while discussing the similarities and the differences of our proposed solution.

Chapter 3 provides a detailed description of the design and architecture of Jeev. It starts by describing the requirements that guided the design of Jeev. Then, it describes the architecture of the system and its interactions. Next, the chapter presents a description of the user interface for the system, and it lists the features that are implemented in each end (i.e. server and client). Finally, the chapter describes the proposed communication protocol that facilitates the exchange of text messages between a client and a server.

Chapter 4 presents the extended, preliminary evaluation of Jeev. It starts by providing a description of the variables and the experimental environment. Next, it introduces the various workloads that were constructed to evaluate the system. After that, it explores the performance results of the evaluation in terms of time in addition to the power consumption of the system.

Chapter 5 draws the conclusions. It summarizes the overall system and its features. It describes key areas the Jeev overcomes. The chapter concludes with our plan for further testing and the deployment of Jeev in a rural population.

CHAPTER 2

BACKGROUND AND RELATED WORK

Cellular Infrastructure in Developing Countries

Cellular infrastructure and its technology are widely spread around the globe. There are more than 6 billion cell phone subscribers [11]. Through cell phones, it is now possible to communicate with vast populations in previously hard-to-reach areas. In India, a middle-income economy [13], about 40% of the rural population has cell phones (or mobile phones) [20]. Similarly in Haiti, a low-income economy [13], the cellular infrastructure has grown quickly since the devastating earthquake of 2010. Haitians are using cell phones to receive relief incentives [24]. Such a ubiquity of cellular infrastructure provides new opportunities to develop cell phone-based solutions for tracking the vaccination coverage of a rural population.

Likewise, smartphones have become popular and affordable. They now possess tremendous computing capability (for a fraction of the cost of a personal computer): powerful multi-core processors, several GBs of storage, high-resolution cameras, several hours of battery life, and touch screen technology. Furthermore, in case of a loss or absence of a mobile data connection (but not the cellular signal), text messages can still be utilized to exchange information through the Short Message Service (SMS). In fact SMS provides an inexpensive way to communicate small amounts of data in all kinds of environments (e.g. hard-to-reach or remote areas), where the cellular signal can be received. This too makes cellular technology an appealing instrument for a practical solution to vaccination coverage tracking.

Quick Response Codes

Quick Response (QR) codes are two-dimensional (2D) barcodes that can encode a wide variety of of data, such as numeric and alphabetic characters. In Jeev, QR codes have been utilized to ease the retrieval process of information. They have been selected as an encoding mechanism for their attractive features. They have fast readability and higher storage capacity as compared to standard barcodes [15], [22]. A typical linear or one-dimensional (1D) barcode (e.g. UPC-A) can encode 13 to 20 digits. On the other hand, a QR code can encode up to 7,089 numeric characters or 4,296 alphanumeric characters [35] (See Figure 1).

O say can you see by the dawn's early light,
What so proudly we hailed at the twilight's last gleaming,
Whose broad stripes and bright stars through the perilous fight,
O'er the ramparts we watched, were so gallantly streaming?

Figure 1. Encoding 227 characters into a QR code

In addition to their high capacity, QR codes have error correcting capabilities. Even with up to 30% damage, a QR code can still be decoded [36] (See Figure 2). QR codes can also be modified for artistic reasons and still be decoded (See Figure 3). The decoding process is instantaneous and can be easily accomplished using applications on smartphones.

Figure 2. Decodable Damaged QR Codes

Figure 3. Decodable Modified
QR Code

Even though QR codes are designed to withstand damage, the grade of the material on which the QR code is printed, and the printer's quality makes a drastic difference on the longevity of the QR code. Every manufacturer has its own variety of printers, and each printer has a wide array of recommended labels that differ in quality and cost. For example, Zebra Technologies offers a standard bright-white paper labels that are intended for normal, low-budget use, as well as matte polyester labels "with good smear and scratch resistance, excellent resistance to harsh chemicals, temperature exposure up to 300 degrees F (149 degrees C) and up to 3 years outdoors" [38].

Identity Cards

National identity (ID) cards have become increasingly important in many developing countries to prevent voter fraud and corruption, and to take advantage of banking services, government incentives and subsidies. For example, in rural India, such cards are required to receive subsidies on food and grains [5] and open bank accounts [9]. In post earthquake Haiti, national ID cards are giving citizens access to work, banking services, and voting privileges [19]. These cards are usually laminated or made of plastic and are more durable than paper records. ID cards are utilized in Jeev in two ways. First, the national identification numbers are used to uniquely identify a patient's parent in the database. However, if a national ID number is not available, a driver license number or any similar unique number can be used instead. The second way ID cards are utilized is as a placeholder for affixing the QR code label. The physical nature of the card acts as protective shell for the label against tear risk. The QR label will be small in size so that it does not obstruct the view or the access to the card's information.

Related Work

E.V-Trax is an employee vaccination tracking system that aims to substitute paper forms and manual data entry with an electronic system that utilizes handheld computers, scanners, and a central database [39]. Using the handheld computer, which is pre-loaded with the employees' vaccination status and data, the caregiver scans an employee badge and brings up the employee's record. At vaccine administration time, the caregiver scans the vaccination barcode to update the record. "Once all vaccinations are complete, the caregiver securely uploads the data from the E.V-Trax handheld computer to the central database" [39].

E.V-Trax resembles a non-identical twin solution to Jeev is in several aspects. First, both use handheld devices (i.e. handheld computers or cell phones) to update or retrieve a patient's vaccination records. Second, they utilize scanning devices (e.g. equipped scanners or cell phone cameras) and barcodes that encode the patient information (e.g. employee ID) to speed up the overall process and mitigate man-made error. Third, they store the patients' vaccination records in a central database, which is synchronized frequently. Fourth, the whole procedure of administrating the vaccines and updating the vaccination record does not have to be performed at a particular location.

Although Jeev might appear similar to E.V-Trax in its approach to track vaccination coverage, there is a number of design and architectural differences that set them aside. Such differences arise from Jeev's aim to overcome the disadvantages that are apparent in E.V-Trax when attempting a large-scale deployment in a rural population, where the computing capability is limited. For example, E.V-Trax requires the handheld computer to be synchronized with the central database (at the headquarter) through a wired or a wireless data connection. Requiring the caregiver to commute frequently between the vaccine administration point and the location of the central database becomes inefficient when the geographical region gets larger, and the Internet connectivity is absent. Jeev overcomes the issue of by using text messages to synchronize the data. The caregiver does not have to go to the location of the database or even use an Internet connection to update the vaccination records.

Also Closely related to our work is VaxTrac, which has received funding from the Bill & Melinda Gates Foundation. It captures and processes infant fingerprints using fingerprint readers and inexpensive netbooks [10]. However, we believe there are some potential limitations: The system may not scale in large geographical regions because images are large in size and have to be physically transferred to integrate them in a central location. This also raises the issue of how to synchronize the data on the netbooks carried by health workers. Furthermore, fingerprints of infants change in size as they grow. Infants may not be cooperative to allow health workers to take good fingerprints (See Figure 4).

Source: VaxTrac [40]

Figure 4. Infant Fingerprint
Captured in VaxTrac

Jeev is different from VaxTrac in the sense that it relies on smartphones, which consume less power than netbooks, and does not rely on infant's biometric data. Jeev uses low-cost SMS text messaging for communication between the server and clients, synchronizes the vaccination records in real-time, and can be deployed in large geographical regions.

Abhisek et al. [17] proposed the notion of mobile health cards to increase the immunization rate in rural areas. They highlighted the current problems with paper-based records in rural India such as lost or damaged paper immunization forms. They suggested that all activities involved during immunization should be moved to the mobile platform using cell phones. Each child would be assigned a unique id generated by the system; the authors mentioned the use of biometric technology. However, no real system has been developed using the proposed ideas.

More recently, Cook Children's healthcare system, in partnership with athenahealth, Microsoft, Sanofi Pasteur and Merck, has begun using QR codes on vaccine bottles [1] (See Figure 5). This will result in easy management of vaccines, tracking of vaccination status, and allow integration of vaccination information with EHR systems. Jeev is different in the sense it uses QR codes to identify children instead of vaccines and is designed for a rural population, where the computing infrastructure is minimal.

Source: Healthcare IT News [1]

Figure 5. 2D Barcode on a Vaccine Bottle

CHAPTER 3

DESIGN AND ARCHITECTURE

Design Requirements

There are a few design requirements for a vaccination coverage tracking application to successfully operate in rural communities. Firstly, a child may be vaccinated at different locations and therefore, must be identified correctly to avoid missing vaccines and receiving unnecessary re-vaccinations. Secondly, cellular coverage in certain areas may unavailable at times, and therefore, the application should cope with such situations. Thirdly, the application should be low-cost and easy to use and deploy in rural communities. Finally, the application should be efficient in performance and energy consumption.

Jeev Architecture

Jeev utilizes the capabilities of smartphones and of cellular infrastructure, QR codes, and national identity cards to accomplish the task of tracking vaccination coverage. Jeev is based on a client-server model: it has client-side software and server-side software. (Hereinafter, we simply use the terms *client* and *server*.) The server (i.e. cell phone application) runs on a smartphone and is responsible for storing and managing the vaccination records of children. A smartphone is a perfect choice because the computing infrastructure in rural areas is minimal; having access to devices such as netbooks or handheld computers with Internet connectivity in these areas would be expensive. The server can be located in a community clinic or health care facility (no specific geographical location is mandated). A health worker carrying a smartphone running the client application can access the vaccination record of a child from the server and request it to update the record with new vaccine doses. The client can also request the server to create a new vaccination record for a child. The clients and server communicate via SMS text messaging and do not require a data communication or an advanced network (e.g. a 3G network). The transmitted data is encrypted for security reasons.

Figure 6 illustrates the architecture of Jeev and how it operates. When a child is immunized for the first time, either at a vaccination camp, clinic, or home, a health worker will collect the name, sex, and date of birth of the child and some information about the parent (or legal guardian) from the his or her ID card (*e.g.*, ID number). This information is then encrypted and a QR code of the encrypted information is generated and printed on a sticker of 1.5x1.5 cm in size (size can set by the user). The printing can be done using a portable label printer priced less than $300. The sticker is affixed on the national id card of the parent. Additional stickers can be printed and affixed on a paper vaccination form if available, or be provided to the parent for safekeeping at home. Also if the parent has a cell phone, then a text message can be sent containing the encrypted information from which the QR code was generated. (Note that the parent's cell phone need not be a smartphone, which is quite realistic in rural areas.) The QR code on the sticker uniquely identifies the child during future immunization visits. Only authorized clients can decode it. The client sends the collected information to the server and requests it to create a vaccination record for the child. The server stores the vaccination records in a DBMS. The database schema in the current design is shown in Figure 7.

When a child is vaccinated in the future, a health worker will scan the QR code affixed on the parent's (or legal guardian's) id card using a smartphone running the Jeev client. Once the QR code is decoded, the child's identity is determined. The child's vaccination record is then retrieved from the server. After vaccination, the client sends a request to the server to update the child's vaccination record. If client-side the smartphone has GPS capability, then the location information is also sent to the server along with the update request. On the other hand, vaccination coverage of children can be mapped and visualized on an interactive geographical map if location information was captured.

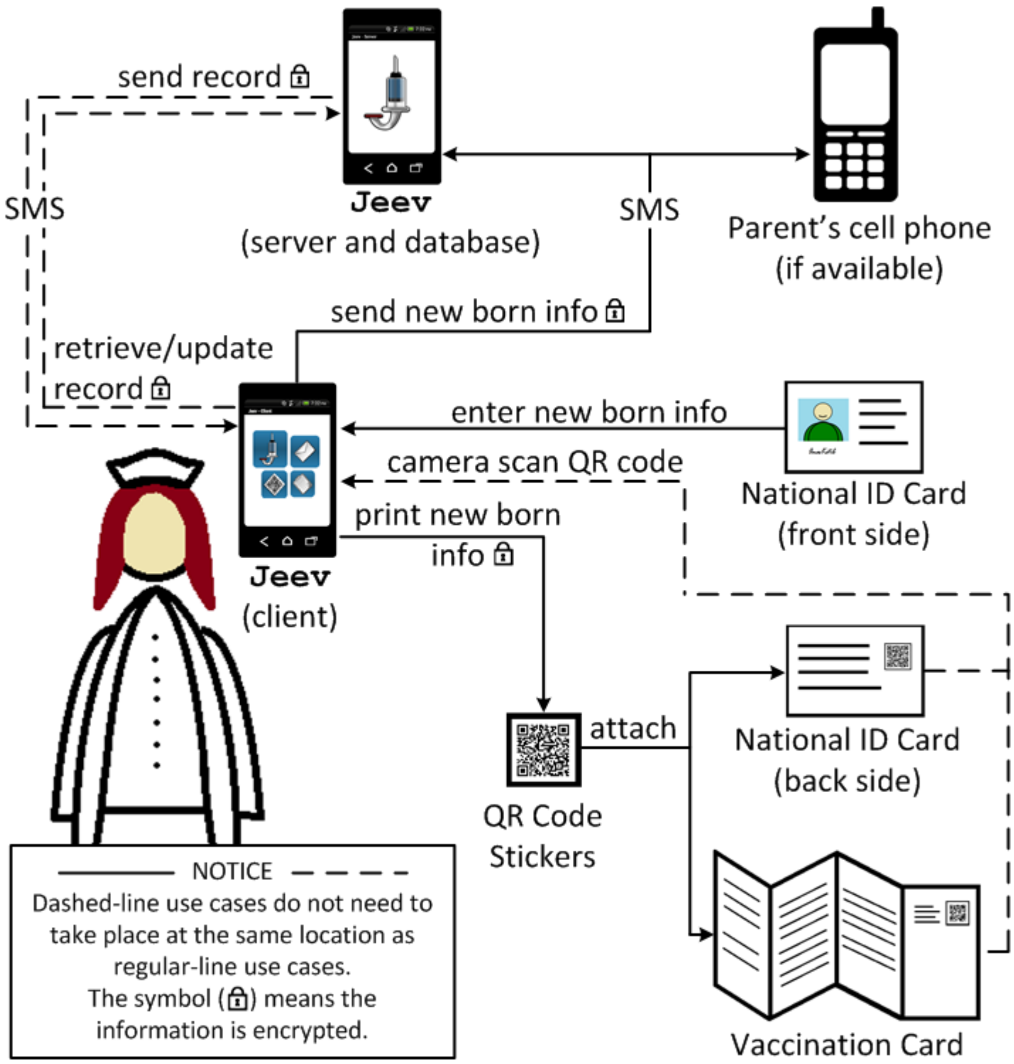

Figure 6. Overview of the Design

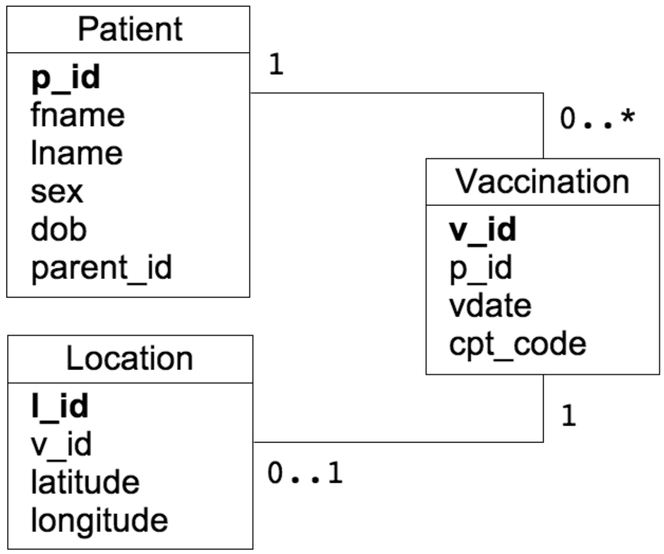

Figure 7. Server Database Schema

It is possible for a parent to lose or misplace her national id card; the QR code sticker on the ID card may be damaged and therefore, cannot be decoded by a client. Then the parent can bring the extra QR code stickers provided during the first visit to identify the child correctly. A health worker can also print a new sticker with the same QR code and affix it to the parent's new or old id card. Another way is to have the health worker receive the text message stored on the parent's cell phone (provided during the first visit) and regenerate the original QR code. If none of the above is possible, the health worker can ask relevant questions to the parent and the server will try to identify the child and locate its vaccination record even if partial information provided by the parent. In the worst case, a new QR code has to be generated and printed.

When cellular coverage is not available, a client can store the vaccination data locally. Once coverage is available, the data can be pushed to the server. Vaccination records can be downloaded ahead of time from the server if needed.

User Interface

Jeev has intuitive user interfaces for health workers and officials both on the client- and server-side (See Figure 8 and 9). In client-side main view the user can generate a QR code for a patient by tapping on the QR code icon. The application will then prompt the caregiver for the patient's information, and print the QR code over the selected printer. To update the patient's vaccination record, the caregiver first taps on the Jeev icon, scans the patient's QR code, selects the appropriate vaccination(s), sends the information to the server by tapping on the mail icon. Tapping on the clipboard icon will display the current patient's vaccination record to the viewer.

If the patient's QR code is not available, the caregiver can tap on the search option from the submenu and enter the relevant information to retrieve the patient's info from the server and print a new QR code label. Additionally, the QR code's (encrypted) information can be sent to the parent's cell phone by tapping on the share option in the submenu. If the cellular signal is not available, the caregiver can backup the the vaccination record and any update by tapping on the save option in the application's submenu.

The server-side application includes several features as well. The user can have the vaccination coverage information displayed from different perspectives. Because vaccination records are stored in an RDBMS on the server, (for analysis or monitoring purposes) the user can query the database on the cell phone though a query portal or connect the cell phone to a computer and execute the same queries. In addition, the server application can display vaccination coverage information on a map if geographical information is available.

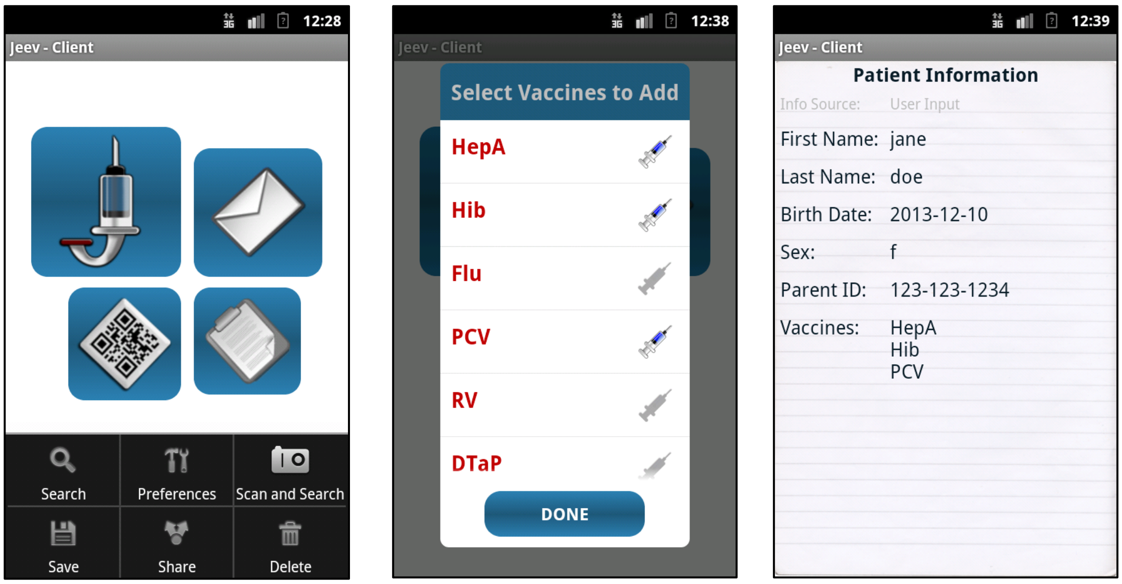

Figure 8. Client-side Screenshots

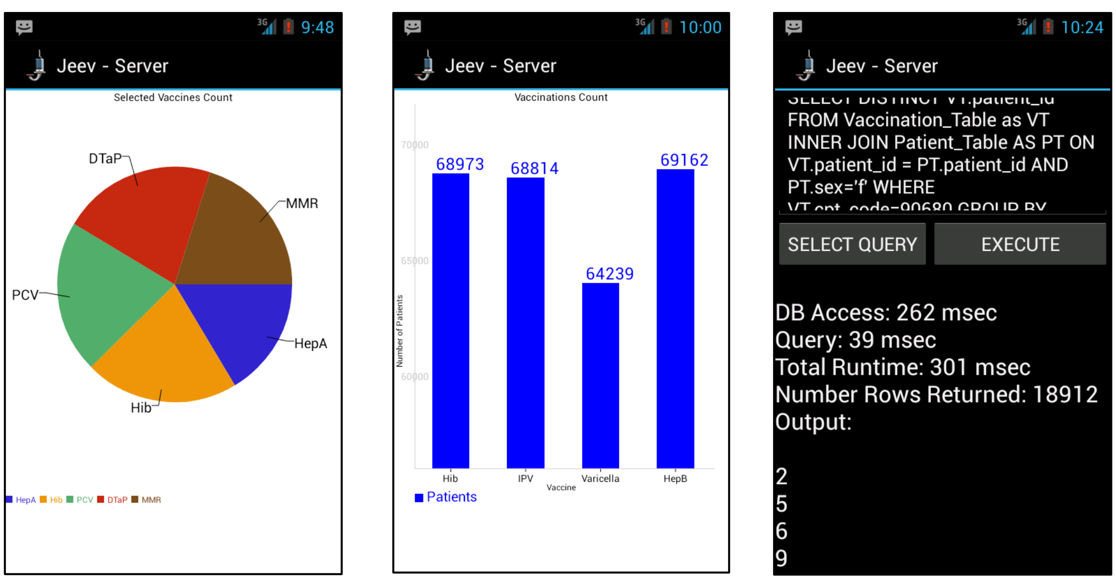

Figure 9. Server-side Screenshots

Communication Protocol

As stated previously, all communication that takes place in Jeev is accomplished through text messaging, and all text messages are encrypted with AES algorithm. Each text message carries a textual segment. The segment consists of two fields: type and content. The type field indicates the type of the segment at hand: InfoRequest, InfoResponse, InfoMultiResponse (i.e. response is split over multiple messages), UpdateRequest, or UpdateResponse. The content field can contain: new patient or vaccinations information, key-value search pairs, acknowledgments, or errors (Examples in Figures 10, 11, 12 13).

Client to Server	Type	Content	Num. of Characters
Segment	infoReq	% fname:jane % dob:2011-12-10	34
SMS	dZiMuJXl7veeZKFCP91+A38b68hBO/0ER/l13OQU1hv6/ TCLuC5wKcGIWUeyZWlBLnKq596Iwel3L5ZpvIBIJg==		89

Figure 10. Example of an InfoRequest Segment

Server to Client	Type	Content	Num. of Characters
Segment	multiRes	% fname:jane % lname:doe % dob:2011-12-10 % sex:f % pid:123-12-1234 % cptcodeX:2 % cptcodeY: 2 % cptcodeZ:4 % cptcodeW:3 % cptcodeO:2 % cptcodeP:2 % cptcodeQ:3 % cptcodeR:3 % cptcodeS:3 % cptcodeT:1 %	34
SMS 1	7lcl0Cj4KBXiGCU3mbjncolePBlSyjC4kcpLq1K4fHNjPbeagdrC2JF y26yHwed6UPagDgrXdlhZ+aBglI8NSJAGm/urEJR8WIdkTYYinPd IhF2VpIW64EbjWnJ4E+9DVv6ejhzEa0TmtYLz1JM9Q8FBnxSgzN M9		160
SMS 2	jtxW+IO68FKunY9nhb320MyMUxydTUfRuFRYRFGGu4QFCCVjf ozjo062aN6Ue42Bx0zanCwmhaYLb3ZGrW9AQqL74aXUntRN4X PHdRdr822Zmf8qybkouKalXHL+4FwKpiM7v9oEn9M=		141

Figure 11. Example of an InfoResponse Segment

Client to Server	Version	Content	Num. of Characters
Segment	updateReq	% fname:jane % lname:doe % dob:2011-12-10 % sex:f % pid:123-12-1234 % cptX: 2011-12-24 % cptY:2012-12-24 %	109
SMS	IovoxEKMWl4RkJzPoYGrwqfJy +dk2Q4jJGFXCjD3xkkD37SlVMyfFOG3Tr0wPF0YcN75IQPMTD 1hLqRya6yegLTbSxNnmdJQNbG8dEMkXYSYpNF/ oVUG5xzUNrtjAgoU		128

Figure 12. Example of an UpdateRequest Segment

Server to Client	Version	Content	Num. of Characters
Segment	updateRes	Ack:Previous_Patient%Vaccination:2%	45
SMS	Ayw3otuPPEqLrTxMmMCzg2Cf+bUXE4x/ x81UZXeOkSkMfqqFfnFI0y40MMWEiJlJSuj5knzjEp3a6cp2jYHXx Q==		88

Figure 13. Example of an UpdateResponse Segment

CHAPTER 4

PRELIMINARY EVALUATION

We implemented the Jeev client and server using the Android SDK. We used SQLite to store the vaccination records on the server, Zxing [12] for QR code processing on the client, AChartEngine [6] for visualizing the vaccination coverage information on the server, and PowerTutor [29] for measuring the power consumption of the client- and server- side smartphones. For the experiments, we used two HTC One V smartphones each has a 5.0 MP camera, 1.0 GHz processor, 512 RAM/4 GB ROM built-in memory, and running the Android 4.0.3 operating system. The smartphones used Sprint's 3G network in Kansas City. The data in the text messages were encrypted using the 256-bit key AES encryption.

Datasets

We did not have access to vaccination records of children from a rural population, and therefore, we used the National Immunization Survey datasets [4], [8] for the years 2001-2011. They were created through a random-digit- dialing telephone survey of households in the United States for children between the ages of 19 to 35 months. The vaccines that we selected were DTaP (diphtheria and tetanus toxoids and acellular pertussis vaccine), poliovirus vaccine, MMR vaccine (measles, mumps, and rubella vaccine), Hib (Haemophilus influenzae type b vaccine), Hep A (hepatitis A vaccine), Hep B (hepatitis B vaccine), varicella zoster vaccine, PCV (pneumococcal conjugate vaccine), and influenza vaccine.

We uploaded the vaccination records of 100, 200, and 300 thousand children into

SQLite on the server. Indexes were built on three attributes: p_id in the Patient table, v_id and p_id patient in the Vaccination table, and l_id in the Location table. The total database size including the indexes is illustrated in Figure 14.

Number of Patients	Database Size
100 000	172.7 MB
200 000	315.4 MB
300 000	447.4 MB

Figure 14. Datasets and Database Information

Workload

We tested Jeev by running the client and server on two smartphones for three different workloads, namely, W_1, W_2, and W_3. Workload W_1 is shown in Table 1 and was used to measure the performance of data storage and retrieval on the server. The operations in the workload were SQL SELECT and INSERT statements, which were executed directly on the server (See Appendix).

Table 1. Workload W_1

Operation	Description
O_1	Find the total number of children in the patient table
O_2	Find the total number of children who received at least one dose of a particular vaccine

Operation	Description
O3	Retrieve the id of a child using first name and date of birth
O4	Update the vaccination record of a child with 5 vaccines along with the date of vaccination
O5	List the vaccines and dates of vaccination for a particular child
O6	Find all vaccines taken by a child with a particular first name and date of birth (join between the patient and vaccine tables)
O7	List all the female children who have received at least two doses of a particular vaccine (join between the patient and vaccine tables)

Workload W2 is shown in Table 2 and was used to measure the performance of Jeev's client-server model in a real-world cellular network. The client initiated each operation in the workload by sending a text message (to the server) containing the information encoded in a QR code. Based on the request, the server executed one or more SQL statements, and if required returned a particular vaccination record. The text messages exchanged by the client and server are shown in Table II. Operations O8 and O9 retrieved a vaccination record from the server and were different in the number of text messages sent by the server to return the vaccination record to the client. Operation O10 updated a vaccinated record on the server with five vaccines. The communication between the server and client was made secure by encryption.

Table 2. Workload W_2

Operation	Description	SMS Message Exchanges	
O_8	Retrieve the vaccination record of the child identified by a QR code (the vaccination record was within 160 characters)	Client ⇒ Server Client ⇐ Server	2 Messages
O_9	Find the total number of children who received at least one dose of a particular vaccine	Client ⇒ Server Client ⇐ Server Client ⇐ Server	3 Messages
O_{10}	Update the vaccination record of the child identified by a QR code with 5 vaccines	Client ⇒ Server Client ⇐ Server	2 Messages

Workload W_3 is shown in Table 3 and was used to measure the energy consumption of Jeev. Each operation in the workload was initiated by the client by scanning a QR code through the phone's camera, communicating with the server and retrieving the vaccination record of a particular child, and finally updating the vaccination record with new information on the server. O_{11} and O_{12} were different in the number of text messages sent by the server to return the vaccination record to the client. The text messages exchanged by the client and server are shown in Table III. As before, the communication between the server and client was made secure by encryption.

Table 3. Workload W_3

Operation	Description	SMS Message Exchanges	
O_{11}	Client scans the QR code and sends information to the server; server returns the vaccination record of the child; client adds new vaccines and sends an update to the server; server completes the update (the vaccination record was under 160 characters)	Client ⇒ Server Client ⇐ Server Client ⇒ Server Client ⇐ Server	4 Messages
O_{12}	Client scans the QR code and sends information to the server; server returns the vaccination record of the child; client adds new vaccines and sends an update to the server; server completes the update (the vaccination record was under 320 characters)	Client ⇒ Server Client ⇐ Server Client ⇐ Server Client ⇒ Server Client ⇐ Server	5 Messages

Performance Results

First, we present the results for workload W_1. Note that the SQL statements were executed directly on the server. We report the average wall-clock time taken (over three runs) to execute operations O_1 through O_7 in Figure 15. O_2 performed duplicate elimination and required more time to finish. O_7 performed a join, followed by grouping and counting, and as expected had the highest average execution time (i.e. 18-50 seconds).

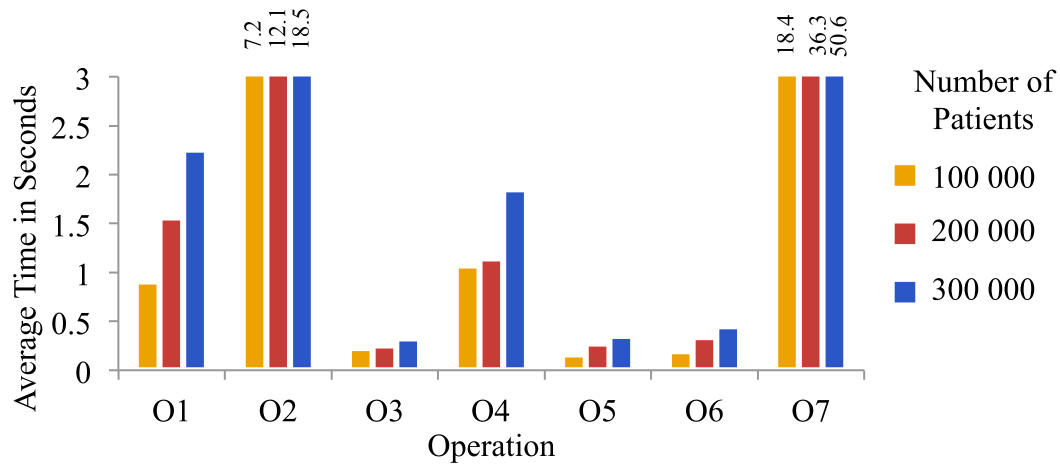

Figure 15. Server Processing Time for Operations in Workload W1

Next, we present the results for workload W2. For O8 and O9, we measured the average wall-clock time taken (over three runs) to process the client's request. This included the time to send a text message to the server, decrypt the message and process the SQL statements on the server, and return the (encrypted) vaccination record to the client and decrypt the vaccination record on the client.

The performance results are shown in Figure 16. Interestingly, most of the time was spent in communicating between the client and the server via text messaging. O9 required more time than O8 because the vaccination record was sent using two text messages by the server. The time taken by the server to process all the SQL statements in each operation was under 1.2 seconds and is shown in Figure 17. Clearly, the response time seen by the client was dominated by the communication latency through the cellular network.

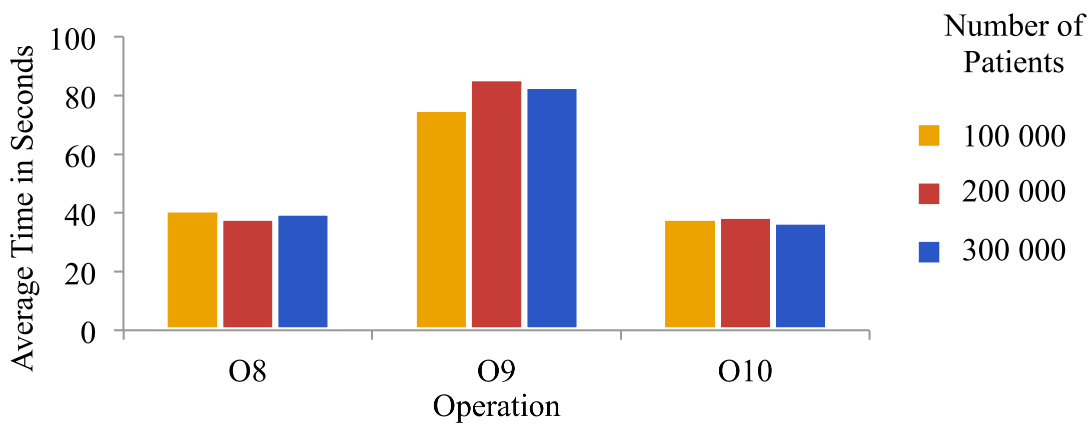

Figure 16. Total Time for Operations in Workload W_2

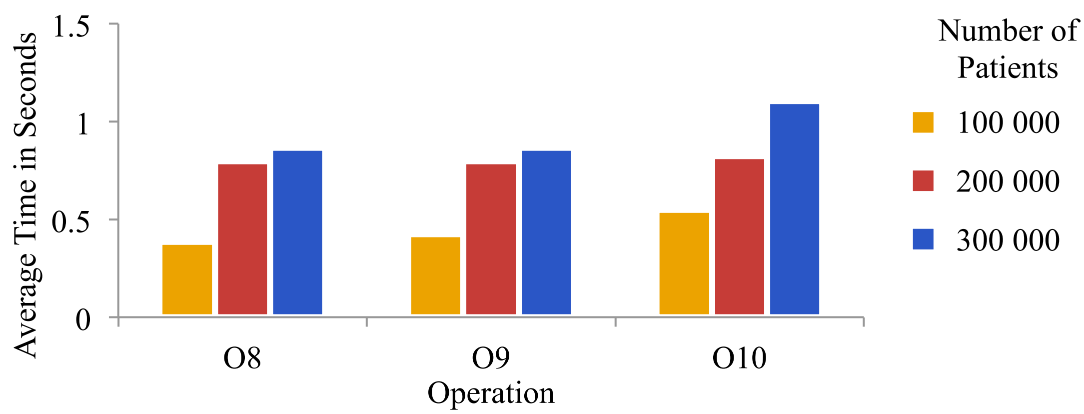

Figure 17. Server Processing Time for Operations in Workload W_2

Power Consumption

We measured the end-to-end power consumption of Jeev using workload W3, beginning with scanning a QR code using the client's camera to completing the update of a vaccination record on the server. We included the energy required for CPU, LCD, GPS, SMS, and system services. (In O12, the size of the vaccination record returned to the client was larger than in O11 and therefore, required two text messages.) The average power consumption (over 3 runs) on the client-side is shown in Figure 18 and each operation consumed less than 1.4 Watts. The average power consumption on the server-side is shown in Figure 19 and each operation consumed less than 0.4 Watts. On the client-side, the user interfaces were active and therefore, led to higher power consumption compared to the server-side. (The LCD/display on the server was turned off.) Note that each phone had a 3.8V, 1500mAh battery capable of steadily despising 5.7 Watts for one hour before becoming depleted.

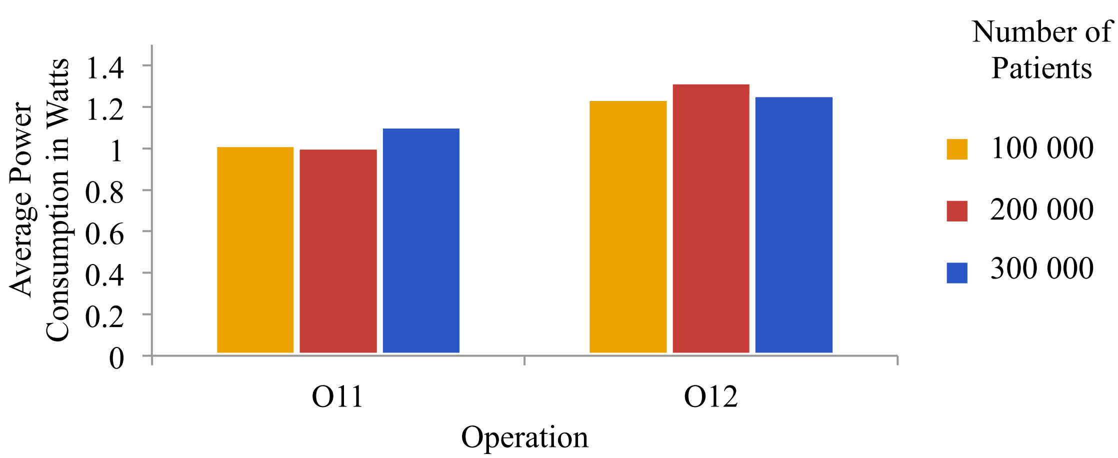

Figure 18. Client Power Consumption for Operations in Workload W3

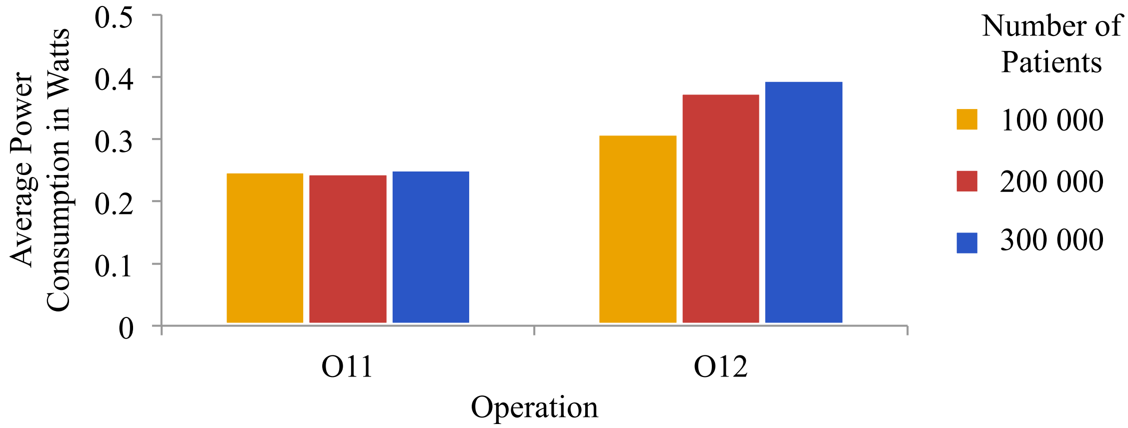

Figure 19. Server Power Consumption for Operations in Workload W3

CHAPTER 5

CONCLUSION AND FUTURE WORK

We presented a low-cost cell phone application called Jeev to track the vaccination coverage of children in rural communities. Jeev synergistically combines the power of smartphones and cellular infrastructure, QR codes, and national identification cards. Jeev does not use any biometric data. It is based on a client-server model and uses low- cost text messaging. Data captured by different clients can be synchronized on the server in real-time. We presented a preliminary evaluation of Jeev's performance and energy consumption using the National Immunization Survey datasets to show its efficiency.

Haiti is an ideal country to test Jeev because it has low vaccination rate, high infant mortality rate, and is an under- resourced country. Since the catastrophic earthquake in 2010, the cell phone market has grown considerably in Haiti through relief initiatives [3]. Two-thirds of Haitians have access to cell phones [24]. Cell phones and SMS messaging have become popular among Haitians for mobile banking and access to other services [3]. We plan to pilot test Jeev in rural Haiti through Maison de Naissance (MN). MN is a modern, community health care facility in Haiti dedicated to delivering healthy mothers and healthy babies in rural areas [14]. MN aims to make innovative use of technology for providing high-quality care to mothers and children. Its existing infrastructure is ideal for pilot testing Jeev [16].

We plan to study the effectiveness of Jeev in terms of the durability of QR code stickers, the robustness of our scheme in correctly identifying infants at different geographical locations and times, cost of operation, scalability, and ease of use by health workers. We will recruit families with infants and newborns under MNs coverage and track their vaccination status for a period of one year. We will measure the vaccination drop out rates for these families. We will also study how Jeev can cope with cellular coverage in hilly areas of Haiti and identify socio-cultural issues that must be addressed for large-scale deployment of Jeev. We are aware that there will be challenges in developing mobile interfaces for low-literacy, rural population [23], [18].

APPENDIX

SQL STATEMENTS

Operation	SQL Statement
O1	SELECT COUNT(*) FROM Patient_Table;
O2	SELECT COUNT(DISTINCT p_id) FROM Vaccination_Table WHERE cpt_code=xxxxx;
O3	SELECT p_id FROM Patient_Table WHERE fname ='xxxxxxx' AND dob='yyyy-mm-dd';
O4	INSERT INTO Vaccination_Table (p_id,vdate,cpt_code) SELECT x AS patient_id, 'yyyy-mm-dd' AS vdate, 90744 AS cpt_code UNION SELECT x,'yyyy-mm-dd' , 90713 UNION SELECT x,'yyyy-mm-dd' , 90633 UNION SELECT x,'yyyy-mm-dd' , 90680 UNION SELECT x,'yyyy-mm-dd' , 90655;
O5	SELECT cpt_code, vdate FROM Vaccination_Table WHERE p_id = xxxxx;
O6	SELECT cpt_code FROM Vaccination_Table as VT INNER JOIN Patient_Table AS PT ON VT.p_id = PT.p_id WHERE PT.fname = 'xxxxxx' AND PT.dob = 'yyyy-mm-dd';
O7	SELECT COUNT(VT.p_id) FROM Vaccination_Table as VT INNER JOIN Patient_Table AS PT ON VT.p_id = PT.p_id AND PT.sex='f' WHERE VT.cpt_code=xxxxx GROUP BY VT.p_id HAVING COUNT(*) > 1;

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VITA

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