A Prototype of a Low-Cost Cell Phone Application for Tracking the Vaccination Coverage of Children in Rural Communities

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Abstract

Immunization saves millions of lives against vaccine-preventable diseases. Yet, 24 million children born every year do not receive proper immunization during their first year. UNICEF and WHO have emphasized the need to strengthen the immunization surveillance and monitoring in developing countries to reduce childhood deaths. In this regard, we present a software 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, QR codes, and national identification cards. We present the design of **Jeev** and highlight its unique features along with a detailed evaluation of its performance and power consumption using the National Immunization Survey datasets. We are in discussion with a non-profit organization in Haiti to pilot test **Jeev** in order to study its effectiveness and identify socio-cultural issues that may arise in a large-scale deployment.

Keywords: QR codes; vaccination coverage; children; cell phones; rural communities

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1. Introduction

Immunization saves millions of lives against vaccine-preventable diseases. Through financial support from organizations such as the GAVI Alliance, and more recently the Bill & Melinda Gates Foundation, a lot of progress has been made in immunizing children since 2000 towards the Global Immunization Vision Strategy (GIVS) [51]. The number of deaths in children under 5 years of age has decreased. Yet, 24 million children born every year, do not receive proper immunization during their first year of life [51].

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 UNICEF and WHO [51], the health care systems are weak in developing countries.¹ There is insufficient political and financial support. The monitoring infrastructure is weak and information systems are lacking. There is a shortage of trained health workers who can deliver immunization to the population. Many children live in poor, remote areas where health care facilities and public services are weak. Due to lack of information about the importance of immunization, many children do not receive the required vaccines. Unexpected deaths and side effects create fear of immunization among parents, thereby reducing the number of children who receive a full course of vaccines.²

UNICEF and WHO have emphasized the need to strengthen immunization surveillance and monitoring in developing countries [51]. Immunization coverage information is useful to monitor the performance of immunization programs and improve the delivery of vaccines to the population [50]. Today, the use of paper records to track the immunization status of children in countries such as India leads to inconsistencies in the way information is recorded; immunization records

¹The World Bank defines a country with low-income or middle-income economy to be a developing country [13].

²Recently, polio vaccines caused paralysis in 47,500 children in India [36].

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9 may be lost or damaged [20, 2, 10]. Lack of immunization coverage information
10 can lead to wastage of vaccines due to unnecessary revaccinations and poor
11 forecasting of the vaccine demand [51, 10].

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14 There has been an unprecedented rise in the use of cell phones worldwide;
15 today, there are more than 6 billion cell phone subscribers [11]. Through cell
16 phones, it is now possible to communicate with vast populations in previously
17 hard-to-reach areas. The ubiquity of cellular infrastructure provides new op-
18 portunities to develop cell phone-based solutions for tracking the vaccination
19 coverage of a rural population. In India, a middle-income economy [13], about
20 40% of the rural population has cell phones (or mobile phones) [29]. In Haiti, a
21 low-income economy [13], the cellular infrastructure has grown quickly since the
22 devastating earthquake of 2010. Haitians are using cell phones to receive relief
23 incentives [42]. Furthermore, UNICEF has identified countries like India and
24 Haiti as priority countries where routine immunization coverage is low and must
25 be improved [44, 45]. (Immunization tracking is a challenge even in countries
26 such as USA, but our focus is on developing countries.)

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29 While tracking the vaccination coverage of a population has become a global
30 challenge in public health³, little research has been done in this domain. This
31 is a timely opportunity for the health informatics community. In this work, we
32 address the problem of tracking the vaccination coverage of children in hard-to-
33 reach areas such as rural India, where cellular infrastructure is available. We
34 present a low-cost cell phone application called **Jeev**.⁴ **Jeev** is unique in the
35 sense that it synergistically combines the power of smartphones and ubiquity of
36 cellular infrastructure, Quick Response (QR) codes, and national identification
37 cards. **Jeev** is based on a client-server model: the data collected by the clients
38 are synchronized at the server; the clients and server exchange small amounts

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³Recently, the Bill and Melinda Gates Foundation solicited proposals for developing low-cost cell phone applications to improve the uptake and coverage of childhood vaccinations as one of the grand challenges for 2011 [2].

⁴**Jeev** means 'life' in the Sanskrit language.

of data using low-cost SMS text messaging. (The transmitted data is always encrypted for security and privacy reasons.) We report a detailed evaluation of **Jeev** to study its performance, scalability and power consumption, 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 Maison de Naissance [14], which is a community health care facility for delivering healthy mothers and healthy babies.

The rest of the paper is organized as follows. Section 2 provides the background and related work. Section 3 presents the design of **Jeev**. Section 4 describes the communication protocol in **Jeev**. In Section 5, we report the performance evaluation of **Jeev**. Section 7 discusses our next steps for pilot testing **Jeev** in a rural community. Finally, we provide our concluding remarks in Section 8.

A preliminary version of this paper appeared in the 2013 IEEE International Conference on Healthcare Informatics [32].

2. Background and Related Work

2.1. Cellular Infrastructure in Developing Countries

Today, there are more than 6 billion cell phone subscribers [11]. The cellular infrastructure is ubiquitous in many developing countries and provides an easy way to connect to vast populations in hard-to-reach areas [21, 29, 42]. Smartphones have become popular and affordable; they have powerful processors, several GBs of storage, high resolution cameras, several hours of battery life, and touch screen technology. SMS text messaging provides an inexpensive way to communicate small amounts of data in hard-to-reach areas. Today, it costs less than \$0.02 to send a text message in countries like India, Pakistan, Bangladesh and Haiti [19]. Data can be encrypted for security and privacy reasons.

2.2. Quick Response Codes

Quick Response (QR) codes have fast readability and higher storage capacity (up to 400 times more) as compared to standard UPC barcodes [15, 38]. QR codes are 2-dimensional and can encode any type of data and even encrypted data. They have become popular in businesses and among consumers. QR codes use advanced error correcting codes. Even with up to 30% damage, a QR code can still be decoded [7]. (See Figure 1(a).) QR codes can also be modified for artistic reasons and still be decoded. (See Figure 1(b).) They can be easily decoded using applications on smartphones [12].

Figure 1: (a) A damaged QR code that can be decoded. (Source: Wikipedia [7]) (b) A modified QR code that can be decoded.

2.3. National Identity Cards

National identity 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 [26]. These cards are usually laminated or made of plastic and are more durable than paper records.

2.4. Technology Advancements for Advancing Immunization Programs

Closely related to our work is VaxTrac, which has received funding from the Bill & Melinda Gates Foundation. It captures and processes infant fingerprints

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9 using fingerprint readers and inexpensive netbooks [10]. However, we believe
10 there are some potential limitations: The system may not scale in large ge-
11 ographical regions because images are large in size and have to be physically
12 transferred to integrate them in a central location. This also raises the issue of
13 how to synchronize the data on the netbooks carried by health workers. Fur-
14 thermore, fingerprints of infants change in size as they grow. Infants may not
15 be cooperative to allow health workers to take good fingerprints.

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

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23 Abhishek *et al.* [20] proposed the notion of mobile health cards to increase
24 the immunization rate in rural areas. They highlighted the current problems
25 with paper based records in rural India such as lost or damaged paper immu-
26 nization forms. They suggested that all activities involved during immunization
27 should be moved to the mobile platform using cell phones. Each child would be
28 assigned a unique id generated by the system; the authors mentioned the use
29 of biometric technology. However, no real system has been developed using the
30 proposed ideas.

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32 In the US, Cook Children’s healthcare system, in partnership with athenahealth,
33 Microsoft, Sanofi Pasteur and Merck, has began using QR codes on vaccine bot-
34 tles [1]. This will result in easy management of vaccines, tracking of vaccination
35 status, and allow integration of vaccination information with EHR systems.
36 *Jeev* is different in the sense it uses QR codes to identify children instead of
37 vaccines and is designed for a rural population, where the computing infrastruc-
38 ture is minimal.

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40 Another prominent effort is OpenLMIS, an open-source platform designed
41 to manage health commodity supply chain in low-income and middle-incomes
42 economies [47]. This platform was implemented in the African countries of
43 Mozambique, Tanzania, and Zambia. More recently, Anderson *et al.* [23] devel-

oped a Cold Chain Information System to improve the immunization program in Laos. This system was designed to regularly report the vaccine stock levels and vaccine refrigerator status using Android phones and SMS text messaging.

2.5. Mobile Health (*mHealth*)

The term mHealth (or mobile health) refers to the practice of medical and public health using mobile technology such as mobile phones, personal digital assistants (PDAs), and so forth [49, 30]. mHealth is a fast growing discipline for public health due to the growth in mobile devices and communication infrastructure in many countries.

More than a decade ago, Srivastava *et al.* [43] discussed the problems associated with the use of information systems in rural economies for healthcare management. They proposed a cost-effective system based on wireless ad-hoc networking by utilizing existing transportation infrastructure to deliver healthcare services to villages. Kato *et al.* [33] studied the different 2D barcodes including QR codes for camera phone applications. They developed a set of criteria for selecting the best 2D barcode given the capability of the mobile phones camera and operating conditions. Later, Navarro *et al.* [41] studied the feasibility of a 3G-based m-Health system for emergency scenarios. Their system used advanced signaling protocols for multimedia multi-collaborative conferences over IPv4/IPv6 networking. It supported simultaneous transmission of both real-time clinical data, videoconferencing, and non real-time medical services.

In 2006, Kaplan *et al.* [31] reported that while there are several attractive reasons to use mobile phones for healthcare interventions in developing countries, the shared ownership of these phones may limit their adoption. They also reported that there is no literature on using mobile phones as a healthcare intervention for diseases like HIV and malaria in developing countries. A few years later, Laakko *et al.* [35] proposed a new mobile platform called the Ubiquitous Personal Health Information Access (UPHIAC) platform for providing connectivity between healthcare providers, patients, and measurement devices

for different telemedicine and wellness applications. HL7 CDA was used to exchange data between different components in the system. The authors developed a mobile tele-ECG application using their framework to demonstrate its feasibility. Black *et al.* [24] proposed to extend a mobile phone's capability with external sensors for providing low-cost mobile health applications in developing countries. They developed five new applications (*e.g.*, respiratory and pulse rate calculator, gestational dates calculator) and sensor modules such as oximeter sensor, ECG sensor, and phonocardiogram.

More recently, there has been increased interest in developing mHealth solutions for low-resource environments. Medhi *et al.* [39] developed a low-cost mobile phone based system for data collection and reporting to improve over paper-record management. This solution was used for a program aimed at prevention of child malnutrition in rural India. Vodopivec-Jamsek *et al.* [48] studied the impact of mobile phone messaging (*e.g.*, SMS) for preventive healthcare and observed positive benefits of messaging in certain patient population. Zhang *et al.* [52] proposed a vaccination strategy for a population to prevent the spreading of diseases. Their strategy was based on analyzing mobile phone records to understand the social-interaction patterns among individuals. Khan *et al.* [34] developed a cell phone based solution for early detection of respiratory disorders for rural children using a modified stethoscope. The sound recording and the case history of the patient were transmitted via email to the health care center. Analysis of the recording was done by training a neural network to detect respiratory disorders and checked by a healthcare practitioner. Vaidya *et al.* [46] developed a portable diagnostic and communication device for remotely monitoring patients in rural areas. They built a health kiosk and smartphone software to present the patient data to doctors remotely and used a cloud platform to store the data. Their system was tested in a rural area of India.

In recent years, a few researchers conducted systematic review and analysis of mHealth for developing countries. Zurovac *et al.* [54] suggested the use of text messaging on mobile phones for malaria control in Africa. They identified six areas of malaria control whose deficiencies could be overcome through text

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9 message based interventions. Deglise *et al.* [27] conducted a systematic review
10 of mobile health applications using SMS for disease control in developing coun-
11 tries. They concluded that most of the applications used bulk messaging and
12 were well accepted by the population. Martinez *et al.* [37] reviewed mobile
13 health applications available for the most prevalent health conditions identified
14 by WHO. They concluded that while there were many applications for depres-
15 sion and diabetes, there was a lack of applications for other conditions like
16 anemia, low-vision, and hearing loss.
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21 There has also been some interest in addressing the security issues of using
22 mobile devices for healthcare services. Ahmed *et al.* [22] explored the key secu-
23 rity threats that arise in handling sensitive data on mobile devices for healthcare
24 use cases. They developed a security framework to protect against these threats
25 by providing physicians and patients a guarantee that sensitive information will
26 not be transmitted without their knowledge. Gejibo *et al.* [28] developed a
27 secure data storage system on low-cost mobile phone with limited software ca-
28 pability for sensitive data in mHealth applications. They tested their approach
29 using an open-source Mobile Data Collection System (MDCS).
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37 **3. The Design of JEEV**

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40 There are a few design requirements for a vaccination coverage tracking
41 application to successfully operate in rural communities. Firstly, a child may
42 be vaccinated at different locations and therefore, must be identified correctly
43 to avoid missing vaccines and receiving unnecessary revaccinations. Secondly,
44 cellular coverage in certain areas may be lacking at times, and therefore, the
45 application should cope with such situations. Thirdly, the application should
46 be low-cost and easy to use and deploy in rural communities. Finally, the
47 application should be efficient in performance and energy consumption.
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52 We have developed a novel application called *Jeev* for tracking the vaccina-
53 tion coverage of children in rural communities. *Jeev* synergistically combines
54 the power of smartphones and the ubiquity of cellular infrastructure, QR codes,
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and national identity cards. **Jeev** is based on a client-server model: it has a client-side software and a server-side software. (Hereinafter, we simply use the terms *client* and *server*.) The server 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 with Internet connectivity in these areas would be expensive. The server can be located in a community clinic or health care facility. A health worker carrying a smartphone running the client 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.⁵ The clients and server communicate via SMS text messaging and do not require a data communication network like 3G. The transmitted data is encrypted for security reasons.

Figure 2 illustrates how **Jeev** 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 national id card (*e.g.*, name). This information is then encrypted and a QR code is generated and printed on a sticker of 50x50 pixels in size. (Printing can be done using a portable label printer priced less than \$100.) 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 string from which the QR code was generated for backup purpose. This is useful in case the national ID card and/or QR code are lost or damaged, and will be discussed later. (Note that the parent's cell phone need not be a smartphone, which is quite realistic in rural areas.) The QR code on the

⁵In the current design, we use one server and multiple clients. If scalability and reliability become an issue, we can opt for multiple servers. We can avoid loss of data on the server by performing routine backups on inexpensive micro SD cards.

Figure 2: Overview of Jeev. (Image sources: www.cdc.org, <https://en.wikipedia.org/wiki/File:AadharBlurred.jpg>.)

sticker uniquely identifies the child during future immunization visits. It can be decoded only by authorized clients. 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 3(a).

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.

Jeev has intuitive user interfaces for health workers and officials both on the client- and server-side. A few screenshots on the client-side are shown in Figures 3(b) and 3(c). A few screenshots on the server-side are shown in Figure 3(d) and 3(e), where the vaccination coverage information is displayed. If

(a)

(b)

(c)

(d)

(e)

Figure 3: (a) Database schema on the server-side. (b)-(c) Screenshots of **Jeev** on the client-side. (d)-(e) Screenshots of **Jeev** on the server-side.

client-side smartphones have GPS capability, then the vaccination coverage of children can be mapped and visualized on an interactive map. Figures 4(a) and 4(b) show the relative size of the portable printer and the scanning process, respectively.

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 as a backup on the parent's cell phone, which was provided during the first visit. The encrypted data can be used to regenerate the original QR code using the

Figure 4: (a) Portable printer for printing QR codes. (b) Scanning a QR code.

software available on the client smartphone. If the parent loses his/her phone or does not use it anymore, then this information is not available for recovering the original QR code. As a final resort, the health worker can ask relevant questions to the parent and try to identify the child and locate its vaccination record on the server. Because vaccination records are stored in an RDBMS on the server, appropriate SQL queries can be posed to retrieve the record using 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.

4. Jeev's Communication Protocol

In this section, we describe the communication protocol in **Jeev**. The communication between the client and the server is carried out by exchanging request and responses messages, via SMS text messaging, that facilitate various interactions such as retrieving and updating vaccination records. The message packet is composed of two sections: a message type and a payload. The message type indicates the purpose of the message and aids in processing the payload. The payload contains name-value pairs depending on the type of message.

In Table 1, we show examples of different messages and their sizes. For example, message ❶ has a message type 101, which specifies a request message to retrieve a vaccination record for the patient and is sent by the client to the server. The payload contains information to identify the patient. Message ❷ has a message type 201 to indicate the response from the server to the client, and the payload contains the vaccination record of the patient. Message ❸ denotes the update request message from the client to the server along with the attributes in the record that must be updated. Message ❹ denotes the acknowledgment from the server to indicate a successful update operation.

In **Jeev**, the messages are encrypted using the 256-bit key AES encryption. Depending on the size of the encrypted message, one or more text messages are sent. For example, the encrypted message ❶ is only 87 characters and hence sent as single SMS text message. However, the encrypted message ❷ is greater than 160 characters and therefore, is sent as two SMS text messages. A sequence number is used to indicate the order of the text messages so that the recipient can reassemble them in the correct order. The (reassembled) message is then decrypted by the server to obtain the original message.

5. Performance Evaluation

We implemented the **Jeev** client and server using the Android SDK. We used SQLite [18] 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 [53] for measuring the power consumption of the client- and server-side smartphones. For the experiments, we used two HTC One V smartphones with 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.

Table 1: Communication protocol in Jeev

Message Direction (Type)	Message Content	Size	SMS	Encrypted Content	Size
➊ Client ⇒ Server (Info-Request)	101%fname:jane%dob:2011-12-10%	30	➊	dZiMnJXI7veeZKFCpP91+A38b68hBO/0ER/113OQU1hv6/CLu C5wKcGIWUeyZWIBLnK4596lwei3L5ZpvIBIJg==	87
➋ Server ⇒ Client (Multi-Response)	201%fname:jane%lname:doe%sex:f% dob:2011-12-10%pid:123-12-1234%cptcodeX:2 %cptcodeY:2%cptcodeZ:4%cptcodeW:3% cptcodeO:2%cptcodeP:2%cptcodeQ:3% cptcodeR:3%cptcodeS:3%cptcodeT:1%	172	➋	7lc0Cj4KBXiGCU3mbjjacolePBISyJC4kcpLq1K4fHNjPbeagdrC 2Jfy26yHwed6UPagDgrXdllhZ+aBgI8NSNJAAGm/urEJR8W1dkT YYinPdthF2VpIW64EbJWnJ4E+9DV+6ejhzEa0TmtYLz1JM9Q 8FBnxSgzNM	160
			➌	9JrxW+IO68FKunY9nhb320MyMUxydTUFruFRYRFGGu4QF CCVjfozjo062aN6Ue42Bx0zanCwnhaYlb3ZG+W9AQdL7aX UntRN4XPHdRdr822Zmf8qybkuKaIXHL+4FwKpiM7v9En9 M=	141
➍ Client ⇒ Server (Update-Request)	121%fname:jane%lname:doe%sex:f% dob:2011-12-10%pid:123-12-1234% cptX:2011-12-24%cptY:2012-12-24%	94	➍	IovoxEKMWl4RkKJzPoYGrwqfJy+dk2Q4jJGFXCjD3xkkD37SIV MyfFOG3T-0wPF0YcN75IQPMTD1hLqRya6yegLTbSxNnmJQ NbG8dEmkXYSYNF/ovUG5xzUNrtjAgoU	128
➎ Server ⇒ Client (Update-Response)	221%Ack:Previous_Patient%Vaccination:2%	39	➎	Ayw3otnFPPEqLrTxMmMCg2Cf+bUXE4x/xs1UZXeOkSkMfqq FfnFI0y40MMWWEiJJISuj5knzIEp3a6cp2jYHXxQ==	88

Table 2: Datasets used for the evaluation of *Jeev*

Data set name	# of children	# of records			Total size (MB)	Survey years
		Patient table	Vaccination table	Location table		
D_1	102,508	102,508	1,692,024	1,692,024	187	2008-2011
D_2	100,000	100,000	1,653,191	1,653,191	173	2001-2011
D_3	200,000	200,000	2,967,207	2,967,207	315	2001-2011
D_4	300,000	300,000	2,967,207	2,967,207	447	2001-2011

5.1. 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 through 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 prepared four datasets as shown in Table 2. Each dataset was uploaded into SQLite (on the server) based on the schema shown in Figure 3(a). 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. For each dataset, Table 2 also shows the number of records in each table and the total database size including the indexes. (Only the performance evaluation of *Jeev* on D_1 was previously reported in the conference version of this paper [32].)

5.2. Workloads used for Dataset D_1

We tested **Jeev** on D_1 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 3 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.)

Workload W_2 is shown in Table 4 and was used to measure the performance of **Jeev**'s client-server model in a real-world cellular network. Each operation in the workload was initiated by the client 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 4. Operations O_8 and O_9 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 Q_{10} updated a vaccinated record on the server with five vaccines. The communication between the server and client was made secure by encryption.

Workload W_3 is shown in Table 5 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 Q_{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 5. As before, the communication between the server and client was made secure by encryption.

5.3. Performance Results for Dataset D_1

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 5(a). O_2

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Table 3: Workload W_1

	Operation
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
O_3	Retrieve the id of a child using first name and date of birth
O_4	Update the vaccination record of a child with 5 vaccines along with the date of vaccination
O_5	List the vaccines and dates of vaccination for a particular child
O_6	Find all vaccines taken by a child with a particular first name and date of birth (join between the patient and vaccine tables)
O_7	List all the female children who have received at least two doses of a particular vaccine (join between the patient and vaccine tables)

Table 4: Workload W_2

	Operation	SMS message exchanges	
		client	server
O_8	Retrieve the vaccination record of the child identified by a QR code (the vaccination record was within 160 characters)	① $\Rightarrow$ ② $\Leftarrow$	
O_9	Retrieve the vaccination record of the child identified by a QR code (the vaccination record was within 320 characters)	① $\Rightarrow$ ② $\Leftarrow$ ③ $\Leftarrow$	
O_{10}	Update the vaccination record of the child identified by a QR code with 5 vaccines	① $\Rightarrow$

(a) Time spent by the server to process operations in workload W_1

(b) Time taken to process requests from the client in workload W_2

(c) Time taken by the server for processing operations in workload W_2

Figure 5: Performance evaluation of Jeev.

Table 5: Workload W_3

	Operation	SMS message exchanges	
		client	server
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)	① $\Rightarrow$ ② $\Leftarrow$ ③ $\Rightarrow$	
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)	① $\Rightarrow$ ② $\Leftarrow$ ③ $\Leftarrow$ ④ $\Rightarrow$	

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 execution time, *i.e.*, 12.9 secs.

Next, we present the results for workload W_2 . For O_8 and O_9 , 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. For O_{10} , the client did not receive an acknowledgment, and therefore, the completion time was when the server finished updating the vaccination record. (It is possible to provide an acknowledgment to the client via a text message. We added this feature for the experiments reported in Section 5.5.)

The performance results are shown in Figure 5(b). Interestingly, most of the time was spent in communicating between the client and the server via text messaging. O_9 required more time than O_8 because its 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 0.3 secs and is shown in Figure 5(c). Clearly, the response time seen by the client was dominated by the communication latency through the cellular network.

5.4. Power Consumption for Dataset D_1

We measured the end-to-end energy consumption of Jeev using workload W_3 , 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 O_{12} , the size of the vaccination record returned to the client was larger than in O_{11} and therefore, required two text messages.) The average energy consumption (over 3 runs) on the client-side is shown in Figure 6(a) and each operation consumed less than 110 Joules. The average energy consumption on the server-side is shown in Figure 6(b) and each operation consumed less than 25 Joules. On the client-side, the user interfaces were active and therefore, led to higher energy consumption compared to the server-side. (The LCD/display on the server was turned off.) Note that each phone had a 4.1V, 1500mAh battery capable of storing 22,140 Joules of energy.

Figure 6: Energy consumption of Jeev.

Table 6: Updated Workloads

Operation	Workload	SMS message exchanges	
		client	server
O_{10}	W_2	① $\Rightarrow$ ② $\Leftarrow$	
O_{11}	W_3	① $\Rightarrow$ ② $\Leftarrow$ ③ $\Rightarrow$ ④ $\Leftarrow$	
O_{12}	W_3	① $\Rightarrow$ ② $\Leftarrow$ ③ $\Leftarrow$ ④ $\Rightarrow$ ⑤ $\Leftarrow$	

5.5. Scalability of Jeev

We tested the scalability and power consumption of **Jeev** using the datasets D_2 , D_3 , and D_4 (Table 2) by increasing the number of vaccination records in the database. We used workload W_1 as shown in Table 3. The average wall-clock time taken to process each query in W_1 is shown in Figure 7(a). As expected, the time increased with increase in the size of the database. Overall, SQLite yielded good scalability as a database system for **Jeev**. For example, O_7 performed a join operation and the total time increased by a factor of 2.7 when the number of vaccination records increased by 3 times. Similar trend was observed for other operations.

Next, we used workload W_2 (Table 4) with a small modification to O_{10} . We added an explicit acknowledgment from the server to the client in O_{10} via an SMS text message. Table 6 shows the updated operation O_{10} . We measured the

(a) Time spent by the server to process operations in workload W_1

(b) Time taken to process requests from the client in workload W_2

(c) Time taken by the server for processing operations in workload W_2

Figure 7: Performance evaluation of Jeev.

Figure 8: Peak power consumption of *Jeev*.

time starting from when an operation was initiated by the client till the receipt of the vaccination record or the final acknowledgment. We report the average wall-clock time taken to process the operations O_8 , O_9 , and O_{10} in Figure 7(b). Similar to the observations reported for D_1 , the communication latency through the cellular network dominated the total response time seen by the client and therefore, there was little change in the total time with increase in the database size.

Next, we used workload W_3 (Table 5) with a small modification to operations O_{11} and O_{12} . We added an explicit acknowledgment from the server to the client as shown in Table 6. The rest of the setup was similar to that described in Section 5.4. We measured the peak power consumption during the execution of the operations in W_3 to understand the power requirements of *Jeev* with increasing size of the database. Figures 8(a) and 8(b) show the peak power consumption by the client and the server, respectively. Clearly, the change in the peak power consumption was small as compared to the increase in the database size. This was because of the relatively small increase in the processing time at the server compared to the communication latency.

6. Plan for Pilot Testing Jeev

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 [42]. Cell phones and SMS text messaging have become popular among Haitians for mobile banking and access to other services [3].

While **Jeev** has performed well in a lab setting in Kansas City, we aim to validate its efficacy in a real environment. We propose to deploy and test **Jeev** in the commune of Torbeck, Haiti, which has a population of about 69,000 people. Torbeck is a low-resourced, rural area ideal for validating our system. Our partner, the Global Birthing Health Foundation, operates Maison de Naissance (MN), a modern healthcare facility for supporting healthy mothers and healthy babies in rural Haiti [14]. MN is committed to expanding their vaccination program by vaccinating all mothers and children in its zone of service against diphtheria, tetanus, polio, and German measles (rubella). MN was established in 2004 in Torbeck, Haiti. MN has delivered more than 4,700 healthy babies and provided 128,000 consultations. MN’s high quality care includes the following: (a) well-trained and supervised midwife and auxiliary-nurse staff for in-facility care 24/7; (b) adequate equipment and infrastructure (*e.g.*, solar panels) for 100 deliveries/month; (c) electronic medical records are being used from when MN was founded; (d) strong private and public financial support and partnerships; (e) a volunteer comité de santé (CS): teachers, clergy, and respected community leaders, with strong “ownership” of the program, and 6 paid Community Health Workers (CHWs) in MN’s zone of service; and (e) a state-of-the-art film about barriers to facility-based deliveries, with the aim of increasing the people’s positive views of in-facility delivery, staff sensitized and trained in patient education, and community awareness and encouragement to utilize free clinic services.

The CHWs are responsible for health education, health screenings, and deliv-

Activity	Completion Time
The team visits Haiti and the project commences.	Month 1
Jeev operates under the real-operating constraints in Torbeck. Jeev supports the Haitian Creole language. The CHWs of MN complete their training on how to use Jeev . Their feedback is used to improve the features and user interface of Jeev .	Month 4
Twenty pregnant women in their third trimester are enrolled for the study and have received adequate education about the benefits of immunization on their child's health.	Month 6
The team visits Haiti to access the progress of the project and address any unexpected challenges and constraints. Enhancements to Jeev are made based on new findings and feedback.	Month 8
The cohort of newborns has been vaccinated and tracked by Jeev for six months.	Month 14
The cohort has been vaccinated and tracked by Jeev for one year. Their vaccination records are transferred to the EMR system of MN to provide continuity of care.	Month 21

Table 7: Timeline of activities

ery of basic medications. They encourage women to engage in healthy behaviors by attending prenatal, vaccination and family planning clinics. They are also trained to identify individuals who would benefit from immediate treatment at MN or a hospital. They are supervised and evaluated by clinical staff before undertaking a particular service. The evaluations are reported to the Clinical Director of MN.

During our first visit to Haiti, we will evaluate the cellular coverage in the areas serviced by MN. We will train one CHW of MN to use **Jeev** through video lectures and hands-on usage. We will also obtain her feedback. Then we will

improve the **Jeev** software to cope with the real-operating conditions in Haiti. We will recruit 20 pregnant women in their third trimester to participate in our study. They will be provided with monetary incentives. We will educate them on the importance of vaccinating children to save their lives. We will discuss how **Jeev** will help us monitor the vaccination status of their children and provide assistance to them. This will be done through video lectures, face-to-face conversations, and community gatherings. The newborns of these mothers will be monitored during their first year. Every week, we will backup the database on the **Jeev** server by copying it to a computer operated by MN. This will prevent loss of data due to cell phone crashes.

We will evaluate the vaccination coverage and drop-out rates of the participants. We will also measure the number of infant deaths. We will compare these results with the trends for the overall population. We will use feedback from the participants to improve the usability of **Jeev**. We also 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, scalability, and ease of use by CHWs. We are aware that there will be challenges in developing mobile interfaces for low-literacy, rural population [40, 25]. In Table 7, we show the timeline of activities for pilot testing **Jeev**.

Using the Internet, we researched the current prices of different hardware and software resources required by **Jeev**. These prices are reported in Table 8. Based on a discussion with the staff at MN, we also report the personnel, training, and supervision costs in Table 8. Overall, **Jeev** requires a small initial investment and low operating cost to sustain itself in a developing country like Haiti.

7. Discussion

Today, people in more than 200 countries use cell phones [16]. While there are some developing countries where cell phone usage is prevalent (*e.g.*, Haiti, India), others are yet to see a rise in cell phone usage. For example, the world's

Resource	Price (in USD)
Two Android smartphones (a client and a server)	$2 \times \$40 = \80
Cellular service plan (www.digicelhaiti.com)	Prepaid (no deposit fee); \$15 for 750 SMS messages (\$0.02 per message)
Portable label printer (Epson)	\$99
Cost of printing paper (Epson)	\$18 (about 360 QR code stickers)
Salary for a CHW at MN	\$150/month
Bonus for a CHW at MN	\$150/year (as per Haitian Labor Law)
Training and supervision costs	\$500/year

Table 8: Cost of operating **Jeev** in Haiti through MN

poorest country [13] has about 4.4 million cell phones for a population of 16.7 million [16]. One may wonder if **Jeev** can operate in such countries. We discuss a few requirements of **Jeev** in this context. First, the region of such a country with low cell phone supply should have a reasonable cellular infrastructure. **Jeev** does not require every parent to carry a cell phone. (If a parent does have a cell phone with SMS capability, then the encrypted data for the QR code can be saved on a parent’s phone as a backup. The parent’s phone need not be a smartphone.) Second, at least two smartphones (with SMS text messaging capability) are necessary for **Jeev** to function. Among these, the smartphone carried by a healthcare worker running the **Jeev** client (at the point-of-care) must have a camera to read QR codes. Thus, **Jeev** cannot work in regions where only non-camera phones are available.

When **Jeev** is deployed in a real-world setting, several technical challenges will arise. For example, the cell phones may fail or crash. To prevent data loss, we must backup the database on the **Jeev** server (*e.g.*, daily, weekly) by copying it to a computer/laptop using a USB connector available for charging cell phones. **Jeev** uses SQLite [18], which is the most popular database software

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9 for mobile devices. SQLite is light-weight and easy-to-manage. It does no
10 require a database administrator or maintenance tasks to be performed unlike
11 a (heavy-weight) relational database system such as Oracle or MS SQL Server.

12
13 The current design of **Jeev** is suitable for a rural district with few million
14 children given the storage capacity of low-cost smartphones. We also assumed
15 that there is no Internet connectivity. To scale **Jeev** to a regional/national level,
16 we will need to assign multiple **Jeev** servers, each responsible for a separate ge-
17 ographical area. Each server will communicate with a set of **Jeev** clients in its
18 area via SMS text messaging. The data on the servers will ultimately need to
19 be pushed to a (private or cloud-based) server so that the entire vaccination
20 coverage data can be viewed and analyzed by upper-level authorities and deci-
21 sion makers. This could be done by integrating **Jeev** with some of the software
22 components in the Open Data Kit (ODK) [17]. ODK enables large-scale data
23 collection and aggregation using mobile phones and provides the ability to cre-
24 ate customizable forms for data collection. Database consistency issues will also
25 need to be handled if a child receives immunization in different geographical
26 areas.
27

28
29 **Jeev** is currently in a prototype stage and several new features can be added
30 to it. For example, we can easily add the capability to alert a parent that a
31 vaccine is due for a child via SMS text messaging. We may require a custom
32 vaccination schedule for a child based on his/her health conditions (*e.g.*, congen-
33 ital heart disease, sickle cell disease). We may also need to support vaccination
34 schedule changes based on recommendations of authorities. Then some of the
35 content shown to a healthcare worker on the **Jeev** client must be changed. To
36 do so, we must copy the changes to the **Jeev** servers so that they can be com-
37 municated to the clients via SMS text messaging. The copying of changes to
38 the servers can be done similar to pushing updates to apps on mobile phones.
39 We also plan to explore how to leverage the customizable form design features
40 provided by ODK.
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8. Conclusions

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 evaluation of **Jeev**'s performance and energy consumption using the National Immunization Survey datasets to show its efficiency and scalability under different workloads. In the future, we plan to conduct the pilot testing of **Jeev** in rural Haiti, to study its effectiveness and to identify socio-cultural issues that must be addressed for a large-scale deployment.

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Appendix

Below are the SQL statements for workload W_1 . Note that the actual values for attributes are not shown.

01: SELECT COUNT(*) FROM Patient_Table;

02: SELECT COUNT(DISTINCT p_id) FROM Vaccination_Table
WHERE cpt_code = xxxxx;

03: SELECT p_id FROM Patient_Table