CyPhyS+: A Reliable and Managed Cyber-Physical System for Old-age Home Healthcare over a 6LoWPAN using Wearable Motes

Haresh Dagale*, Anand S V R†, Malati Hegde† Neeraj Purohit*, Supreeth M K†, Gurinder Singh Gill*, Ramya V†, Akshay Shastry*, Sathya Narasimman †, Lohith Y S †, and Surya P †
* Department of Electronic Systems Engineering and † Department of Electrical Communication Engineering
Indian Institute of Science
* [haresh,neeraj,gsgill,akshayks]@dese.iisc.ernet.in † [anand,malati,supreeth,ramya,sathya,lohith,surya]@ece.iisc.ernet.in

***Abstract*—We present design and implementation of CyPhyS+, a comprehensive, low-cost and standards compliant Cyber-Physical System (CPS) using 6LoWPAN based Internet of Things for remote health monitoring of elderly staying in old-age homes. It is a closed-loop system that incorporates an end-to-end reliable message transfer scheme for the resource constrained environment, data security, real-time medical signal processing and data analytics, and FHIR/HL7 compliant web services. The low power operation of CyPhyS+ allows the CPS an extended uptime, ensuring connectivity to the medical sensors, via the Internet, anytime/anywhere. The end-to-end reliable and secure messaging mechanism of CyPhyS+ does not necessitate intermediate application end-points at the old-age homes. This enables easy deployment with low operational overheads, scalability as well as easy introduction of newer applications or application upgrades.**

The paper describes system architecture, design and implementation details of software and hardware sub-systems. HealthMote, a power efficient Bluetooth-6LoWPAN mote was designed and deployed as a sub-system. We describe the novel low power end-to-end multi-stage message reliability scheme for UDP based sensor applications that does not require intermediate application-aware devices within the network. The experimental results presented show the efficacy of the approach. CyPhyS+ employs an application performance aware SNMP based network monitoring for robust operations of the 6LoWPAN multihop network. It incorporates a 128-bit AES, CBC-MAC based encryption and authentication mechanism for security and privacy. CyPhyS+ is compliant with FHIR/HL7 standards framework, with support for RESTful FHIR, and medical data analytics of ECG. We report on the extensive field trials carried out across a city.

I. Introduction

A World Health Organization(WHO) report [1] indicated that in the year 2012, chronic diseases were the leading cause of deaths worldwide. It is alarming that the disabilities related to these chronic diseases will soon become the top contributor for the overall disability in the population of the country. Chronic diseases are responsible for drastic deterioration in the quality of life of the affected people, notably among the elderly. Aging in Asia [2] reports a growth estimate of 7% in 2010 to 11% in 2025 for the elderly population in India. A remote health monitoring system that monitors vital parameters such as blood pressure (BP), blood glucose, ECG will facilitate disease management thereby, improving the quality of life of the individual. Such monitoring enables early disease detection and timely treatment. This enables better recovery and overall reduction in medical expenses. Remote health monitoring systems typically comprise low power wearable medical sensor devices with Internet connectivity. Early deployment of these systems have been catalyzed by advanced medical data analytics models, and the standardization efforts of medical information exchange. Given this background, we consider two usage models which, independently or in combination, provide efficient remote healthcare service to the elderly.

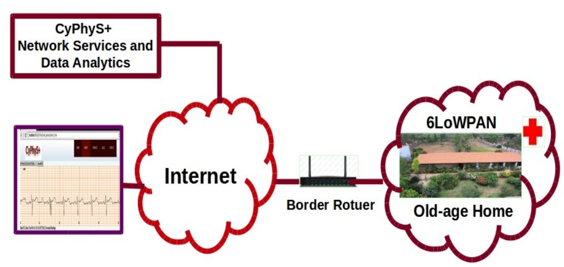

Figure 1: The picture shows the 6LoWPAN enabled old-age home connected to CyPhyS+ system's back-end servers on the Internet by a border router. The FHIR compliant web GUI is also shown.

Individual-centric healthcare: In this model, individuals collect medical data from medical wearable sensors (BLE enabled) on to their SmartPhones and send it to a Cloud via the Internet. SmartPhones, in the role of a personal mobile router between the body network and the Cloud, have made this model easy to deploy as a personalized monitoring solution. However, wide-spread deployment requires consideration of the technical and economical aspects. For a remote medical practitioner or a system to collect medical data at anytime and anywhere from the Internet depending on the medical condition of the person, the healthcare device needs to be "always connected and available" not just "always on", implying the Smartphone needs to be always connected to the Internet. This requirement causes usage and cost implications such as frequent Smartphone battery power drain and re-charging

978-1-4673-7281-7/15 $31.00 © 2015 IEEE
DOI 10.1109/SCC.2015.50

cycles, recurring non-negligible Internet broadband charges. The limited range of Bluetooth forces the old-age person to carry the Smartphone with him/her all the time which can be problematic due to the fragile and deteriorating physical and mental health condition. There could also arise radio coverage issues with the broadband Internet connectivity from the provider to which the user has subscribed to. The end-to-end security, software robustness, medical standard compliance of the application software running on Smartphone can be matters of concern. The "buy your own device and monitor yourself" mode, makes it hard to provide service guarantees required by a medical healthcare system.

Community-centric healthcare services : In this model, an old-age home offers a reliable, always-connected and managed healthcare services by deploying a robust network infrastructure in its premises which will be a shared resource to support medical services to all its inmates. The Figure 1 depicts this scenario. The low power operation and the Internet connectivity to the healthcare devices is enabled by setting up a 6LoWPAN multihop network in its premises. The medical data is forwarded to a 6LoWPAN-Internet border router which, could be multi-homed across providers, for reliability. At the home, the inmate is provided with a low power wearable mote with Bluetooth and 6LoWPAN interfaces. The Bluetooth interface receives data from medical sensors and sends it over 6LoWPAN. Such a *gatewaying* model has the following advantages to its credit.

The low power operation of Bluetooth and 6LoWPAN combined with reliable Internet connectivity enables access to the medical device any time from anywhere on the Internet. Since the network is used as a shared resource, it offers the benefit of statistical multiplexing gain and lowering the costs. The Service Level Agreement (SLA) with the Internet providers, and redundant Internet access links further improves the Internet performance. Since 6LoWPAN makes the wearable device to be directly addressable from anywhere on the Internet, remote doctors or a medical system can actuate the sensors on-demand by directly interacting with the devices. The old-age home can also implement unified end-to-end security policies. Considering the advantages offered by community healthcare service model in the context of old-age homes, we have chosen this model for the development of cyber-physical system for old-age homes, CyPhyS+, which is the focus of the paper.

In the sections II and III, we present the related work and our contributions respectively. The section IV provides overviews of the CyPhyS+ system architecture and the various building blocks of the system. The design and implementation of HealthMote, a wearable mote which provides Bluetooth-6LoWPAN connectivity is described in section V. In section VI the network sub-system that comprises data transport services, network monitoring and security modules are explained. Section VII briefly mentions the medical data analysis algorithms implemented in CyPhyS+. Section VIII describes the FHIR medical standards compliant RESTful web services offered by CyPhyS+. Section IX presents our field experimentation results and deployment experiences of CyPhyS+, followed by conclusion.

II. Related Work and Contributions

The IETF's low power 6LoWPAN over IEEE 802.15.4 extends the Internet to the health devices by providing them with IPv6 connectivity. In [3], the authors propose an interconnection framework for a patient's personal environment for continuous monitoring of medical vitals using a protocol YOAPY. It aggregates and pre-processes the medical sensor data before transmitting it over 6LoWPAN, to conserve the amount of data that is being sent. In [4] a prototype implementation of remote patient monitoring system based on 3G/4G and 6LoWPAN is described. The authors in [5] describe a healthcare system which comprises wearable sensors, 6LoWPAN for relaying medical data to a remote server for medical data processing, and visualization on a Android based Smartphone.

III. Our contributions

- We have designed and implemented an open standards compliant, reliable, secure, scalable, managed, low cost, and easily deployable healthcare system over 6LOWPAN, CyPhyS+. It is based on a system architecture that works on the end-to-end design principle and low power system operation for ensuring long lifetime of the resource constrained 6LoWPAN.
- We have developed an energy efficient wearable Bluetooth-6LoWPAN gateway mote, HealthMote, for medical data acquisition from Bluetooth enabled medical sensors and providing Internet connectivity.
- We propose a low power two-stage message recovery strategy for ensuring end-to-end message reliability of the medical data which passes through 6LoWPAN Low Power Lossy Network and the Internet over UDP. Our strategy does not require any additional middlebox.
- Our system integrates medical data analytics and FHIR medical standards based web services.

IV. CyPhyS+ System Architecture

The core design objectives for the CyPhyS+ are enumerated below:

1) The network deployment costs should be minimal. Post-deployment, the operational and maintenance overheads at the old-age home site should be minimal and the deployed system must function with minimal intervention, for a long time.
2) In order to minimize operational costs and maintenance overheads, there shall be no application aware middleboxes at the old-age homes. Application level middleboxes make it difficult to introduce new applications and/or upgrade them, increase the installation and operational costs, limits the use of low cost third-party network devices, and makes the deployment process hard.
3) An inmate of the home should be able to comfortably wear the monitoring device and perform her/his normal routine without the device causing any significant intrusions/limitations. The device should be accessible from the Internet at all times.

4) The medical data transfer should be reliable and secure, perform medical data analysis in real-time, should be based on open medical standards, and support remote networking monitoring.
5) The system should enable a remote doctor or a medical analytics system take medical vital readings of an old-age person from anywhere/anytime. This is a key requirement that makes CyPhyS+ a closed loop system.

The Figure 2 shows the system architecture and various software components which together meet all the design objectives.

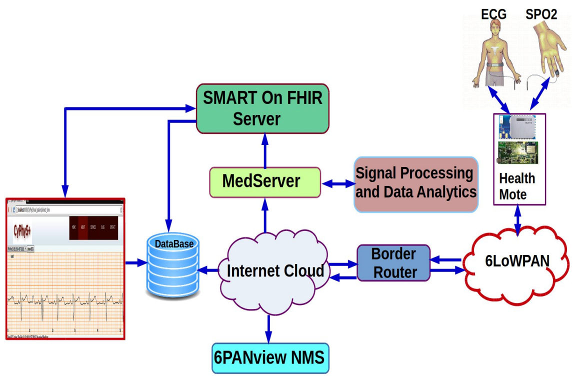

Figure 2: CyPhyS+ system architecture

CyPhyS+ system comprises set of building blocks as depicted in the figure. The wearable device, HealthMote, shown on the left side of the figure interfaces with various medical sensors over low energy Bluetooth that constitutes a Body Area Network (BAN). The other interface of HealthMote provides Internet addressability via 6LoWPAN. The HealthMote is part of a 6LoWPAN multihop network that interfaces to the Internet through a Border Router. The MedServer processes medical requests posted by a medical health professional over web portal, co-ordinates medical transfers by interacting with the HealthMote, ensures data reliability, invokes medical data analysis operation, and finally stores the medical data and the corresponding results in the FHIR medical records. The front-end GUI supports FHIR compliant RESTful web services. 6PANview is an SNMP based remote network monitoring system for 6LoWPAN network. In the following sections we describe the details of these building blocks.

V. HealthMote Design and Implementation

The primary design constraints for HealthMote are size, comfort, reliability, power consumption and safety of the end-user. This device needs to auto-configure itself and work in the field without any user intervention.

A. Hardware Design

HealthMote is designed using STM32 SoC that has 32-bit Cortex M3 core and 802.15.4 radio integrated. The HealthMote design differs from currently available gateways in the following aspects:

- Bluetooth 4.0 support using BLE113 module
- Analog front end for acquisition of any analog signal(up to uV range)
- Configurable low power architecture

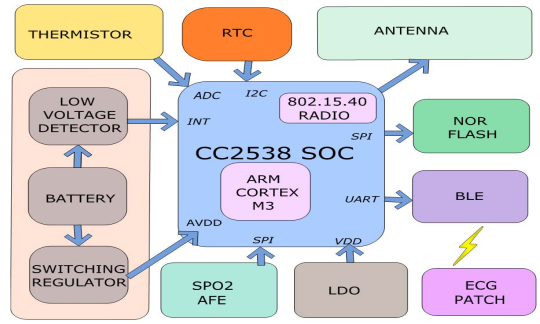

Figure 3: HealthMote block diagram

HealthMote can be remotely configured for periodic data acquisition and time period for which the data is to be sensed. The HealthMote then communicates with the sensors for example, IMEC ECG module over Bluetooth and BPL SPO_2 sensor using on-board analog front-end. The acquired data is then uploaded to the remote server reliably.

The system level block diagram is shown in Figure 3. ARM Cortex-M3 (part of CC2538 SoC) is the main controller of the HealthMote. Power gating is used to selectively power on the required peripherals. Bluetooth Low Energy (BLE) connectivity is provided by using BlueGiga's BLE113A module. The BLE module communicates with ECG patch over Bluetooth v4.0 interface. The data received by the BLE is forwarded to CC2538 over UART interface. AFE4490 (analog front end from TI for SPO_2 signals)is used to drive the LEDs of SPO_2 sensor and also to acquire the analog signal from the photo-detectors of SPO_2 sensor. AFE4490 sends the digitized value of signal acquired from SPO_2 sensor over SPI interface to CC2538. A thermistor is connected in Wheatstone bridge configuration to measure skin temperature accurately. Differential nature of the bridge is utilized to remove the power supply noise. A NOR flash M25P32 from STmicroelectronics is connected to the SPI interface for temporary data storage.

B. Specifications of HealthMote

The designed HealthMote has following specifications:

1) **Heart Rate:** PPG based, Measurement range: 40 to 200 beats/Min, Accuracy: +/- 5beats/Min, Resolution: 3 beats/Min.
2) **Blood Pressure:** Cuff based, Measurement range: Systolic 60 to 200 mm Hg and Diastolic 40 to 160 mm Hg, Accuracy: +/- 5mm Hg, Resolution: 1mm Hg.
3) **Temperature:** Measurement range: 0°C to 50°C, Accuracy: +/-1°C, Resolution: 1°C
4) **SpO2:** PPG based, Measurement Range: 70 to 100 %, Accuracy: +/- 2 %, Resolution: 1 %.

5) **ECG:** Third party device, 1 Lead ECG, BLE4.0 enabled.

C. Industrial design

Some pictures of product after integration of all components PCB, Cannon battery, SpO_2 connector, custom switch and RTC battery.

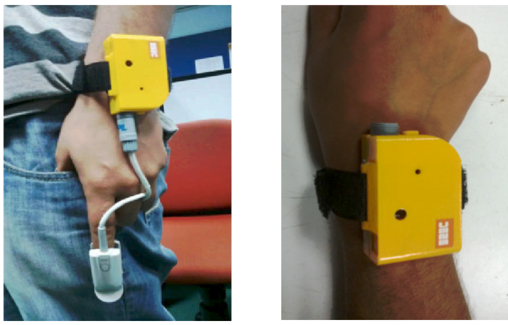

Figure 4: Some pictures of HealthMote

VI. Network-subsystem

The functional components of the network subsystem of the CyPhyS+ comprises of network monitoring and message reliability and security.

A. Message reliability

Data packets originating from the HealthMote experience losses as they traverse through the multihop 6LoWPAN network and the Internet segments before reaching the MedServer. It is imperative that CyPhyS+ ensures reliable message delivery of the critical medical vital data to the end applications. Note that 6LoWPAN applications use UDP as the transport because TCP is considered too heavy for the resource constrained motes and inappropriate for multihop wireless network.

Message reliability is typically addressed by deploying an application level gateway at the 6LoWPAN-Internet border. However, this is against the design objective laid out earlier. In addition, unpredictable wireless channel conditions, wireless node failures, packet losses due to channel contention, collisions, and so on have to be dealt with, on the multihop 6LoWPAN network segment.

- **Achieving loss free packet transmission**
  Loss free transmission is addressed in two steps. First, as a proactive measure against packet losses due to channel contention, packet collisions, and buffer overflows on the 6LoWPAN relay network, we limit the number of simultaneous application flows that can be active by considering the aggregate network capacity that is supported on the 6LoWPAN. The per-flow bandwidth depends on the nature of medical vital an application flow carries. The MedServer schedules the application flow requests and in effect does *flow admission control*. A critical parameter in this scheduling is the performance measurements available via 6PANivew.
  The second step requires the optimal rate at which the source should send the data into the network. In the absence of TCP, the source node on the 6LoWPAN sending data over UDP to the receiver on the Internet has no easy means of estimating the effective end-to-end capacity of the network without introducing some kind of feedback mechanism between the end points. The MedServer probes the 6LoWPAN border router using “pings” to estimate the bandwidth availability on the potential path to the MedServer, before initiating a connection. The MedServer, from these two steps, computes a source data rate and sends it to the source.
  In addition to the rate based control, a packet recovery mechanism is necessary, since transmissions are never loss free. “LinkPeek", a lightweight hop-by-hop IP layer message forwarding mechanism, ensures high PDRs on the 6LoWPAN segment. In addition, an energy efficient application level end-to-end NAK based loss recovery procedure that operates between the MedServer and the HealthMote, recover the remaining missed packets.
- **A reliable packet forwarding scheme for 6LoWPAN**
  LinkPeek is a lightweight add-on functionality to the network layer’s packet forwarding mechanism that works on a RPL/6LoWPAN stack [6]. When the network layer of the forwarding node detects a failed link level packet transmission to its best RPL parent (decided by its internal route decision logic), LinkPeek forwards the same packet to the next best parent in the available parent set ordered by path metric belonging to the same DODAG (Destination Oriented Directed Acyclic Graph). This process iterates over several parents depending on the application QoS requirements, memory and other constraints. The MAC retry limit, set by LinkPeek to decide when to explore the next parent in the sequence, is the critical parameter that influences the performance. Too small a retry limit value causes leaving the current parent to explore a parent with lesser path metric. A larger retry limit results in persisting with the "bad" parent for too long leading to packet delays, energy consumption and increased queueing.
  LinkPeek is implemented as a network software plugin module over the RPL network stack implementation of Contiki-2.7. The LinkPeek parameters required such as maximum parents, maximum buffers to be reserved for storing backup packets are configurable. The corresponding code occupies 2KB of program flash memory. The Figure 5 shows LinkPeek code placement in the packet forwarding chain of the IP layer, and its interface with with RPL and the link layer.
  To illustrate the performance improvement with LinkPeek, physical test-bed experiments were set up with an indoor multi-hop 6LoWPAN/RPL network with TelosB/Sky motes in the ground floor of the department’s main building (ref. Figure 6). Static and slowly moving data source scenarios were used for the experiments.
  Refer to 6 for the node placement. The dashed lines show the network connectivity after RPL DODAG tree is formed. The relay nodes were placed at a distance of

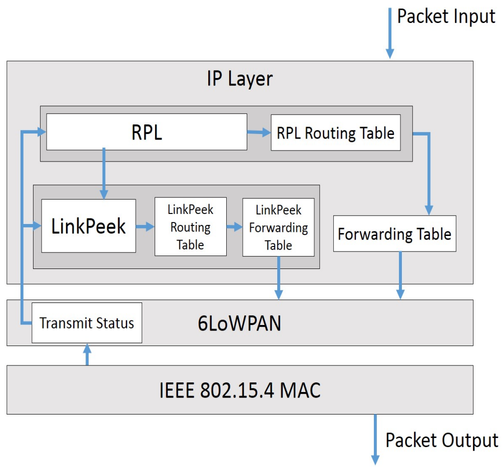

Figure 5: IP layer packet forwarding operation with LinkPeek

10 meters apart. The network is set up such that all the nodes will have at least two parents. The source node 8 generated UDP traffic of 33750 packets at 2 packets/sec to the base station. LinkPeek was configured with MAC retry limit of 2. Our experiment showed with LinkPeek the PDR was above 99% whereas we obtained PDRs of 76% without LinkPeek. Similar result was observed even at 4 packets/sec.

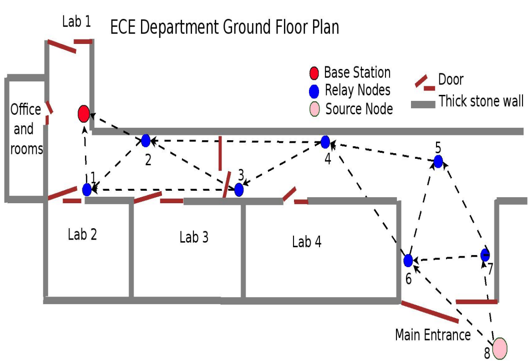

Figure 6: Physical 6LoWPAN/RPL LLN test-bed

With the same set up shown in the Figure 6, we had an "inmate" carrying a Sky mote generating UDP data at 2 packets/sec and walking at 1m/sec from the base station towards the main entrance of the department and retracing the path back to the base station. At the end of this short journey we noted that total of 250 packets have been generated. Here too we observed similar results as in the previous experiment.

- **Application Level Loss Recovery over UDP**
  Application level loss recovery is necessary in addition to loss recovery measures at the link layer, to minimize the end-to-end PDR at the application layer. First, the sender transmits sequence numbered data to the remote server as CBR traffic at a conservative rate so as not to exceed the end-to-end network capacity. The receiver maintains a timer set to conservatively large value so that the possibility of receiving a packet beyond this interval is minimal. The receiver requests for missed segments by sending a NAK packet containing sequence numbers of all the missed segments. The sender retransmits these missed segments exactly the way it has sent the original data. This method conserves energy because of the block NAK message rather than per packet NAK message. The process continues till all the packets are received.
  It is important to note that the receiver on the Internet has no means of knowing if the packet loss is taking place within the Internet or the 6LoWPAN segment. Because of this uncertainty, it is possible that the receiver might request the sender to retransmit the same data packet which was earlier successfully transmitted over the 6LoWPAN to the border router and the packet loss was actually on the Internet segment. This could result in additional power consumption on the 6LoWPAN. But as we show in the field experiment section later, the amount of this extra traffic handled by the 6LoWPAN nodes is so low that we can achieve our goal of providing end-to-end message reliability with a negligible increase in the power consumption.

B. Monitoring of CyPhyS+ system using 6PANview

For monitoring and management of a remotely deployed CyPhyS+ 6LoWPAN network, we use 6PANview [7], a SNMP based network monitoring system for 6LoWPAN networks, developed in-house. In order to maintain the performance of the application traffic flows over the 6LoWPAN network, 6PANview features an application performance conscious monitoring activity scheduler which schedules SNMP queries by detecting the network idle periods online. 6PANview comprises a light-weight SNMP agent, occupying a small memory footprint of 4KB flash, can run on several resource constrained mote platforms running Contiki and TinyOS 6LoWPAN RPL protocol stack. Some of the monitored information parameters include, node battery voltage, link and network layer packet counters, wireless link quality metric, RPL routing information. The RPL parent switch counter gives the number of times a node has switched its parent indicating the stability of routes.

6PANview GUI offers features such as online time series graphs and reports for various monitored variables. A typical display showing the route taken from a source to destination can be seen in Figure 7.

C. Secure Message Transfer

There are several security mechanisms proposed for WSNs. Physical layer attacks such as radio jamming, flooding, DOS attacks at the network routing layer, eves dropping and data modifications are some of the security threats that have been addressed in the literature. Message security and authentication are the primary focus in this implementation. Mitigation of attacks less likely in an old-age home scenario have not been considered.

Figure 7: 6PANview GUI showing node status, route from a node to the border router, and online time-series plots.

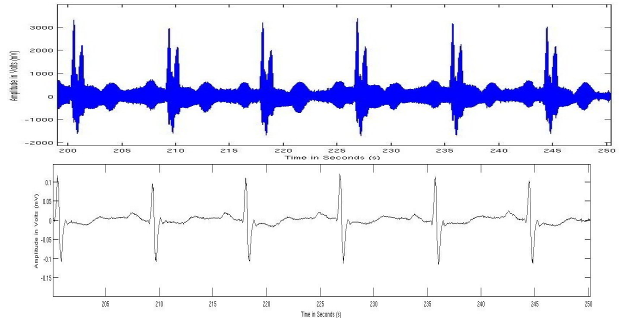

Figure 8: Raw (above) and de-noised ECG signal (below) after applying filtering, SURE, and wavelet techniques.

128-bit AES encryption is used for message encryption. Gladman's public domain **C** implementation is ported to Contiki OS for use in the motes. CBC-MAC is used for authentication and message integrity check and uses AES as the block cipher.

VII. ECG Analysis and Annotation

As medical data like Electro Cardiogram (ECG)and pulse-oximeter are highly susceptible to power line interference from near by devices due to improper grounding, Electromyographic noises,base line wandering caused due to activities like respiration and movements. The data is first subjected a series of low pass, high pass, and band pass FIR filters and passed on SG Filters using Stein's Unbiased Risk Estimator (SURE) to remove additive noise [8]. The DC drift is eliminated using a windowed normalization.

The Pan-Tompkins algorithm was modified to suit the needs of the system and the parameters i) False Positives ii) False negatives iii) True Positives iv) Sensitivity v) Positive Predictivity and vi) Average time error(ms) were obtained. The feature extraction, identifies other points P,Q,S,T once R peaks are identified through a logical sequence and statistical checks using window whose length is one third from current R-wave to next R-wave. Here in CyPhyS+, we use wavelet analysis using cross wavelet transform [9] to find out the level of uniformity between the input signal.Once the input ECG and the sample ECG are marked to a same sampling frequency, through interpolation and decimation, the CWT (Continuous wavelet transform) of the input is obtained by the "Morlet Wavelet" using the scales 5:15 and the output signals are time aligned for comparison. The cross wavelet transform (XWT) does a sequence of co-relation and time shifting to find out the exact amount of matching in time and frequency domain. The choice of wavelet for CWT has been chosen as morlet because of more adaptability to the continuous time analysis and the choice of XWT is symbiotic wavelet, and make use of their near symmetric property, orthogonality and bi orthogonality.

ECG analysis/annotations algorithms were evaluated on with data from Physionet Data Base and Real ECG data obtained from the ECG sensor used in CyPhyS+ system. The results were encouraging. Figure 8 shows the de-noised ECG section after the processing.

A. CyPhyS+ RESTful web services with FHIR

Fast Healthcare Interoperability Resources (FHIR) [10] defines a set of "Resources" that represent granular clinical concepts. The resources can be managed in isolation, or aggregated into complex documents. Technically, FHIR is designed for the web; the resources are based on XML or JSON structures. Clients have been developed for creating a patient resource and the family history of the patient. In order to store the data generated by a device, Device Observation Report resource is created and the the Diagnostic Report resource for the generation of reports. Each resource is linked with the patient resource as reference. It is easy for any doctor to view his patients records in a pile with links to multiple reports of a particular patient. The Practitioner resource, created, enables patients to view their doctor scheduled timings.

Figure 9: Screenshots of GUI

The front-end is a RESTful web-application at the server side and is a dynamic web portal at the client side which features role based access to the users, user-friendly display of medical health information, medical history retrieval, prescriptions and recommendations, and so on. The web portal lets the doctor/medical attendant request for medical vitals of their choice, from an inmate, in real-time. The progress status of the request is displayed at various stages of the back-end operation.

HAPI FHIR [11], a simple-but-powerful library, is used for adding FHIR messaging to the application. The HAPI FHIR library is an implementation of the HL7 FHIR specification for Java. In this effort, the full blown FHIR server implementation called 'Smart On FHIR', is used. FHIR compliant clients developed for CyPhyS+ are able to generate FHIR compliant resources like patient, doctor and exchange information between them with ECG readings, medical prescriptions and many more such information.

The web application of CyPhyS+ is designed and developed using Hibernate and Spring based RESTful web framework, Grails, backed by PostGreSQL database to store medical data and patient information in FHIR format.

VIII. CyPhyS+ Field Experimentation

We conducted extensive field trials across various parts of Bangalore City, India to evaluate the system under different deployment scenarios. Our sample set was based on the distribution of old age homes in Bangalore, and features that capture typical layout and construction characteristics of these homes. The field trials have been conducted to cover various regions of the city which represent a high density of old age homes as can be seen from the Fig.10. From our survey we found that old-age homes can be categorized as standalone independent homes, campus-like setting with vegetation, and multi-storied apartment complexes. Our experimentation was conducted in all such environments.

For the field experimentation we deployed CyPhyS+ at 25 different locations and conducted 100 experiment runs in all. In the rest of the section we describe the operational flow of a typical experiment run, specific details of the deployment and experiment, and share our network deployment experience along with performance evaluation of the network side of the operation.

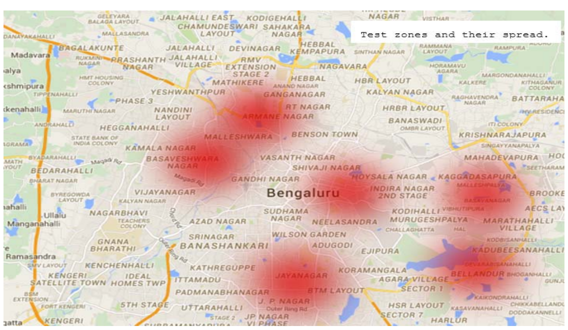

Figure 10: Old age home distribution in Bangalore

A. A typical experiment operational flow

After deploying the CyPhyS+ network at the experiment site and performing end-to-end reachability tests between MedServer and HealthMote, the experiment sequence proceeds as follows. First, a new medical data request for ECG is initiated through the CyPhyS+ web portal. This request is stored in a MySQL database to be served by the the MedServer. The MedServer then serves the pending request by using a message exchange sequence with the HealthMote resulting in medical data transfer. After ensuring all the data is received reliably, MedServer performs medical data analysis and stores both the raw data and the analyzed data in the database. The data is then accessed over the web using front-end GUI.

B. Field Experiment Details

At the field experiment site, we have set up a TelosB mote based multihop network running Contiki/6LoWPAN/RPL network stack enabled with LinkPeek packet forwarding mechanism described earlier. The 6LoWPAN border router which connects 6LoWPAN to the rest of the Internet is run on a Ubuntu Linux laptop equipped with a 3G USB dongle. Apart from the natural convenience 3G has offered us in getting Internet connectivity on-the-go, it is a widely used wireless access technology, and is well suited for deploying CyPhyS+ in remote places. The unpredictable 3G network performance also helped us in evaluating the CyPhyS+ performance in terms of overheads involved in packet loss recovery and end-to-end delays. The MedServer is remotely located in our lab.

For the medical data acquisition, we have used ECG data obtained from a single-lead ECG sensor sampled at 250Hz by the 12-bit ADC of the HealthMote. When the request is made by the MedServer, the HealthMote collects the samples in an 16-bit variable array for an interval of 8 seconds. This amounts to 3840 bytes of data. To minimize packet loss in 6LoWPAN and Internet, the data is broken into 80-byte chunks and sent over UDP to the MedServer at the rate configured by the MedServer.

As we have emphasized earlier, one of the primary design goals of the CyPhyS+ architecture is to provide end-to-end two-way connectivity between the remote IPv6 enabled HealthMote and the CyPhyS+ servers located on the Internet, and in doing so, we should avoid deploying additional middleboxes. A natural requirement therefore is an end-to-end IPv6 connectivity between the MedServer and the HealthMote connected to 6LoWPAN. The lack of IPv6 support from the 3G broadband service providers has forced us use 6to4 tunneling mechanism between MedServer and 6LoWPAN border router and thereby establish end-to-end IPv6 communication between MedServer and the HealthMote.

C. Network Deployment Scenarios

CyPhyS+ was deployed in several settings including independent residential houses, multi-storied apartment complex, old-age home, and outdoor locations. The test sites are shown in 11.

A single relay mote was sufficient to cover an entire residential house, making the deployment faster and easier. But for ensuring high message reliability in the advent of mote failure and to combat wireless channel outages, more relay nodes are required so that LinkPeek packet forwarding mechanism comes into play.

In the 7-floor apartment complex where we conducted the experiment, a relay network of 3 motes was required to provide network connectivity from any floor to the 6LoWPAN border router located at one end of the complex separated by 100 meters. As in the earlier case, more relay nodes are required to improve message reliability. We observed that the location of the border router is important to get good 3G coverage as it varies at different parts of the building.

Figure 11: CyPhyS+ Testing locations(clockwise): Apartment, Residential house, Old age home

D. Discussion on Field Experiment

For the evaluation of CyPhyS+, we have primarily considered two metrics that impact the performance of the system. These are packet loss recovery overheads, and end-to-end delays incurred in a executing one complete run from request to the results. The packet loss recovery process takes place at the MedServer which recovers lost packets through the NAK procedure described earlier. As LinkPeek mechanism ensures high packet delivery over the 6LoWPAN, if MedServer observes packet loss, it can be attribute to losses on the Internet. Since MedServer recovers these packet losses from the HealthMote, it is an overhead on the resource constrained 6LoWPAN network. The plot in the Figure 12 shows the number of missed packets and the number of NACK requests that have been sent before all the packets have been received for a given ECG request.

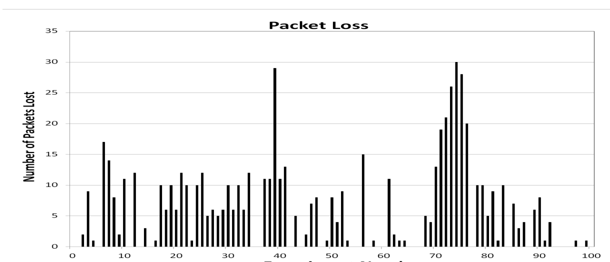

Figure 12: Packet loss measurements

As can be seen from the figure, except on two occasions, the average packet loss is 6.2 ± 6 packets. We also observed that with one NAK request we were able to recover all the lost packets. With the actual data being 60 packets, this amounts to 6 % overheads.

IX. Conclusion

In this paper we presented the design and implementation of CyPhyS+, a cyber-physical system we developed for remote health monitoring of elderly living in old-age homes from anywhere/anytime using the 6LoWPAN based Internet of Things. We gave the hardware design aspects of the low power wearable mote, HealthMote, a Bluetooth-6LoWPAN gateway. We highlighted the end-to-end design principle adopted by CyPhyS+ in its architecture, and described energy efficient message reliability mechanisms that have been implemented. We showed that the low power and low cost operation makes CyPhyS+ scalable, flexible and easily deployable in practical real-world scenarios. We corroborated this claim by sharing our experience of the field experiments we carried out across many parts of a city. We note that, while the real-time medical data analytics enables timely action performed on the remote medical sensors, the FHIR/HL7 standards compliant web services can be integrated with the other Hospital Management Systems to provide comprehensive healthcare services to the elderly.

X. Acknowledgment

The authors would like to thank Mr. Gopi Krishna Garge for his valuable feedback which greatly improved the manuscript. This work was supported by the Department of Information Technology (DeitY), India.

References

[1] WHO. *The top 10 causes of death*. 2012. URL: http://web.media.mit.edu/~msung/livenet-mobisys2004.pdf.

[2] Subhojit DEY et al. “Health of the Elderly in India: Challenges of Access and Affordability.” In: chap. 15.

[3] Antonio J. Jara, Miguel A. Zamora-Izquierdo, and Antonio F. Skarmeta. “Interconnection Framework for mHealth and Remote Monitoring Based on the Internet of Things.” In: *IEEE Journal On Selected Areas in Communication* (2013).

[4] Rohan Tabish et al. “A 3G/WiFi-enabled 6LoWPAN-based U-Healthcare System for Ubiquitous Real-Time Monitoring and Data Logging.” In: *Middle East Conference on Biomedical Engineering (MECBME)* (2014).

[5] Dr.Prakash.H.Patil and Seema.V.Kamkhedkar. “Wireless Machine to Machine (M2M) based e-Healthcare System.” In: *International Journal for Research in Applied Science & Engineering Technology (IJRASET)* (2014).

[6] T. Winter and et al. *RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks*. RFC 6550. 2012.

[7] Bhadriraju A.R. et al. “6PANview: Application performance conscious network monitoring for 6LoWPAN based WSNs.” In: *National Conferene on Communications (NCC)* (2012).

[8] Krishnan S.R. and Seelamantula C.S. “On the Selection of Optimum Savitzky-Golay Filters.” In: *Signal Processing, IEEE Transactions on* 61.2 (2013), pp. 380–391.

[9] Banerjee S. and Mitra M. “Application of Cross Wavelet Transform for ECG Pattern Analysis and Classification.” In: *Instrumentation and Measurement, IEEE Transactions on* 63.2 (2014), pp. 326–333.

[10] *FHIR: Fast Healthcare Interoperability Resources*. 2013. URL: http://hl7.org/implement/standards/fhir/.

[11] *HAPI FHIR: FHIR made simple*. 2014. URL: http://jamesagnew.github.io/hapi-fhir/.