Customizable, Scalable and Reliable Community-Based Mobile Health Interventions

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ABSTRACT

In pursuance of the Millennium Development Goals (MDGs) set by United Nations in 2000, both Community Based Participatory Research (CBPR) and Mobile Health (mHealth) have proved to be a great tool for advancements in patient monitoring, emergency care and community empowerment. Rapid proliferation of mobile telephony in low income, rural and underserved populations in the absence of other information and communication technology media have prompted the interests of researchers in public health sector. Exploiting mobile communication has resulted in formulation of a dependable and effective socio-technical ecosystem for public health. Whereas, involving academic researchers and community partners to collaborate and develop social and computational models, Community Based Participatory Research (CBPR) approach targets building communication, trust and capacity, with the final goal of increasing community participation in the research process. CBPR is a collaborative approach to research which equitably involves all partners in the research process for betterment of the targeted community. In this paper we present a conceptual and implementation architecture for conducting mHealth assisted community-based interventions. The framework allows CBPR partners to customize the system and design interventions around locale, technology, geographic, scale, and nonetheless social and cultural aspects. We also present the design of our planned intervention addressing prenatal monitoring of underserved populations in the Andean regions of Perú.

Categories and Subject Descriptors

C.2 [**Computer Communication Networks**]: Miscellaneous; C.2.4 [**Distributed Systems**]: Distributed applications

Keywords

Interventions; mHealth; Community Based Participatory Research

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1. INTRODUCTION

United Nations in its Millennium Summit (2000), established eight Millennium Development Goals (MDGs), to be achieved by the year 2015. The eight MDGs are: *i*) To eradicate extreme poverty and hunger; *ii*) To achieve universal primary education; *iii*) To promote gender equality and empowering women; *iv*) To reduce child mortality rates; *v*) To improve maternal health; *vi*) To combat HIV/AIDS, malaria, and other diseases; *vii*) To ensure environmental sustainability and *viii*) To develop a global partnership for development. Enormous progress has been made to achieve them, however, despite the continued efforts, improving maternal and child health still remains the biggest challenge in underserved populations. According to the latest report by World Health Organization (WHO), poor maternal health in developing countries leaves about one million children each year motherless. The report also estimates that every year more than 500,000 women and girls die during pregnancy or childbirth or in the 6 weeks post-delivery. Of these deaths, 99% occur in the developing world, with mortality rates in sub-Saharan Africa and Southern Asia accounting for 85% of all maternal deaths. Among various approaches to achieve the MDGs, Community Based Participatory Research (CBPR) and Mobile Technology (mHealth) solutions have proved to be highly effective.

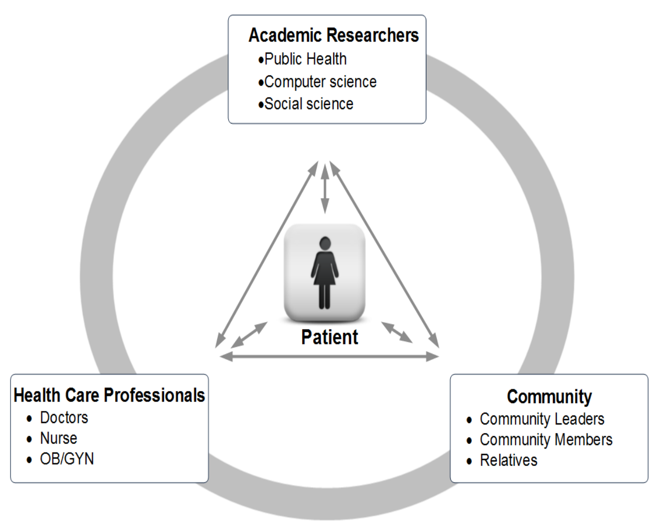

Figure 1: Operational design of system

Community Based Participatory Research (CBPR) is a collaborative approach to research that equitably involves all partners in the research process for the betterment of the targeted community and harnesses the unique strengths of all collaborating partners [8]. CBPR based approaches aim at combining knowledge with action and achieving social change and have proved highly successful in community improvement by adhering to the following principles: *i*) Recognizing the community as a unit, *ii*) Building on strengths of and resources within the community, *iii*) Facilitating collaborative partnerships in all phases of research, *iv*) Integrating knowledge and action for mutual benefits of all partners, *v*) Promoting a co-learning and empowering process that attends to social inequalities, *vi*) Involving a cyclical and iterative process, *vii*) Addressing health from both positive and ecological perspective (Physical Mental and social well being) and *viii*) Disseminating findings and knowledge to all partners. Health disparities are mostly governed by multiple factors and hence, require an advocacy approach involving multiple partners for conducting the research. Therefore, addressing the social and economic policy to achieve the structural changes required to eliminate health disparities becomes the 'modus operandi' for all CBPR partners [8]. Knowledge of local contexts and deeper understanding of socio-cultural behaviors, policies and policymakers, makes community partners a great asset in conducting community-based research. As highlighted in Fig. 1, the unique positioning of partners ensures problem identification, engagement of community members in research and interventions, dissemination of research findings, and mobilizing of community members. Both CBPR and mHealth based approaches individually, have succeeded in challenging complex health issues which remained unanswered with the traditional methods.

Mobile Health (mHealth) based solutions harness deep proliferation of mobile phones and their ubiquitous computation and connectivity for remote monitoring and diagnosis of the community residents. Mobile phones being cheap, reliable make them most attractive to the healthcare sector in low- and middle-income countries. The mobile technology's most notable features include, but not limited to, are their capacity to communicate and transfer information in both urban and rural setting, scalability, affordability, mobility etc. Mobile communication offers an effective means of bringing healthcare services to developing-country citizens. With a deep penetration of mobile phone networks globally, millions of communities that never had regular access to a fixed-line telephone or computer now use mobile devices as daily tools for communication and data transfer. With the features like Short Message Service (SMS), Interactive voice response (IVR), native and custom mobile applications, ability to communicate with ad-hoc devices, facilitate a quick transfer of information and patient data to central servers. These data can then be used for monitoring by healthcare professionals. Critical information to patients such as reminders to take medication or dates for appointments can also be provided in real-time.

In this paper we present the design of a mHealth toolkit for conducting community-based participatory interventions in underserved populations. Our approach generalizes both mobile based and participatory intervention principles. The proposed framework of the mobile health toolkit allows flexible feature selection, such as SMSs, IVRs, custom and native mobile applications, web based monitoring etc. The framework also supports integration of peripheral medical sensors in both wired and wireless settings for remote and clinical interventions. The modular architecture advocates the reliability and scalability of the framework and dictates feasibility in both scarcity and adequacy of resources based on the intervention locale. Our proposed approach allows the CBPR partners to modify the system around the intervention style, scale and operation to conduct and optimize successful interventions. To the best of our knowledge this is the first attempt of designing a customizable mobile health solution to assist such interventions in the Andean region of Perú.

The rest of the paper is organized as follows: Section 2 presents the related work . Conceptual design and architecture of our proposed system are presented in Section 3 and 4. We discuss implementation scenarios in Section 5 and finally conclude in Section 6.

2. RELATED WORK

Since the formal definition and adoption of mobile health in 2003 [6, 13], a large number of successful deployment and interventions have been conducted in the fields of treatment adherence and patient monitoring , especially for Tuberculosis, HIV and Diabetes. The major advantage of using mobile based approaches in respect to adherence to medicine is their ability to create a multi-way interaction model between patient and healthcare professionals and in our case CBPR partners. Using a mHealth approach also facilitates the dynamic nature of the doctor and patient relationship. Mobile Health based interventions have also been successful in emergency medical response [10] and epidemic tracking [3]. The authors in [17] and [10] present an extensive review of the design, implementations and evaluation of mobile technology based emergency response systems in Low- and Middle Income countries (LMICs). These approaches compare the developing system to five different type of EMS delivery: hospital-based, municipal, private, volunteer, and complex. They conclude that using a community-based approach leads to formulation of a system to function within a primary health network without overtaxing scarce resources. Such a system approach provides a creative and effective solution for pre-hospital care in developing countries. These systems also advocate the feasibility of an effective and low-cost emergency care systems in LMICs. The literature also highlights another set of interventions which use a more advanced networking solution such as mobile images and multimedia messaging service (MMS). The major applications target tele-consultation, tele-medicine and prognosis in some cases [15].

A review of the literature, provides substantial evidence that both CBPR [16] and Mobile Health solutions [14, 12] have greatly affected the achievement of MDG 5, i.e., improve maternal mortality by *'reducing by three quarters the maternal mortality ratio'*. These studies also claim that solutions like, distribution of cellphones or application alone are not sufficient enough. Implementing successful programs which incorporate a comprehensive approach addressing the logistical and human resource constraints, are indeed necessary for the intervention to be successful.

In another style of interventions, the RESCUER program in Uganda targeted the empowerment of community-based health workers with mobile communication for strengthening the linkages between community members and health facilities [11]. Similarly, the “Lady Health Worker” initiative in Pakistan worked with ubiquitous and socially accepted health workers who had easy access to mothers and could bridge disenfranchised populations with the formal health system [4]. These intervention demonstrate the variation in style of using mobile health based systems based upon the local context and resources while still introducing an innovative tool for healthcare delivery. We generalize these different style of intervention techniques into one generic toolkit allowing CBPR partners to pick-and-choose various technologies best suited for their planned interventions.

A few approaches aiming at the generalization of data collection and aggregation are present in the literature. Open Data Kit (ODK) [5] and JavaRosa [9] provide a set of tools to help and manage mobile data collection using generic applications. However, these approaches do not allow communication with ad hoc devices such as Bluetooth based blood pressure monitors, fetal monitors etc. Also, these do not have support for custom application designed by the researchers, which are paramount while conducting interventions involving nurses and OB/GYN. In such interventions, mobile applications are designed with a similar look and appearance as paper based EHR used by these nurses and OB/GYN in the intervention locale. In CBPR interventions a hierarchical data abstraction scheme is also important because the data is collected remotely and aggregated at clinics, hospital and the cloud levels, thus allowing CBPR partners to exert judgment and decision-making to improve the system. The approaches in [5] and [9] do not provide such hierarchical data collection support. Whereas, our proposed framework supports ad hoc device communication, custom application support with multilevel data abstraction and aggregation.

3. CONCEPTUAL FRAMEWORK

In this section, we formally define an “object-task” relationship model for the various components of the system. In this framework we identify objects which directly interact with the system under different access levels and perform respective tasks. The object model is highlighted in Fig. 2. The object model and their associated tasks are described as follows:

1. **Objects**

   (a) **Patients**: May interact with the system for retrieving or updating personal data at the individual level.

   (b) **Healthcare Professionals**: Collect patient’s data both, remotely or in a clinic setting and manage appointments or visits for multiple patients.

   (c) **Doctors**: Mainly responsible for diagnosis, prognosis and monitoring of multiple patients, mostly in the clinic or hospital setting.

   (d) **CBPR partners**: Responsible for collaborating with doctors and healthcare professionals for conducting research for the intervention. After designing the intervention CBPR partners collaborate for optimization and customization of the system based on the social, technical and cultural needs of the community.

2. **Tasks**

   Clinic Monitoring: Both healthcare professionals and doctors interact with the system at clinic or hospital settings for patient monitoring, data collection, diagnosis and prognosis.

   Electronic Health Record (EHR): Healthcare professionals and doctors maintain the EHR for multiple patients in the system.

   Remote Patient Monitoring: Healthcare professionals perform home visits and collect patient’s data through mobile health devices. Tele-medicine and consultation is also supported in resource adequate interventions.

   Epidemic Monitoring: CBPR partners analyze the collected data on real time basis and design and implement algorithms for epidemic monitoring in the region.

   Disease Classification: CBPR partners collaborate in designing and implementing disease classification and characterization algorithms for a software assisted diagnose and monitoring.

   Education: Doctors, healthcare professionals, other CBPR partners and patients exchange educational resources within the system. This is usually achieved using Short Messages (SMS), Multimedia Messages (MMS), Interactive Voice Response (IVR) and notifications in mobile or web based applications.

   Emergency Medical Response: Health care professionals, emergency response teams collect vital markers relevant to the patient in events of an emergency situation.

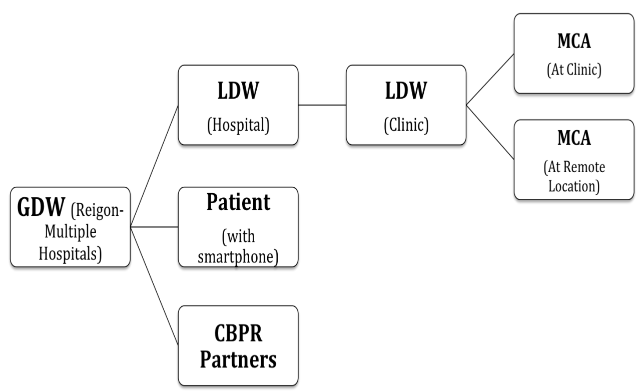

Figure 2: Operational design of system

Fig. 2 shows the set of relationships between the various components of the system. From the nature of abstraction we identify that, the patient is involved in one-to-one data relation with the healthcare professional, doctor and the system. However, the doctors and healthcare professionals monitor multiple patients so they indeed have a many-to-many data relation. Another important observation is that CBPR partners must be involved and interact with all the components of the system and hence we articulate that CBPR partners observe a many-to-many data relation with all other components of the system which are important for the evolution, growth and optimization of the system with the progress of intervention.

4. SYSTEM ARCHITECTURE

4.1 System Design

The architectural and operational design presented in Fig. 3, highlights the key components of the system. We divide the system into following major parts:

Local Data Warehouse (LDW): It is an on-site server at the hospital and clinic levels which serve as a local repository for data aggregation from different mobile devices at a clinic level. A LDW is also installed at the hospital to collect and aggregate data from the clinical LDWs under its purview as shown in Fig. 2. Due to limited availability of 3G and other wireless technologies in remote locations, we follow a passive data aggregation strategy, i.e., the data is stored locally on the mobile devices and is synchronized with its respective LDW when synchronization event is triggered on the mobile devices.

Global Data Warehouse (GDW): GDW is typically a cloud based infrastructure to collect and aggregate the data. All the LDWs at the hospital level aggregate data and then synchronize with GDW for data aggregation. In case of an emergency the healthcare professionals can accesses the medical record using the provided web based or mobile application interfaces.

Public Health Workers (PHW): These are the healthcare professionals working at clinics. The PHWs physically interact with the patients to collect data in a clinic or in remote setting during their home visits.

Sensing Device Array (SDA): A collection of mobile devices utilized by the PHW to collect patient data in a remote or clinic settings such as thermometers, fetal monitors, ECG/EKG, blood glucose and blood pressure monitors, etc. It is important to note here that these devices may or may not be wireless in nature.

Mobile Collection Agents (MCA): These identify a data collection node such as a smartphone or tablet device through which the PHW collect patient data. Also these devices have the capability of interacting with other peripheral medical devices through communication channels, wired or wireless.

Patient: In specific interventions patients can also be a user of MCA and subset of SDA. For example, interventions focusing on domestic diabetes monitoring or drug adherence reporting in tuberculosis and asthma. In these cases we allow patients to directly interact with the system and vice-versa.

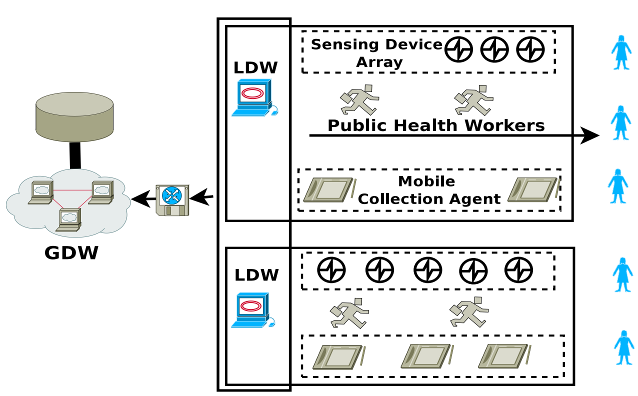

Figure 3: Operational design of system

As reliability of data transfer and management forms the key aspect of the system, we use a two step data warehousing scheme. We maintain two data warehouses namely, Global Data Warehouse (GDW) and Local Data Warehouse (LDW). GDW is a typically a cloud like infrastructure, however, the framework has multiple on-site LDWs which synchronize the data collected at the the LDWs. The data warehousing and synchronization is done in a hierarchical manner, i.e., the LDW at the clinic updates the LDW at the hospital which in turn synchronizes with a central GDW warehousing server. The framework employs an "Event Based" data synchronization mechanism between GDW and LDWs at hospital. LDWs at clinics serve as a data aggregator for devices (MCA) allocated to "Public Health Workers" (PHW).

After the interaction and operation model we now discuss the system architecture in detail. The architectural design of the approach is highlighted in Fig. 4.

- **Setup Manager**: This unit is mainly responsible for setting up the intervention specifications. CBPR partners interact with this unit through a web based interface and select feature for the specifications such as, whether the intervention uses features like SMS, IVR, generic or custom mobile application, survey questionnaire etc. Based on the selection the system compiles a list of needed actions such as IVR setup, SMS setup, database creation and management etc. In case of native mobile applications and questionnaires it allows CBPR partners to input questions or data points to be collected and creates a xml-based representation. Based on this specification the UI manager on a mobile device creates the application interface and database tables are created. We use Open Data Kit (ODK) [5] to provide the generic application functionality.

- **User Manager**: This unit is responsible for user management. All CBPR partners, doctors, healthcare professionals and patients use a login and passkey based access. Privilege based data access model allows data abstraction based views to users.

- **Database Manager**: This unit maintains multiple parallel data tables such as patient data including patient personal information, data for each home visit by a PHW, patient family health history etc. A separate table is used for scheduling PHW visits and archives for past visits. The system also maintains a separate database for user access privileges.

- **Data Aggregator**: Data aggregator unit is used for data aggregation on the event of data synchronization from lower nodes of the hierarchy, i.e., between LDWs at clinics and hospital and between MCAs units and LDWs at clinics.

- **Form Manager**: This is basically for the UI manipulation at the mobile interface. All the information needed to be collected for a user is stored in an XML based form. This XML based form is used by the UI controller to populate the user interface. It also serves as a guideline for the data collection by the PHW when represented visually.

- **Network Manager**: The basic role of network manager is to manage connections at different interfaces,

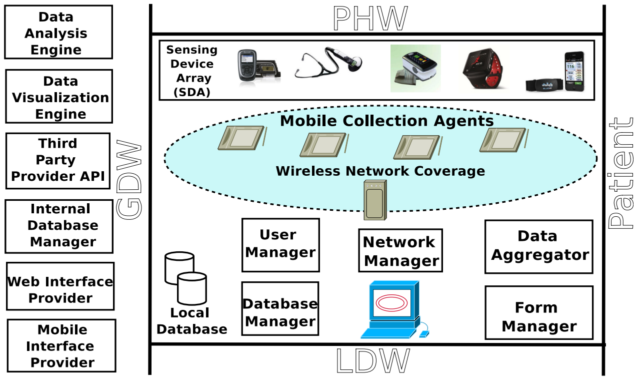

Figure 4: Architecture and components of the system

especially at the MCA as it connects to multiple peripheral devices in the Sensing Device Array (SDA). It is also responsible for maintaining secure and reliable connections with GDW, LDWs and MCAs.

- **Data Visualization Engine**: Backed up by the data mining and statistical analysis, the system supports an interactive data visualization environment for personal monitoring by the patient, doctors and healthcare professionals. It also assists CBPR partners in visually analyzing the trends in epidemic monitoring.

- **Third Party Provider API**: This unit provides APIs for third party applications to interact with the system through an OAuth based authentication model [7].

4.2 Abstraction based Data Access Model

We use the abstraction of data as the fundamental distinction between the operation of the system. We use a hierarchical replication of the system at both, the GDW and LDW level, i.e., all the features the system are available at all levels despite the access level of data as shown in Fig. 2. In a typical use case scenario, patient has access to only personal data. Also, a doctor and a healthcare professional can access the electronic health record of all the patients under its purview. Healthcare professionals at a clinic have access to all the patients observed by the clinic only, whereas they cannot access to the other clinics. CBPR partners have access to all the patient records in the system. This data abstraction model is very well suited for both scarce and resource adequate setting. This also ensures that at each level of hierarchy respective patient data is always accessible to the concerned healthcare professional or the doctors.

5. DEPLOYMENT CASE STUDY

In this section we discuss our deployment strategy for a community-based participatory intervention for prenatal monitoring in remote areas of Perú [2]. The project aims to reach underserved populations with health education, information and diagnosis through the use of mobile health system. The research endeavor follows a formal institutional partnership between the University of Massachusetts Lowell and the National University of Huancavelica and the establishment of a research partnership between academia, healthcare, and community stakeholders. Poor maternal and child health characterizes the region of Huancavelica, Perú. Recent data indicates a current maternal mortality rate (MMR) of 93 deaths/100,000 live births which sets Perú as a country in the high MMR category (between 50 and 149, based on WHO). In the underserved and indigenous communities of the Andean region, the MMR goes up to 152/100,000 live births. Very limited knowledge exists about the behavioral, psychosocial and cultural factors that negatively impact maternal health in underserved and indigenous communities in the developing world. The maternal and child health problem in this region is particularly acute. Factors shown to impact child and maternal health are all present in this region and mainly include: *a*) a language barrier, as most residents are Quechua-speaking; *b*) extreme poverty; *c*) malnutrition; and *d*) lack of access to health care in this rural, mountainous region.

In this intervention, we deploy a central GDW and deploy a LDW in a major hospital in city of Huancavelica. We also deploy LDW units at multiple clinics falling under the purview of the hospital. We facilitate healthcare professionals at these clinics with multiple sets of Nexus 7 tablets and Bluetooth based glucose monitors, blood pressure monitors, weighing scale, thermometers and fetal monitors provided by ForaCare [1]. We have also developed a custom android application based on the current paper based health record to facilitate the data collection process. PHWs use these devices to collect patient health information during their home visits or at the clinic using MCAs as shown in Fig. 5. The data collected is synchronized with the LDW at the clinic, hospital and finally with the GDW. Our mobile application mainly addresses the following issues in the region:

Figure 5: Mobile Health For All application

- *Network Unavailability*: In case of unavailability of cellular network (3G/GPRS) in rural areas, our system uses a passive multi-level data collection and aggregation which ensures patient's data availability at the clinic and hospital levels. We deploy multiple LDWs and a GDW for data aggregation. The data collected remotely is synchronized on availability of a stable 3G or WiFi network.

- *Disease Characterization and Alert Mechanism*: We deploy a disease characterization algorithm for risk classification during the pregnancy and alerts the public health workers, especially in an emergency medical response.

- *Compliance and Patient Reminders*: The system periodically sends educational information and reminders for appointments and taking medication. These reminders are usually in form of SMS, MMS and application notifications.

- *Adequacy of language*: We have developed a mobile application using current paper based forms, to ease the patient data collection by public health workers. The mobile application is designed in local language, i.e., Spanish, which is also used in the current paper based forms.

We have also developed a web based application which is used by the CBPR partners in multiple roles and settings based on their access privileges. For example, computer science researchers use it for disease characterization and epidemic monitoring, whereas social science researchers use it for understanding the social and cultural aspects of the community. Doctors in the hospital and healthcare professional access individual patient data for diagnosis and prognosis in maternal health. In this interventions we also allow patients to send and receive short messages (SMS) about their upcoming or missed appointments. Patients also receive preset informational messages based on their current stage of pregnancy. These messages include dietary information and healthy practices for a healthy pregnancy.

In the next stage of this endeavor, research partners including, *Universidad Nacional de Huancavelica*, researchers at UMass Lowell and rural clinics and the Hospital of Huancavelica, will implement the proposed intervention. We will collect the user behavior data and system performance data during this intervention. We will also analyze the acceptability of our proposed socio-technical framework by performing questionnaire-based surveys of patients, health care professionals, etc.

6. CONCLUSIONS AND FUTURE WORK

In this paper we have presented the architecture of a generic framework of a mobile health solution to conduct successful community-based interventions in public health. We also presented the implementation details and an abstraction based data access model at multiple levels of the data aggregation hierarchy. We assert that this congruence of mobile technology and CBPR based interventions is highly successful in conducting customized intervention. We also discuss the design of our proposed deployment in remote areas of Perú. We also discus the robustness, scalability, reliability and customization aspects of our framework, paramount for designing interventions in both remote and urban setting. In the future we plan to deploy the mHealth system for remote monitoring and data collection in the Andean region of Perú and analyze the performance of the system considering the socio-technical and ecological context.

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