Multi-Layer Architectures for Remote Health Monitoring

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***Abstract*— Remote health monitoring and delivery through mobile devices and wireless networks offers unique challenges related to performance, reliability, data size, power management, and analytical complexity. We present a multi-layered architecture that matches communication performance to medical importance of data being monitored. The priority of vital data and the context of sensing are used to select the communication medium and the power management policies. Further smartness is introduced into data summarization by employing a severity level quantizer, followed by a consensus abnormality motif discovery and an alert mechanism that prioritizes doctors' consultative time. We also present our successful implementation of the above multi-layered architecture in a system developed to remotely monitor cardiac patients.**

***IndexTerms*— Wireless networks, remote health monitoring, health informatics**

I. Introduction

More than 60% of the population in the developing countries resides in rural regions. There is a startling lack of accessibility to hospitals in most villages. In most cases, the patients have to travel at least 2-3 hours to reach the nearest hospital, leading to heavy impact on their health or even loss of life. Even in the urban centers, the hospitals are witnessing a huge shortage of doctors and beds to support high patient volumes. Patients who have undergone critical operations or surgeries are kept in the ICUs or CCU for monitoring purposes alone. Occupancy of ICU beds for non-critical reasons, such as telemetry, is a waste of resource as well as unnecessary economic burden on the patients too.

Together, these factors are contributing towards higher mortality as well as falling standards of health care. To overcome these challenges we propose the design and architecture of a novel heterogeneous communication framework consisting of IoT devices coupled with body sensors, smart data summarization and severity level classification technique using Consensus Abnormal Motif (CAM), and cloud analytics. We also report the development and testing of this framework using a wearable remote cardiac monitoring system, called Amrita-Spandanam ("Amrita Pulse"). This system is capable of real-time monitoring of cardiac patients, issuing early warning to doctors and relatives in case of emergencies, tagging the ECG with the patients' daily activities for better analysis of the health of the heart, automatically diagnosing of some of the cardiac diseases etc. This system has been developed and tested extensively at one of most popular tertiary hospitals in India, Amrita Institute of Medical Sciences and Research.

In an extensive study [1] of existing tele-medicine and remote health monitoring systems, it was identified that one of the major unsolved challenges is reliability and efficiency of wireless technology. Related works in this area include [2], [4], [5], and [8]. Data prioritization is discussed in detail in [3]. Various power management policies for ad hoc networks are discussed in [6].

The rest of the paper is arranged as follows. Section II describes various services, which will ensure reliable remote healthcare delivery. Section III details a novel framework for implementing these services using sensors, IoT devices and cloud. Different sensing methods are discussed in section IV. We present a health context based heterogeneous network selection and routing in section V. A power management policy based on data priority and location is presented in section VI. A smart data summarization based disease detection and decision support algorithms are presented in section VII. Our implementation of a fully functional wearable cardiac monitoring system is discussed in section VIII.

II. Services For Better Healthcare Access

In order to solve the challenges described above, various services need to be provided to each of the stakeholders: the patients, the doctors, the nurses and other healthcare professionals. From our experience in the development of the remote cardiac monitoring framework, we identified that the essential services that need to be offered are:

A. Real-time remote vitals monitoring

Vital signs such as BP, blood glucose, pulse rate, ECG, SpO2 etc. are indicative of a patient's current health. In order to have the first level analysis of whether the health is deteriorating, these vitals need to be monitored in real-time so that the professional healthcare providers would be able to arrive at a conclusive decision.

B. Decision support and disease detection

Though remote monitoring of thousands of patients at the same time enables scaling up of healthcare delivery, it also poses a different challenge. The huge data that is collected needs to be analyzed automatically. Analysis of some of the vital parameters like BP, blood glucose, SpO2 are easy when compared to the others since they have well defined upper and lower thresholds beyond which proper interventions need to be taken. Others vital signals like ECG, would need detailed signal processing algorithms for detecting abnormalities.

Long term monitoring will also provide an opportunity for automated disease detection from temporal analysis of a patient's data. For instance, a patient having a history of high BP and glucose might be in high risk of heart diseases. If irregularities in ECG could be connected with previous history of the patient, a sound prognostic conclusion could be made.

In this context, a smart data summarization based on the severity level of vital data is an essential technique to prioritize the patient data for the doctor's consultative time as well as achieve reduction in bandwidth usage.

C. Real-time warning

The data that is automatically or manually analyzed needs to be classified according to the priority and then disseminated to the healthcare professions and responders in order to help them arrive at prognostic conclusions. For example, when a patient's BP is very high along with symptomatic discomforts, this information needs to be automatically detected and sent to nurses in the nearby health center. In sparsely connected regions, where cellular data network is unavailable, the warning could be sent using SMS along with a summarized vitals data. The CAM technique can be applied to detect abnormalities and derive the summary for the emergency warning messages.

D. Real-time context

Context of the patient while taking vitals measurement is extremely important. The measurements are highly dependent on: 1) physical activity, such as resting, walking, jogging etc. 2) social context, such as when the patient is in a meeting, relaxing at home, sleeping, on a vacation etc. Otherwise, false alarms will be initiated; if the context is not considered during the detailed signal analysis. For example, when a patient is running, it is expected that his heart rate would increase, and this has to be considered while automated disease detection is performed. Therefore, context awareness is a necessary service for enabling decision support and real-time warning.

E. SoS services

In case of any emergencies, a remote patient must be able to intimate all the stakeholders. Such emergencies might be triggered by the patient or through an automated system. For example, when a patient feels extreme discomfort and pain, he should be able to trigger an SoS. This message needs to reach various stakeholders along with the vital measurements during that time if possible within a minimum delay. In case of asymptomatic or silent heart attacks, the system should generate an automated SoS, based on the analysis. Various strategies need to be evolved in order to reduce false positives too.

III. FRAMEWORK FOR REMOTE HEALTHCARE ACCESS

We propose a framework that combines sensors, IoT devices and communication network to achieve this goal. The system architecture is depicted in Fig. 1. The whole architecture is divided into different layers, which are discussed below.

Patients can be at home, inside a hospital ward or outdoor based on different usage scenarios.

Sensing Layer includes wearable or any other type of sensors that can continuously monitor vitals (BP, glucose, SpO2, ECG etc.) as well as the context (accelerometer etc.). These sensors are attached to the patients' body in order to obtain the signals. They are also interfaced with an IoT device over a short-range communication network such as Bluetooth or Zigbee.

Routing Decision Layer (IoT device layer) has three functionalities: a) to decide where and when the sensed data needs to be stored, analyzed and transmitted b) to decide the routing path or the next hop for the data c) to interface and exchange data with the nearby IoT devices over ad hoc networks. The IoT device could be integrated with a local processing, analytics and storage (PAS) module as well. For example, simple PAS algorithms can run as background services in the smartphone itself. Here, the smartphone is the IoT device that has a direct link with the local PAS layer. The IoT device can also be interfaced with existing hospital infrastructure (Hospital Information System PAS) or to a back-end cloud (Cloud PAS). The connection to the former could be over Wi-Fi or wired Ethernet while to the latter it could be over GSM, 2G/3G, Wi-Fi etc. For example, the patients' smartphone can act as an IoT unit if he is inside the house. On the other hand, if this sensor is used in a general ward for "in-ward telemetry", the IoT device could be Bluetooth dongles or any other short-range receivers near the patient bed that can communicate to the HIS PAS over wired or wireless media.

Local PAS is a processing, analysis and storage module that has simple algorithms for initial analysis of data. This includes summarization of the data and identifying the severity of data using a novel technique called Consensus Abnormality Motif (CAM), which is described in one of our earlier works [7]. Using CAM, a large time series data is summarized using various medically accepted severity levels resulting in reduction of data size as well as obtaining succinct information about the patient's health status.

The data comes from the IoT layer and the results are sent back to the device itself over a direct or wired link. The local PAS can also use the APIs provided by the cloud PAS to do complex PAS tasks.

Complex PAS Layer implements disease detection, big data analytics, complex storage policies and computationally intensive algorithms that are not possible to be implemented in local PAS due to it's processing and power constraints. These can either be implemented in a cloud or could be local to a HIS.

Application Layer includes various visualization, monitoring, analysis and intervention tools for the use of health professionals and emergency responders. The applications can run on multiple platforms (web, mobile etc.).

Health Service Personnel (HSP) are the consumers of the data provided by different applications. They include doctors, nurses, technicians and emergency responders who analyze the data and take necessary steps. The emergency responders use the most reliable SoS communication channel from the available ones while responding to any contingencies.

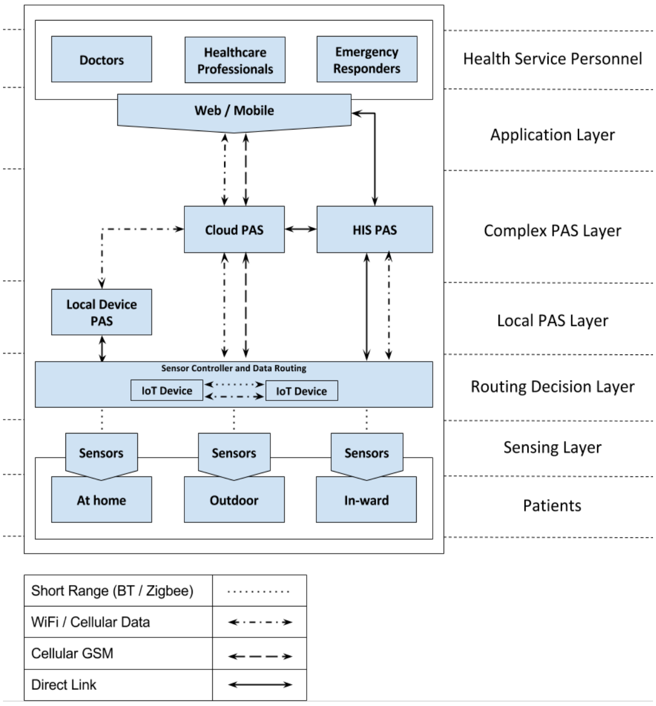

Fig. 1. System Architecture for remote health care service delivery using sensors, IoT devices, cloud and heterogeneous ad hoc networks. Various stakeholder are also shown in this figure.

Here, we see that a combination of sensors, IoT devices, networks with multiple link connectivity options and cloud service APIs can enable delivering various digital remote healthcare services. Next, let us look at how the context of sensing is integrated into heterogeneous link selection.

IV. Real-time Data Acquisition Scenarios

A heterogeneous medium selection should be based on factors such as source of sensor trigger, patient condition, medium availability, IoT device capabilities, availability of local device PAS and time criticality of the information. In healthcare applications, sensing of data could be triggered in different ways. The sensing of a parameter can be initiated by the patient, the healthcare professional or could be according to a preset frequency. Accordingly, we have three categories of sensing methods.

A. Routine sensing

In many applications, the patient data needs to be collected in predefined intervals of time. For example, the BP and ECG measurements would be collected in the morning and at night.

B. Patient initiated sensing

Whenever the patient feels discomfort or pain, he can trigger the sensors to record his vitals. This is very useful in capturing symptomatic events, where the patients are aware of such occurrences.

C. Doctor initiated sensing

In many patients, the doctors might need to measure the current vitals. In such a scenario, the doctor triggers the sensing. The instruction to sense goes from the HIS or the cloud PAS to the IoT device, which in turn triggers the sensors.

V. Health Aware Medium Selection And Routing

One of the essential requirements to provide the required services is the availability of a reliable, low delay tolerant communication network. In most rural regions, availability and reliability of networks is a challenge. In urban settlements, there are challenges such as selecting the least cost network, ensuring continuous bandwidth availability. In case of highly mobile patients, the problem of managing frequent change in mobile base stations also arises. With the goal of overcoming these challenges, we propose a novel health aware network selection and routing in heterogeneous ad hoc network for communication between IoT devices and the cloud.

Some of the common considerations for medium selection in any heterogeneous network are availability, range, cost, and bandwidth requirements. However, factors such as health data priority and patient location play a central role in healthcare services. The IoT device needs to consider these factors prior to making the choice.

A. Data priority

The priority of the data can be determined based on the type of sensing and the analysis results from local PAS. Accordingly, we define two data priority levels; routine and critical data.

Routine data is collected during routine sensing acquisition scenario. The IoT device sends the routine data to the local PAS, if it is present. The data is summarized and analysed using the CAM technique followed by the calculation of a severity score of the data that we call Alert Measure Index (AMI). Based on the result of local analytics, if the CAM shows wide variation from normal motif, it is tagged as critical. Otherwise, it could be stored in the IoT device cache and transmitted at a later time over a non-time critical medium.

In case the IoT device does not have connectivity to a local PAS, it has no other choice but to transmit the summarized CAM to complex PAS layer. Upon analysis at complex PAS, it can request for more data from the sensors. However, since the data is obtained from routine sensing, it can be assumed to be not of immediate use by the HSP. Hence, a delayed transmission through non-time critical route can be adopted here as well.

The routine data may be viewed by the HSP at a later point of time, and hence we can adopt a delayed push notification of the data to the HSP applications.

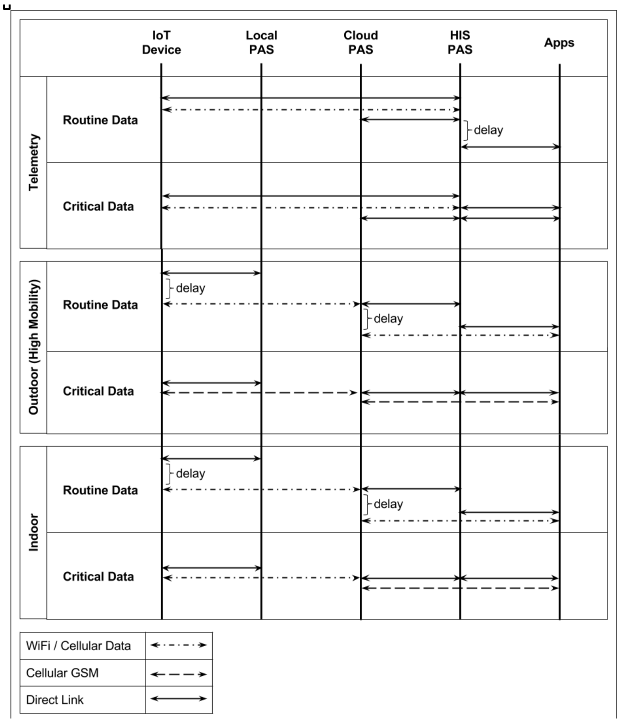

Fig.2. Heterogeneous medium selection and data transmission policy based on the priority of the data and location of the user is summarized in the figure. Note that in many scenarios the data can be stored and send at a later time.

Critical data consists of data collected during patient or doctor triggered sensing. Once again, before deciding the communication medium, it needs to be sent to the local PAS and analysed for any deviations from normal values. If the CAM suggests that there are no noticeable change from normal severity levels, then the data is tagged as routine data. In the absence of any conclusive results from the local PAS (or even non-availability of local PAS), the summarized data needs to be transmitted to the complex PAS through a time-critical route.

The data needs to be notified to the HSP immediately in order to help them make emergency interventions. The summarized data is presented to the HSP, who can then request for complete data from the patient's smartphone.

B. Patient location

In-ward telemetry is one of the applications of remote health services for patients who are inside the hospitals, especially when they need to be monitored after a critical operation. The IoT device could communicate with the existing hospital infrastructure using WiFi or wired ethernet connection. The IoT device need not send the data to a local PAS, since there is a reliable low cost route to reach the HIS PAS itself.

Outdoor patient monitoring poses significant challenges. The patient could be highly mobile in case he is travelling. The IoT device transmits the data to the cloud PAS based on the data priority. While selecting a time critical route, a route based on cellular network is the most reliable option. For routine data, a combination of delayed transmission and least cost medium is adopted.

Indoor monitoring offers a much more reliable communication environment. The IoT device can forward the data to the local PAS and based on the result decide the heterogeneous medium. Since there is very less mobility, the data can be transmitted over WiFi or cellular data network, even in critical situations.

Heterogeneous medium selection based on data criticality and user location is a very specific requirement in healthcare services (Figure 2). The patient context, which includes his health status, activity, and location, along with the power policy dictates which path to be taken and when the data needs to be transmitted. This ensures that critical data is always transmitted, while routine data can be transmitted at a later time. Power management can also be an important factor in medium selection, as elaborated in the next section.

VI. POWER MANAGEMENT

In sensor networks, power is a major consideration for frequency of sensing, data processing, medium selection and transmission frequency. In our architecture, these decisions need to be taken at both the sensor and IoT device.

IoT device power policy: We define different levels of available battery power. For healthcare applications, we can assume that the devices are attached or are near to the user. This implies that these devices can be recharged at least once in a day if required.

Each sensor has different sensing frequencies. For instance, BP and blood glucose would be measured only twice or thrice in a day. If the patient is on continuous ECG monitoring, the sensor has to transmit or record the data continuously. Also, there is difference between the sensing and transmission energy requirements for different sensors. Because of these reasons, we define the available battery power of IoT devices and sensors as the time up to which it can carry out sensing and transmission.

- **Low**: When there is only enough battery power to sense and transmit for below three hours.
- **Medium:** When there is enough battery power to support sensing and transmission between 3 - 12 hours.
- **High:** When there is enough battery power to support sensing and transmission between 12 - 24 hours.

A power management policy based on available battery power, the data priority and location of the patient is summarized in Table I. Three actions need to be taken at any point of time. First, the data can be transmitted immediately (specified as "Immediate"). Second, the data can be stored and send (specified as "Delayed") at a later point of time, when the battery level improves. Finally, the data can be sent to the local PAS for processing (specified as "Local PAS"), such as data summarization and severity analyzer. First decision results in higher battery drain, while the second results in savings. The third decision drains the battery due to local processing and analytics. Here we intend to provide a policy framework and describe a policy that we have adopted for efficient management of power in healthcare monitoring scenario. As the reader is aware, this policy will differ from application to application.

TABLE I. POWER MANAGEMENT POLICIES BASED ON PATIENT LOCATION AND DATA PRIORITY.

Power Management Factors		Battery Level		
Location	**Priority**	**Low**	**Medium**	**High**
In-ward Telemetry	**Routine**	Delayed	Immediate	Immediate
	Critical	Immediate	Immediate	Immediate
Outdoor	**Routine**	Delayed	Delayed	Local PAS + Delayed
	Critical	Immediate	Immediate	Local PAS + Immediate
Indoor	**Routine**	Local PAS + Delayed	Local PAS + Immediate	Local PAS + Immediate
	Critical	Immediate	Immediate	Local PAS + Immediate

VII. DISEASE DETECTION AND DECISION SUPPORT SYSTEM

The smartphone analytics and processing which is called here as Local PAS helps in first level of disease detection and alerting. We have used a technique called Consensus Abnormality Motif (CAM) discovery, which is explained in detail in one of our earlier works [7]. For the clarity of the reader, we detail the essential steps of the process here. The sensor values are quantized into severity symbols such as A, A+, A++ based on medically accepted severity levels of vital parameters. For instance, a systolic BP of above 180 is quantized to A+++, while that between 80 and 130 is quantized to A (normal) level. These symbols are then arranged into a multi-sensor matrix (MSM), where in severity levels from different sensors are sequentially arranged into 'f' columns and 'w' rows, where f is the frequency of sensing and w the observation window which the doctors wants to summarize the data. Typical values of f and w would be 3 and 10 if the data for 10 hours (each hour consisting of 3 sensed values) need to be summarized. From the MSM, we derive a Severity Profile Matrix (SPM), which lists a weighted frequency of occurrence of severity symbols in each column of the MSM. Based on the most frequently occurring severity symbol in SPM, we derive a Consensus Abnormal Motif that effectively summarized the abnormality in the entire $f * w$ data set. Finally, a weighted sum corresponding to the severity symbols in CAM is calculated to obtain a inter-sensor Alert Measure Index (AMI) that provides a single real number representing the immediacy of data to be pushed to the doctor. The local PAS can use the AMI to decide the severity of the patients and the CAM can be sent as a summarized data to the cloud or remote HSP in case of emergencies. The HSPs, on the other hand, can use CAMs to classify patients and attend to the most needy ones first. In the following section we describe a case study involving the development of a continuous cardiac monitoring device that was developed by our research team.

VIII. AMRITA SPANDANAM: A CASE STUDY

Using the above presented architectural framework, we have implemented an end-to-end solution for remote cardiac healthcare delivery using sensors, mobile phones, and the cloud. We call this system as "Amrita Spandanam" (meaning Amrita-Pulse) [9]. The key components of this system are described below.

A. Wearable device

The Amrita-Spandanam wearable device is a lightweight ECG acquisition hardware and firmware, built into a wearable profile. This device is required to acquire the ECG data from the human body through electrodes, digitize it and stream it to the patients' smart phone upon commands from it. The device should operate in aggressive power save modes for extending battery endurance. A standard lithium-ion 3.7v, 890mAH battery is used as the power source. A provision for USB charging of the battery is provided.

B. Mobile device (IoT device)

The ECG device needs to be controlled through a master smart phone for its operation. The smartphone acquires the ECG data stream through the Bluetooth. Further it connects to the backend server through Internet and transmits the ECG data after some minor signal processing. The doctors' side smart phone also needs to have the necessary mobile application to enable ECG visualization to the doctor. The android application has a background service that waits in a listening mode for triggers from the Bluetooth and the network interface. This trigger can be an alarm from the remote server or trigger from the wearable device, to start streaming the ECG data. This background service can also intermittently acquire the ECG data for analyzing potential anomalies. In case of the doctor's smartphone, this service receives the intimation about a potential ECG anomaly from the server. This will raise a pop-up dialog and alarm to the doctor so that he/she may chose to view the real-time ECG stream for further inspection.

C. Local PAS in mobile

The Android mobile application also implements these algorithms: activity recognition, motion artifact removal and smart summarization through heart rate extraction.

The android application uses the accelerometer input from the device to find out the user activity and classify those using existing algorithms. Depending upon the activity, the app uses different motion artifact removal algorithms based on wavelets, such as db2, db4 etc. Once the motion artifact is removed, the signal is ready for further processing or transmission.

D. Cloud PAS

The backend server acts as the communication hub for this architecture. The patient's mobile which is the source, the doctor's mobile which is one of the sinks and the browser based web-client from a hospital monitoring station which is another sink; all could connect to this backend server. The cloud PAS acts as a middleware, which post process and analyze the incoming ECG stream from the source, and then relay it to all sinks corresponding to appropriate transmission and privacy policies. A DSP engine performs post processing on the source ECG stream. The storage engine stores the streams as files. The analytics engine performs various diagnostics analytics over the ECG stream. The analytics engine is a scalable engine which currently has two algorithms implemented. It currently has a feature extraction algorithm to detect P wave, QRS complex and the corresponding duration and segments of an ECG signal. Using this various disease detection algorithms can run. We have implemented and tested Left Anterior Hemi Block detection as a sample real-time disease detection algorithm with very high sensitivity and specificity [10].

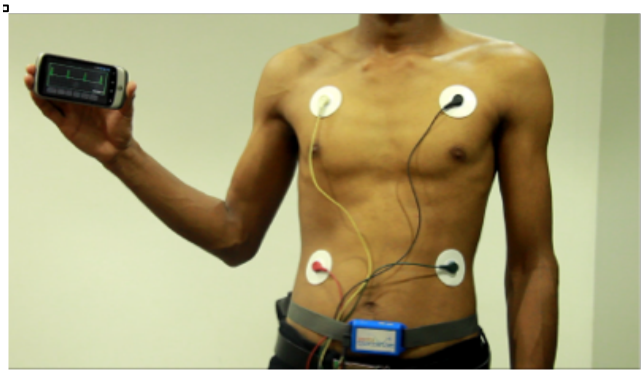

Fig. 3. A patient wearing the Amrita Spandanam ECG sensor device (as a belt). The four body electrodes are connected to the device. The smartphone in the patient's hand shows the live ECG stream as sent from the sensor.

IX. Testing and Evaluation

The Amrita-Spandanam device is fabricated as a wearable belt solution as shown in the Fig. 3. This framework was extensively tested in a tertiary hospital, Amrita Institute of Medical Sciences, which is a 1200 bed hospital with about half a million patients visiting annually. The device was tested on out patients as well as patients in intensive care units. The device was also tested on patients with very high mobility. The patients were given these devices, so that they can use it during their daily activities. The data was collected and transmitted from the smartphone to the server in our research center. An initial pilot study of 50 people has been conducted using this device in various settings (indoor, outdoor, telemetry). The data is AAMI/EC13 compliant, and the doctors and the technicians were satisfied with the quality and reliability of the data. The network selection and sensor power management policies have helped in delivering continuous, reliable monitoring, warning analysis and SoS services among remote patients. The continuous monitoring has also helped in identifying asymptomatic occurrences of ischemia and arrhythmia in patients. The summarization algorithms have shown to reduce the power and bandwidth requirement for transmission of large time series ECG data.

X. Conclusion

A complete framework that includes sensors, IoT devices, cloud and the corresponding heterogeneous network architecture is required to support the service requirements of remote healthcare delivery. A health data and context aware approach for network selection and power management ensures quality and reliability of service delivery. The development and testing of a wearable wireless cardiac ECG monitoring solution using this framework has shown promising result, both in terms of performance and user satisfaction. We are currently preparing for a large scale field deployment and testing in remote villages in India.

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