Telehealthcare M-Health Case Study

-- Proposed by Fei Hu; Only for UA students

Print out hard copy and give to students

A. Introduction

A.1 *Background and Project Goal*

Current U.S. health care systems -- structured and optimized for reacting to crisis and managing illness -- are facing new challenges: *rising health care spending.* The overall health care expenditures in the United States reached $1.8 trillion in 2004 with almost 45 million Americans uninsured. It is projected that health care expenditures will reach almost 20% of the *Gross Domestic Product* (GDP) in less than one decade, threatening the wellbeing of the entire economy [1, 2].

Tele-healthcare would largely benefit our society by improving life quality as a result of providing coordinated and continuous care for patients and highly effective tools for decision support. Especially, *tele-healthcare system plays important roles when we face deadly viruses today*. By summer of 2009 Swineflu virus has spread over 60 countries, imposing an unprecedented threat to the world. By using a low-cost, wireless-sensor-based (<$100 each sensor) *tele-healthcare monitoring* system, a doctor's office can remotely collect patients' body parameters at any time and make timely treatment decisions [3].

Tele-healthcare Computing (THC), which targets the *computing engineering / science* topics in tele-healthcare research, has become one of the hottest research fields today. For example, *CardioNet* is the first service provider of *mobile cardiac outpatient telemetry* (MCOT) in the U.S. for monitoring of a patient's heartbeat [4]. A combined hardware / software platform, known as *CodeBlue* [5], provides protocols for bio-signal collection and multi-hop routing, besides *SMART* [6] and *WiiSARD* [7].

Project Goal: This project will establish a *research infrastructure* for the cutting-edge studies on tele-healthcare **accuracy** (*noise-resistant* medical signal processing), **reliability** (*error-resistant* medical data transmission), and **security** (*attack-resistant* medical data sharing). Especially, we will build two types of *research* ***primitives*** (see **Fig.1**): (1) *Individual hardware / software primitives* for 4 sub-systems (body sensing, signal measurement, patient monitoring, and system control); (2) *Co-design primitives* with re-adaptable hardware/software interactions to enable compelling **ARS (Accuracy, Reliability, and Security)** research opportunities. In addition, the THC *research primitives* will be converted into **educational** labs through a *multi-level*, *building-block*-based class lab development approach.

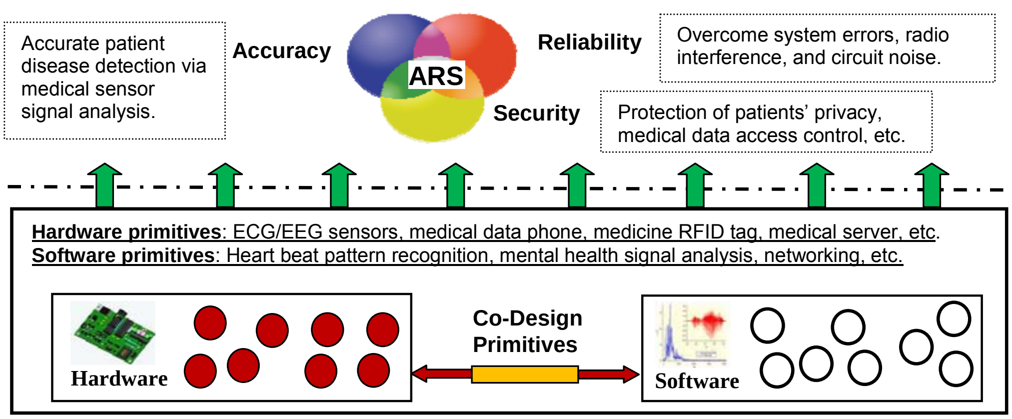


Fig.1 *Tele-Healthcare Infrastructure: Enable Research of* ***Accuracy, Reliability and Security (ARS)***

In the following discussions we will provide more background knowledge on **ARS** research:

(1) Accuracy (i.e., *noise-resistance*): Lots of system noise (coming from patient organs, circuit thermal noise, electricity current oscillation, etc.) can be mixed into medical sensing data, which makes accurate medical signal pattern detection very difficult. A typical example is that a brain sensor cannot obtain accurate neural activity data due to the noise caused by eye blinking [8]. Therefore, much research is conducted on *noise-resistant* medical signal collection and recognition [8-10].

(2) Reliability (i.e., *error-resistance*): It is extremely important for a tele-healthcare system to be fault-tolerant [11-13], i.e., reliably delivering medicine-taking instructions and other diagnosis results to a patient even though medical errors (such as intermittent bio-signal data missing) could occur in the system. Moreover, THC typically uses wireless networks (such as wireless sensor networks) to achieve remote monitoring. Thus reliability also means overcoming *high data loss rate* due to radio interference. Reliability also means overcoming *dynamic communication topology* due to patient movement.

(3) Security (i.e., *attack-resistance*): An important concern needs to be addressed before any THC platform is deployed in the nation, that is, the system should support strong *medical security* [14-17]:

> *U.S. HHS issued patient privacy protections as part of the Health Insurance Portability and Accountability Act of 1996 (HIPAA). HIPAA included provisions designed to encourage electronic transactions through networks and also* ***required new safeguards to protect the security and confidentiality of electronic health information****. Health insurers, pharmacies, doctors and other healthcare providers were required to comply with these federal standards beginning April 14, 2003.*
>
> *-- See HIPAA Privacy Rule [18], U.S. Department of Health and Human Services*

As a matter of the fact, many hospitals and patients are afraid of using electronic systems because of immature patient *privacy-preserving* technology [19]. For example, a patient may carry RFID tag that corresponds to the patient's profile data in the medical database. The disclosure of data during RFID tag-to-reader communications can cause the violation of patients' privacy.

A.2 Intellectual Merits

Contribution 1: Developing Essential Backbone Primitives for 4 Tele-healthcare Sub-systems.

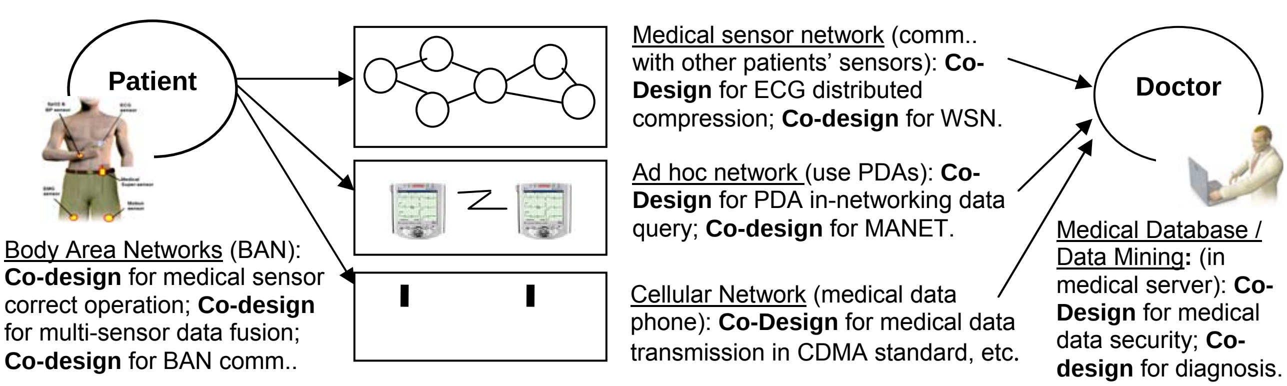
This project will first build "bricks of the building", i.e., important hardware and software primitives that are commonly used in the infrastructure backbone. Specifically, we will design *individual primitives* for the following 4 infrastructure sub-systems: *(1) Body bio-signal sensing units* (such as heart beat sensor). *(2) Signals measurement units* (such as spectrum analyzer, etc). *(3) Remote patient monitoring units (such as wireless networking systems)*. *(4) System management software units* running in the medical server for system control purpose (such as medical database management).

For some hardware primitives with high-resolution requirements on data collection (such as brain signal sensor), instead of simply purchasing commercial products (which are expensive, and typically not re-programmable), we aim to design extra-portable, low-cost circuits based on VLSI chip design. Such a customization approach allows flexible research experiments through re-programmable chip interfaces.

Contribution 2: Building *Plug-and-Adapt, ARS-Oriented* Co-Design Primitives.

Our above hardware /software primitives do not operate independently. Instead, a series of hardware /software co-design primitives will be built to integrate those basic primitives to achieve different ARS research goals. As shown in **Fig.2**, a typical tele-healthcare system includes: (1) local patient sensing through a body area network (BAN), (2) different types of medical transmission approaches (such as sensor networks, cellular networks), and (3) system management in the medical server. Each sub-system (in the patient, network or doctor sides, see **Fig. 2**) consists of a series of **task-oriented** co-design primitives, which are based on the integrated hardware /software design.

Since the THC infrastructure is built to enable NEW research, our co-design primitives will be built as **plug-and-adapt**, i.e., they have flexible interfaces for new task functionalities. For instance, we will build a co-design primitive on hop-to-hop packet loss recovery to serve as a *reliability* research **baseline**. However, one can easily revise the software interface to adapt to new loss recovery algorithms.



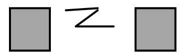


Fig. 2 *Hardware & software primitives: Co-Design*

<u>Contribution 3:</u> Developing Inter-domain *Programming Environment* and Integrative *Evaluation / Test Tools* for Fast and Reliable System Development.

Our THC infrastructure will provide an inter-*domain* programming environment with seamless integration of the following **domain**s: tele-healthcare sensor models, bio-signal analysis, tele-healthcare computational and communication resources. To achieve such a goal, we will develop a set of tools for the performance test of a new developed sub-system that is added to the infrastructure. Such tests are under a unified theoretical and numerical framework. Based on the test results, the individual or co-design *primitives* in the research infrastructure can be improved in the next design iteration.

Figure 3 illustrates the relationship among the above three contributions: the theme of this project is to develop a *computing research infrastructure (**CRI**)* based on tele-healthcare data processing hardware /software to enable remote patient monitoring and diagnosis. To achieve such a goal, **Contribution 1** targets the distributed system operations in each backbone primitive. **Contribution 2** builds a reconfigurable platform with ARS-oriented co-design primitives. And **Contribution 3** provides performance evaluation /test tools to enable fast and reliable THC design and development.

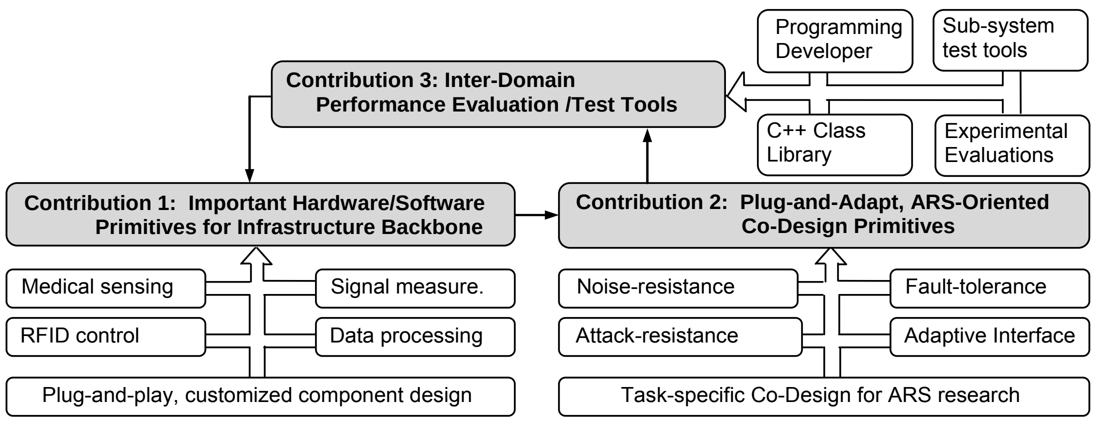


Fig. 3 Relationship among the 3 main innovations of the proposed THC research infrastructure

B. Infrastructure Establishment

Infrastructure Overview: Our proposed THC infrastructure consists of 4 sub-systems (see **Fig. 4**): **Part 1: Sensing**. In this part, we design a series of **medical sensors** with 3 capabilities: *life parameters sensing*, *local bio-signal CPU processing*, and *RF (Radio Frequency) communications*. Besides, Part 1 also includes RFID reader. **Part 2: Signals**: Signal analysis is important to the detection of medical system noise. **Part 3: Networking**: This part emphasizes the *networking* functionalities through wireless systems such as medical sensor networks. **Part 4: System**: This part controls the tele-healthcare system operations through the software primitives in the medical server.

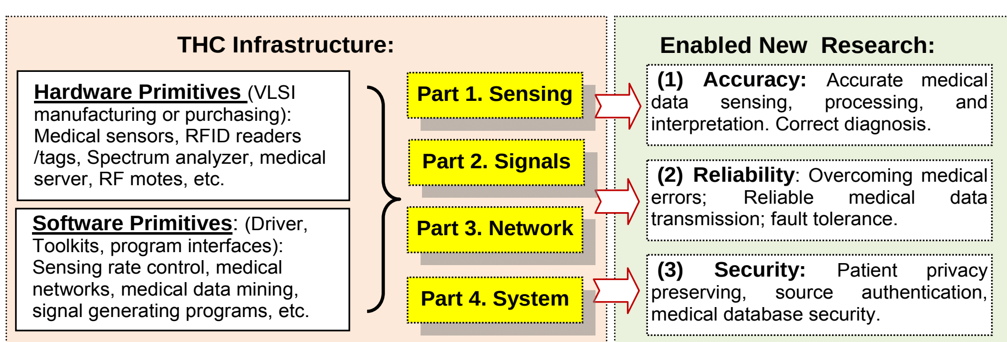


Fig. 4 *THC Insfrastructure Architecture*

B.1 <u>Hardware</u> Primitives Development

We will first explain **hardware primitives** to be built in our research infrastructure. The purpose of hardware primitives is to **collect, process, and transmit healthcare parameters** (see **Table 1**).

Table 1.
Some healthcare parameters collected by hardware primitives

Healthcare parameters	**Alert conditions** [3]
Oxygen saturation	SpO2 < 90% (default values, adjustable)
Bradycardia	*Heart beat Rate (HR)* > 40 bpm (adjustable)
Tachycardia	HR > 150 bpm (default values, adjustable)
HR change	| ΔHR per 5 minutes | > 19%
Blood Pressure change	Systolic or diastolic change > ± 11 %

B.1.1 <u>Part 1</u> (Sensing) Hardware Primitives: Part 1 of the infrastructure includes medical sensors, RFID, and other portable devices. Typically, a patient could carry the following hardware units (see **Fig.5**): *(1) ECG (Electrocardiograph) sensor, see* **Fig.6** (a). It uses at least 3 leads to measure heart beat signals to detect heart disease; *(2) EEG (Electroencephalography) sensor,* measuring brain signals for mental health problems; *(3) EMG (Electromyography) sensor*, measuring the patient's muscle movement status; *(4) RFID reader* to read RFID tags. The tags can be attached to a medicine bottle to monitor patient's medicine-taking. **Fig.6** (b) shows a mini RFID reader by SkyeRead Inc. *(5) Patient simulator (***Fig.6** *(c)):* In many cases it may not be easy to find real patients to test those sensors. We propose to use patient simulators (such as Model 430B ECG simulator by Medi Cal Instruments, see **Fig.6** (c)) to generate medical signals (such as normal or disease-like signals).

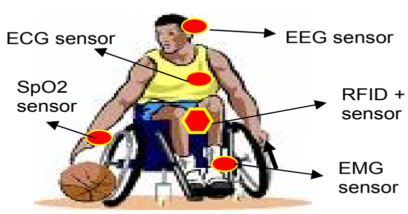


Fig. 5 Medical Sensors in a patient's body

(a) ECG Sensor [5]
(b) SkyeRead M1 Mini RFID reader
(c) Patient simulator

Fig. 6 Some Part 1 hardware primitives

<u>This project will adopt the following three approaches to design *Part 1* hardware primitives</u>:

Approach 1: Purchase existing products: Some devices are not easy to design. They can be purchased from companies. These include patient simulators, SpO2 / blood pressure sensors, etc.

Approach 2: PCB *(printed circuit board)* assembly based on COTS *(commercial off-the-shelf)* chips: To reduce the infrastructure cost, this project will design some devices through the assembly of COTS chips. For instance, we will fabricate an ECG sensor PCB from microcontroller, RF transceiver, memory, batteries, and other electronic components (e.g., capacitors, resistors, etc.). Our PCB fabrication will be achieved through a high-resolution **PCB Milling Machine** (to be purchased).

Approach 3: System-on-chip VLSI (*Very Large-Scale Integrated circuit)* manufacturing: Due to the complexity of measuring brain signals (for instance, the eye blinking and hairs/scalp can add noise to EEG sensor data), we plan to use VLSI technologies to manufacture a tiny EEG sensor with all electronic components integrated in a **system-on-chip (SoC)**. **Fig.7** shows our VLSI design procedure.

Note that Approach 1 typically has higher cost than Approaches 2 and 3 (i.e., self-design). Approach 3 has best circuit performance in terms of chip size, running speed and power consumption.

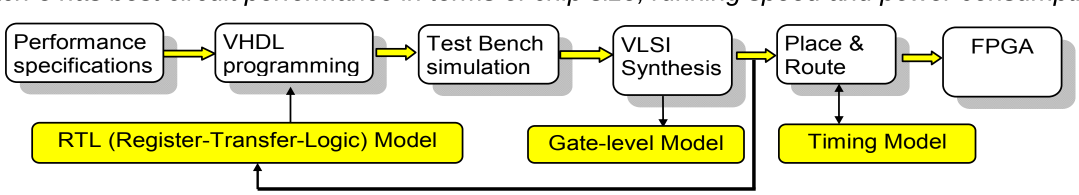


Fig. 7 Customized VLSI design for low-power, tiny EEG sensors

B.1.2 <u>Part 2</u> (Signals) Hardware Primitives: In Part 2 of the infrastructure, we will use the following hardware primitives for signal measurement: *(1) RF Detector* (Fig.8 (a)): It measures wireless signal strength to analyze the interference / noise levels. (*2) Spectrum analyzer* (Fig.8 (b)): It can find out what type of wireless networks is used for medical transmission, and search the best RF bands to transmit data*. (3) Wave Generator (Fig.8 (c)):* It is used for system test purpose by generating arbitrary format of test signals.

(a) RF Detector [41] (b) Spectrum Analyzer [42] (c) Wave Generator [43]

Fig. 8 Hardware Primitives for Signals Measurement /Analysis

B.1.3 <u>Part 3</u> (Networking) Hardware Primitives: The hardware primitives in Part 3 of THC infrastructure mainly include the following devices to achieve *remote patient monitoring* at any time and any place*: (1) Programmable PDA (Personal Digital Assistant)* (Fig.9 (a)): It operates like a portable, tiny PC. If carried by a patient, it can aggregate all medical sensors' data and send them out together; if carried by a doctor, it can receive and display the medical data. *(2) Programmable medical data phone (Fig.9 (b)):* Since cell phone is the most popular wireless communication tool today, we can use it to send out medical data. It is re-programmable to allow us to change its network interfaces (e.g., communicating with both a body area network and a cellular network). *(3) Crossbow radio board (Fig.9 (c)):* It is a widely used wireless communication board with analog sensor interfaces; *(4) Wireless base station (Fig.9 (d)):* It is used in the doctor's office (or in the hospital) to control remote wireless terminals (such as PDAs).

(a) Programmable PDA (b) Programmable Medical Data Phone (c) Crossbow Radio Board [44] (d) Wireless Base Station

Fig. 9 Hardware Primitives for Remote Patient Monitoring

B.2 <u>Software</u> Primitives Development

We will design software primitives for Parts 1~4 (see **Fig.4**) in the infrastructure. All software modules will be written in either C / C++ (for toolkits), or Assembly Language (for device drivers), or Java (for Internet applications). <u>This project will adopt the following three ways to develop software primitives:</u>

Approach 1: Open source programming: This project will utilize open-source codes to develop OS software and networking protocols in C/C++ language. For example, we will use open-source ZigBee protocol stack (*http://www.zigbee.org*) to develop ECG sensor network lower layer protocols.

Approach 2: Drivers for self-designed hardware: Because we will design most of the medical sensors by ourselves (through *Approaches 2 or 3* described in Section B.1.1), we need to write the device drivers / toolkits for the sensors' routine operations (e.g., reading analog ECG signals).

Approach 3: Customized programming for toolkits and equipments: For some equipment directly purchased from companies, we still need to write some programs for the convenience of building special applications. For instance, we need to write customized programs for the Wave Generator in order to generate special test signals (such as 2.4G Hz free-band radio signals).

B.2.1 Software primitives for *Part 1* hardware (medical sensors / RFID): Part 1 hardware primitives (medical sensors and RFID readers / tags, see Fig.5) operate with the support of the following software modules: *(1) Sensing control software (i.e. sensor driver):* after we design the medical sensors, we will design *program interfaces* in each sensor to prepare for remote over-the-air sensor control such as the change of sensing rate (i.e. how many samples to sense per second), stop / resume of sensing, the change of alert threshold (note: the sensor sends out alert signals when the sensing value goes beyond a threshold), and other tasks*.* *(2) Medical data cleaning software:* Typically we pre-filter the sensed data to reduce the noise before we send it out. For instance, we will design EEG brain signal filtering software to remove the effects of eye-ball movements. *(3) RFID reader control software:* We will build our own RFID readers because current commercial RFID products do not allow convenient re-programming. We will design the RFID control software to avoid multi-tag read conflict.

B.2.2 Software primitives for *Part 2* hardware (signal measurement): Part 2 has hardware for signal measurement purpose (see Fig.8). We will build two software primitives for such equipment: *(1) Spectrum classification software:* Most commercial Spectrum Analyzers do not have straightforward classification software to identify the operating *radio frequency (RF)* bands. Such a RF analysis program is needed to find out the best interference-resistance effect among the RF spectrum. *(2) Wave Generator programs:* For medical systems, we need to generate some special signals to test the remote control capability. For instance, a pulse-like wave can test the sensors' command capture speed; a sinusoidal wave can test the sensors' antenna power adjustment features. This project will design a set of programs to generate special system test signals.

B.2.3 Software primitives for *Part 3* hardware (remote monitoring): Part 3 of the infrastructure achieves *remote patient monitoring*. We plan to build the following software primitives for Part 3 hardware (see Fig.9): *(1) Programmable PDA:* It is typically carried by a patient to aggregate all medical sensors' data and send them out together. Therefore, data aggregation software needs to be built in a PDA. The software needs to record different formats of medical data (ECG, EMG, pulse rate, etc.). *(2) Programmable Data Phone:* Today's cell phones can be used for both voice and data communications. We will build medical data transmission software in the cell phone. Such software needs to perform two tasks: On one hand, it needs to aggregate the medical sensor data through a body area network; on the other hand, it needs to support the cellular network protocols such as CDMA. (*3) Crossbow RF motes programming:* Although many network protocols have been built into the Crossbow motes, they do not have many features such as network congestion avoidance.

B.2.4 Software primitives in Part 4 (System control): System *management and control* software primitives reside in the medical servers (located in a doctor's office or a hospital). The following basic software modules are needed: *(1) Medical data to Internet ODBC (Open DataBase Connectivity) interface* for Internet sharing; *(2) Medical data statistical analysis:* The statistical data (such as abnormal heart beat patterns, low oxygen level) also needs to be automatically generated from medical data.

B.3 <u>Co-Design Primitives</u> *for ARS Research*

In the above sections we have *separately* described 4 parts of hardware primitives and their corresponding software primitives. On the other hand, the proposed THC infrastructure is used to support *Accuracy, Reliability and Security (ARS)* research in *integrated* application scenarios which typically require **task-specific** *hardware / software co-design (called* ***Co-design Primitives****).* In the following sections we shall discuss *co-design primitives* that are critical to ARS research.

B.3.1 Co-design primitives for *<u>Accuracy</u>* research: Medical *accuracy* research mainly includes *sensing accuracy* and *data interpretation accuracy*: *(1) Co-design primitive for Sensing Accuracy:* when an EEG sensor is used to collect humans' brain activities, the scalp and hairs weaken the electric current passing through the analog part of the EEG sensor. Therefore, a special *hardware/software co-design primitive* is needed to *design noise-free sensor circuit with intelligent signal filtering*. *(2) Co-design primitive for Data Interpretation Accuracy:* After the collection of sensor data, the next step is to *accurately interpret* the data to make correct medical diagnosis. This project will consider the hardware and software co-design to accurately identify ECG / EEG patterns and human diseases.

B.3.2 Co-design primitives for *<u>Reliability</u>* research: (1) *Overcoming medical errors through data prediction*: Data prediction software based on Kalman filter and Particle filter will be built to compensate for damaged data due to medical errors. *(2) End-to-end vs. hop-to-hop loss recovery*: Reliability is achieved through loss recovery

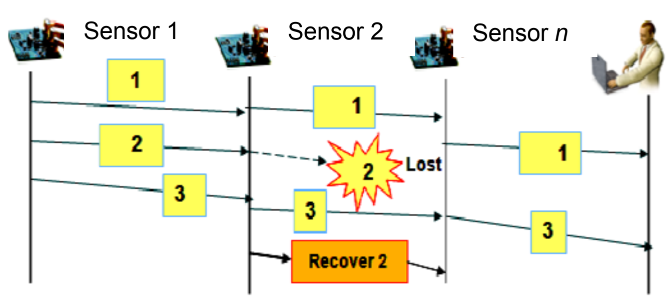


Fig.10 Hop-to-hop data loss recovery

during the medical transmissions. Two *co-design primitives* will be designed for reliability research: one is to use traditional TCP-like end-to-end retransmission scheme to recover lost packets; the other one is to recover the lost packets in each wireless link (i.e., hop-to-hop, see **Fig.10**). *(3) Uplink (sensor-to-server) and Downlink (server-to-sensor) reliability:* From medical sensors to a server (uplink), we can tolerate some data loss. From a server to sensors (downlink), the command data requires 100% reliability. Hardware/software co-design primitives are needed for both uplink and downlink reliability.

B.3.3 Co-design primitives for *Security* research: Two type of basic *co-design primitives* are needed for security research across hardware primitives such as medical sensors, RFID reader, data phone, PDA and medical server: *(1) Low-complexity medical server authentication primitive* (such as a sensor's authentication of medical server): three *broadcast authentication* protocols (based on µTesla [45], RSA [46], and NTRU [47], respectively) will be designed for researchers' convenience of comparing different source authentication schemes. *(2) Patient privacy preserving primitives:* During the transmission of medical data from sensors to a server, how do we protect the patient's data from *both internal and external attacks*? For *external* attacks, the following two types of primitives will be built: stream ciphers (such as LFSR [48] and RC4 [49]), and block ciphers (such as DES [50], FEAL [51]). For *internal* attacks, a node's reputation model and trust calculation scheme will be built.

B.4 Inter-Domain Programming and Integrative Evaluation/Test Tools

Ideally, the THC infrastructure's programming environment should support the distributed coordination among multiple individual / co-design primitives, and provide common, easy-to-use *middleware layer* programming interfaces. (Note: *middleware layer* can hide all physical device concrete implementations from an application programmer). Besides programming environment, a set of integrative performance evaluation / test tools will be developed in this project to provide feedbacks for system improvement during the infrastructure design and implementation iterations.

B.4.1 Inter-Domain Programming Developer. We define *domain* as a tele-healthcare sub-system that consists of individual and co-design primitives (such as a patient's *body area network*, ECG anomaly detection system, medical database access control, etc.). *This project will develop an inter-domain **programming environment** (called **developer**) for convenient programming under different medical sensor modalities, noise / error sources, and computational and communication (C&C) resources*. Such a **developer** will be constructed through a library of C++ classes. These classes contain intuitive abstraction of the medical sensors, bio-signals, network physical architecture, and logic models of tele-healthcare sub-systems.

B.4.2 Integrative Evaluation / Test Tools. The proposed infrastructure should have a set of *evaluation tools to test the performance of any new designed tele-healthcare sub-system* that may be added to the current research infrastructure. Such tests should be under a unified theoretical and numerical framework. *Therefore, we will develop a set of integrative evaluation / test tools that enable numerical simulation, model analysis and experimental tests*. For instance, we will use Matlab (*MathWorks Inc.)* to develop a software tool for *EEG signal compression* performance test. Such a tool can quickly find out the compression ratio / signal quality of a proposed new compression algorithm.

Table 2 provides a summary of evaluation metrics, test tools, test methods, and improvement suggestions (based on test results) for some typical sub-systems (from the perspective of medical accuracy, reliability and security). *Based on the tools' evaluation / test results, each co-design primitive and THC sub-system can be improved during the next design and implementation iteration.*

Table 2. Summary of evaluation metrics, methods, measures and optimization components

Metrics	Test Tools	Test Methods	Improvement suggestions
EKG pattern recognition accuracy	Medical data mining Tool	Track pattern detection errors among EKG generator's signals	Go back to check the issues in ECG hardware chips (such as amplifier, filter) and ECG signal classification algorithm
Medical Sensor Resolution	Data displayer & statistics Tool	Use a medical network to test the received sensor data quality	Re-design the sensor sampling structure, chip architecture, analog-to-digital data transformation
Patient Tracking accuracy	RFID Test Tool	Use mobile humans with RFID to test trajectory tracking	Re-design the RFID reader's hardware and / or control software

Medical Transmission reliability	Data Loss Statistics Tool	Use a medical network to test the data arrival statistics	Re-design loss prediction and network recovery algorithms
Medical Privacy strength	Attack Test Tool	A man-in-middle attack will be used in a medical network to test the encryption performance	Improve /change the cipher algorithms and network key management protocols
EEG (brain signal sensor) accuracy	Anti-noise analysis Tool	Add artificial noise to EEG sensor input and test the patient's drowsiness detection	The EEG sensor's anti-noise filter circuitry needs to be investigated
Sensor Energy Efficiency	Energy Statistics Tool	Measure the sensor sampling frequency and voltage level	Check the sensor's power leakage and RF transceiver's hardware

C. How does the proposed CRI enable new, compelling ARS Research?

Research Area 1: Medical Accuracy:

The most important task of a remote tele-healthcare monitoring system is to accurately identify the patients' health status. Let's look at a *mental health* monitoring scenario. As shown in **Fig.11**, the raw EEG signals pass through signal amplifier, noise filter, and ADC (analog to digital converter). Then they become CPU-understandable data. After the removal of eye blinking effects (via Data Cleaning algorithms), an EEG sensor could use compression scheme to remove "normal" EEG signals, i.e., only keeping abnormal signals. Next, a RF mote uses a wireless sensor network to transmit the EEG data to a medical server where the **accurate** EEG feature analysis is conducted.

In **Fig.11**, some interesting research issues either remain unsolved (e.g., accurate drowsiness detection from very noisy EEG data stream), or need further *accuracy* improvements (e.g., EEG pattern recognition and classification). Obviously, those research activities should be based on realistic experiments through our proposed infrastructure with co-design hardware and software primitives.

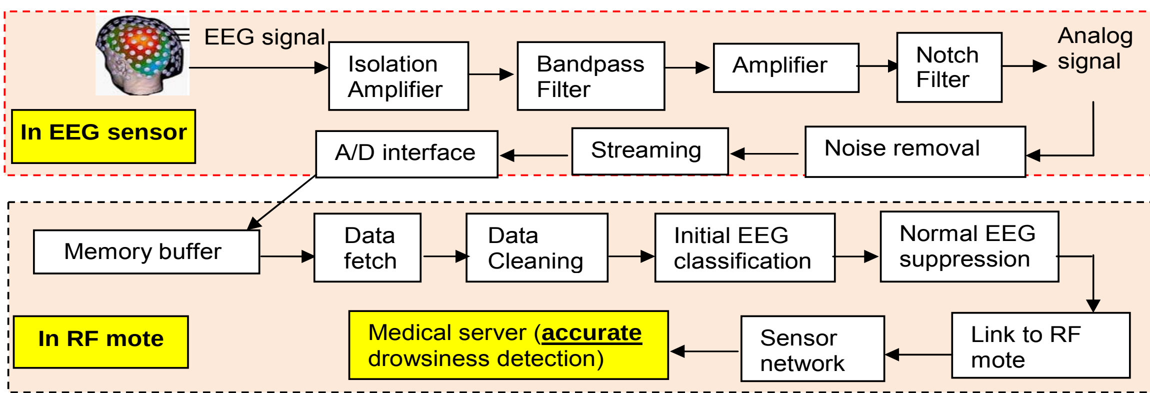


Fig. 11 **Accurate** Mental Health Monitoring

Research Area 2: Medical Reliability:

Reliability in tele-healthcare system typically relies on **loss-resistant** medical data transmissions. The packet **loss** could come from *radio interference* (which damages some data bits and causes the entire packet useless) or *network congestion* (a routing node drops the packets due to buffer overflow). In the following two loss-resistant research approaches (**Fig.12**), it is still unclear which one is better in terms of supporting reliable medical data collection in large-scale medical networks:

Approach 1: Reliability in the destination side (**Fig.12** top): To reduce the network protocol complexity, we may just achieve reliability in the server side. For ECG/EEG data streams, some future value prediction algorithms, such as Kalman Filter, Sequential Monte Carlo, etc., can utilize the cross-correlation among ECG/EEG data to estimate the lost values.

Approach 2: Reliability in the network side (**Fig.12** bottom): To reduce network traffic, this approach first compresses the medical data through feature coefficients extraction. The coefficients are then forwarded to the destination. We cannot lose any of those coefficients since we need ALL of them to reconstruct the original ECG/EEG signals. The network needs to provide 100% error recovery schemes.

Fig.13 shows that our proposed infrastructure enables the above compelling research.

ECG / EEG sensors

Raw Stream

{X1, X2, …, Xn}
Feature extraction

Pass sensor network without loss recovery

Pass network with 100% loss recovery

Prediction-based loss recovery

Destination

Signal reconstruction

Fig. 12 Two approaches to overcome packet loss

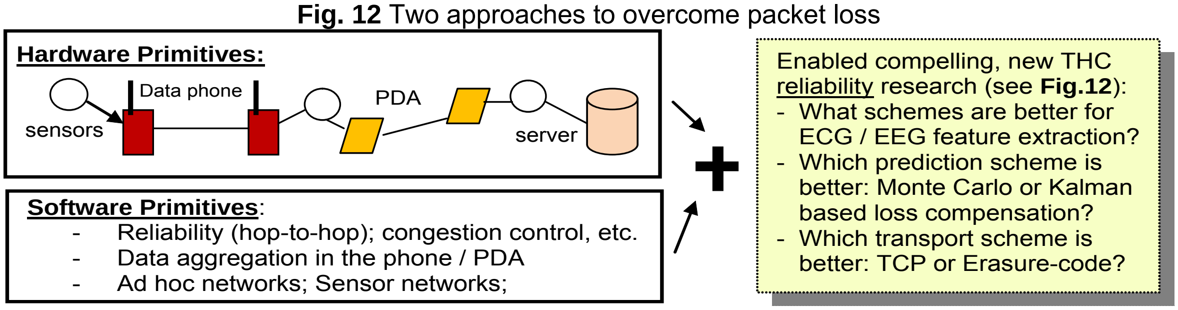


Fig. 13 Use the proposed THC infrastructure for "reliability" research

<u>Research Area 3</u>: Medical Security:

There are many compelling <u>medical security</u> issues in a large-scale medical network with ECG/EEG sensors and RFID-based medicine tracking system. Here we list two examples:

Example 1: Medical Accountability: A Medical Sensor Network (MSN) should be *accountable*, i.e. it should have the following two features during ECG / EEG and other medical data transmissions:

(1) Spatial Accountability*:* A MSN should have strategies to *physically* trace the ECG/EEG data flows.

(2) Temporal Accountability*:* This refers to the *trust* level of the timestamp information exchanged between sensors for accurate ECG/EEG logging. *Temporal Accountability is very important in the MSN because all ECG/EEG anomaly detection depends on the accurate time interval analysis of different medical signal changes.* As shown in **Fig.14**, we need to detect the timing gaps for ECG PR / ST wave segments in order to make correct heart disease classifications for the following arrhythmic heart beatings**:** NSR, Paced, A-Fib, Nordal, V-Fib, etc. [52].

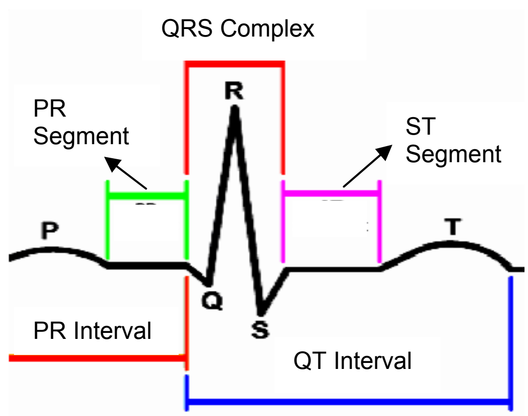


Fig. 14 *Timing detection in heart beat signals*

Example 2: Medical sensor / RFID privacy preserving: This issue aims to design an extremely low-complexity key generation / refreshing scheme to achieve *confidential* <u>medical sensor-to-RFID reader</u> and <u>RFID reader-to-tag</u> wireless communications. **Fig.15** shows that the proposed infrastructure enables such a RFID/sensor security research.

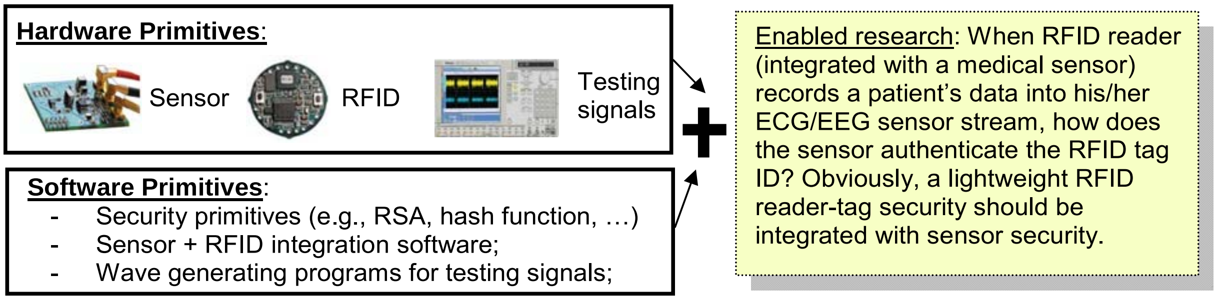
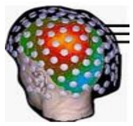


Fig. 15 The *THC* infrastructure enables research on medical privacy preserving

Table 1: Equipment (Detailed budget for major Items)

Equipment Name	Purpose	Design method	Company name	Quantity	Price / cost
 **ECG** (Electro-cardiograph) **sensor**	Also called EKG sensor; used for the collection of patients' heart beat patterns.	<u>COTS & PCB manufacturing</u>: we'll assemble an ECG PCB board through COTS chips (e.g. CPU, leads, etc.).	Most COTS components will be from www.ti.com	40	Components cost: $70 PCB fabrication fee: $80 each **Total cost: $6,000**
 **EMG** (Electro-myography) **sensor**	To detect patients' muscle movement.	<u>COTS & PCB manufacturing</u>: we'll assembly COTS chips into an EMG board	After ordering components from www.ti.com, we make PCB	40	Components cost: $50 PCB fabrication fee: $50 each **Total cost: $4,000**
 **SpO2 sensor**	To measure Blood oxygen saturation level.	Company Purchase	From www.spo2.com	30	Price:~$150 **Total cost: $4,500**
 **RFID reader**	To read RFID tags attached in medicine or other places	<u>COTS & PCB manufacturing</u>: we'll design RFID reader by assembling chip components	After ordering components from www.ti.com, we make PCB	40	Components: $50;fabrication fee: $50 each **Total cost: $4,000**
RFID Develop Kit (ALR-9900)	Verification of subject identity	Company Purchase	Alien Inc.	2 (see **Appendix 1-**	Each kit: ~$2,000 **Total: $4,000**

	(calibration tools)			**quote**)	
 **EEG** (Electro-encephalography) **sensor**	To measure brain activity signals; can detect mental health issues.	<u>VLSI & SoC fabrication</u>: we'll use VHDL to design FPGA chips for low-power EEG signal sensing	After VHDL design, send to FPGA manufacturer www.atmel.com/ (cost with educational discount)	10 (note: chip cost will be much lower when in high quantity)	(delete) Chip fabrication fee (when in low quantity): ~$600 each **Total cost: $6,000**
 **Patient simulator**	To generate abnormal ECG signals	Company Purchase	Medi Cal Instruments, Inc. www.ecgsimulators.com	20 (see **Appendix 1- quote**)	Price: $280 **Total cost: $5,600**
 **RF detector**	To detect radio signals	Company Purchase	spyZone: www.spyzone.com	4 (see **Appendix 1- quote**)	Price: $250 **Total cost: $1,000**
 **Spectrum Analyzer**	To analyze RF commu. Features / interference	Company Purchase	Agilent Technologies	2 (see **Appendix 1- quote**)	Price: $8,000 **Total cost: $16,000**
 **Wave Generator**	To generate test signals	Company Purchase + self-programming	Agilent Technologies	2 (see **Appendix 1- quote**)	Price: $7,500 **Total cost: $15,000**
 **PDA**	Personal Digital Assistant (data aggregator)	Company Purchase + self-programming	HP iPAQ programmable handheld	15 (see **Appendix 1- quote**)	Price: $450 **Total cost: $6,750**

 **Data phone**	To use cell phone to transmit medical data	Company Purchase + self-programming	T-Mobile (program-able phone)	5 (see **Appendix 1-quote**)	Price: $500 **Total cost: $2,500**
 **RF motes**	To serve as wireless relay points	Company Purchase + self-programming	Crossbow Inc. www.xbow.com	~ 90 sets (see **Appendix 1-quote**)	Price: each set ~$300 **Total cost: $27,000**
 **Wireless Base-Station**	To serve as a system wireless destination	Company Purchase	Cisco Aironet Series Access Point	5 (see **Appendix 1-quote**)	Price: ~$600 **Total cost: $3,000**
 **PCB Milling Machine**	PCB board fabrication machine with tools	Company purchase	LPKF Laser and Electronics Inc.	1 (see **Appendix 1-quote**)	Price: $28,000 **Total cost: $28,000**
Daintree Sensor Network Analyzer	Medical Sensor Net. Evaluation	Company Purchase	Daintree Inc.	1 (see **Appendix 1-quote**)	**Total Cost: ~$7,500**
			Total cost:		**$140,850**

References

[1] U.S. Bureau of the Census, on adult ages statistics, see http://www.**census**.gov/population/pop-profile/**2000**/chap18.pdf. *Accessed in May of 2009.*

[2] National Coalition on Health Care: http://www.nchc.org/facts/cost.shtml, accessed in June 2008.

[3] G.R. Schwartz, Principles and Practice of Emergency Medicine. King of Prussia, PA: Rittenhouse Book Distributors, 1999.

[4] CardioNet, see http://www.cardionet.com/. Visited in May of 2009.

[5] V. Shnayder, B. Chen, K. Lorincz, T. R. F. F. Jones, and M. Welsh, “(Codeblue) Sensor networks for medical care,” Technical Report TR-08-05, Division of Engineering and Applied Sciences, Harvard University , 2005.

[6] Ohno-Machado et al., "SMART: Scalable Medical Alert Response Technology," http://smart.csail.mit.edu/.

[7] Lenert et al., "WiiSARD :Wireless Internet Information System for Medical Response in Disasters," https://wiisard.org

[8] Votaw, J.R., "Signal-to-noise ratio in neuro activation PET studies," IEEE Transactions on Medical Imaging, Volume 15, Issue 2, April 1996 Page(s):197 – 205.

[9] Mneimneh, M.A.; Corliss, G.F.; Povinelli, R.J., "A cardiac electro-physiological model based approach for filtering high frequency ECG noise", Computers in Cardiology, Sept. 30 2007-Oct. 3 2007 Page(s):109 – 112.

[10] Windyga, P.S.; Wink, D.M., "A wearable computing based system for the prevention of medical errors committed by registered nurses in the intensive care unit," Engineering in Medicine and Biology, 2002. 24th Annual Conference and the Annual Fall Meeting of the Biomedical Engineering Society, EMBS/BMES Conference, 2002. Proceedings of the Second Joint, Volume 3, 23-26 Oct. 2002 Page(s):1940 - 1941 vol.3.

[11] Zvikhachevskaya, A.; Markarian, G.; Mihaylova, L,."Quality of Service Consideration for the Wireless Telemedicine and E-Health Services," IEEE Wireless Communications and Networking Conference, 2009. WCNC 2009. 5-8 April 2009 Page(s):1 – 6.

[12] Vergados, D.J.; Vergados, D.D.; Maglogiannis, I., "NGL03-6: Applying Wireless DiffServ for QoS Provisioning in Mobile Emergency Telemedicine," IEEE Global Telecommunications Conference, 2006. GLOBECOM '06. Nov. 27 2006-Dec. 1 2006 Page(s):1 – 5.

[13] Tomozawa, Hiromitsu; Oguchi, Kiyoshi; Shigeno, Hiroshi; Okada, Kenichi, "Message Sending Method Using Patients' Priority for Medical Sensor Network," 29th IEEE International Conference on Distributed Computing Systems Workshops, 2009. ICDCS Workshops '09. 22-26 June 2009 Page(s):194 – 200.

[14] Mihui Kim; Kijoon Chae, "Adaptive Authentication Mechanism using Node Reputation on Mobile Medical Sensor Networks," 10th International Conference on Advanced Communication Technology, 2008. ICACT 2008., Volume 1, 17-20 Feb. 2008 Page(s):499 – 503.

[15] Morchon, O.G.; Baldus, H., "Efficient distributed security for wireless medical sensor networks," International Conference on Intelligent Sensors, Sensor Networks and Information Processing, 2008. ISSNIP 2008. 15-18 Dec. 2008 Page(s):249 - 254

[16] Andersen, J.; Lo, B.; Guang-Zhong Yang; "Experimental platform for usability testing of secure medical sensor network protocols," 5th International Summer School and Symposium on Medical Devices and Biosensors, 2008. ISSS-MDBS 2008. June 2008. Page(s):179 – 182.

[17] Malasri, K.; Lan Wang, "SNAP: an architecture for secure medical sensor networks," 2nd IEEE Workshop on Wireless Mesh Networks, 2006. WiMesh 2006. 25-28 Sept. 2006 Page(s):160 – 162.

[18] Office for Civil Rights – HIPAA Medical Privacy - National Standards to Protect the Privacy of Personal Health Information, see http://www.hhs.gov/ocr/hipaa/.

[19] A. Moorse, "Confidentiality mandate is next major health care hurdle," The Business Review (Albany) - March 24, 2000, see website "Telemedicine information exchange," available from: http://www.telemed.org/legal/privacy/pubs.asp; visited on November 2006.

[20] Lin Yang; Tuzel, O.; Wenjin Chen; Meer, P.; Salaru, G.; Goodell, L.A.; Foran, D.J., "PathMiner: A Web-Based Tool for Computer-Assisted Diagnostics in Pathology," IEEE Transactions on Information Technology in Biomedicine. Page(s): 291-299, Volume: 13 Issue: 3 Date: May 2009.

[21] Niiranen, S.T.; Yli-Hietanen, J.M.; Nathanson, L.A., "Toward Reflective Management of Emergency Department Chief Complaint Information," IEEE Transactions on Information Technology in Biomedicine, Volume 12, Issue 6, Nov. 2008 Page(s):763 – 767.

[22] Hu, P.J.-H.; Zeng, D.; Hsinchun Chen; Larson, C.; Wei Chang; Chunju Tseng; Ma, J., "System for Infectious Disease Information Sharing and Analysis: Design and Evaluation," IEEE Transactions on Information Technology in Biomedicine, Volume 11, Issue 4, July 2007 Page(s):483 – 492.

[23] Ogiela, L., "Cognitive Computational Intelligence in Medical Pattern Semantic Understanding," 2008. ICNC '08. Fourth International Conference on Natural Computation, Volume 6, 18-20 Oct. 2008 Page(s):245 – 247

[24] Soda, P.; Iannello, G., "Aggregation of Classifiers for Staining Pattern Recognition in Antinuclear Autoantibodies Analysis," IEEE Transactions on Information Technology in Biomedicine. Volume: 13 Issue: 3, Page(s): 322-329, Date: May 2009.

[25] Ogiela, M.R.; Tadeusiewicz, R., "Nonlinear processing and semantic content analysis in medical imaging," IEEE International Symposium on Intelligent Signal Processing, 4-6 Sept. 2003 Page(s):243 – 247.

[26] Morchon, O.G.; Baldus, H.; "Efficient distributed security for wireless medical sensor networks," International Conference on Intelligent Sensors, Sensor Networks and Information Processing, 2008. ISSNIP 2008. 15-18 Dec. 2008 Page(s):249 – 254.

[27] Park, D.G.; Kang, S.W.; "Development of reusable and expandable communication for wearable medical sensor network," Engineering in Medicine and Biology Society, 2004. IEMBS '04. 26th Annual International Conference of the IEEE Volume 2, 1-5 Sept. 2004 Page(s):5380 – 5383.

[28] Mihui Kim; Kijoon Chae; "Adaptive Authentication Mechanism using Node Reputation on Mobile Medical Sensor Networks.," ICACT 10th International Conference on Advanced Communication Technology, 2008. Volume 1, 17-20 Feb. 2008 Page(s):499 – 503

[29] Dabiri, F.; Massey, T.; Noshadi, H.; Hagopian, H.; Lin, C.K.; Tan, R.; Schmidt, J.; Sarrafzadeh, M., "A Telehealth Architecture for Networked Embedded Systems: A Case

Study in In Vivo Health Monitoring," Page(s): 351-359, IEEE Transactions on Information Technology in Biomedicine. Volume: 13 Issue: 3 Date: May 2009.

[30] Xuekun Song; Wen Zhang; Qinglei Li; "Design of a Medical Sensor's Key Circuits Based on Evolvable Hardware," Second International Symposium on Intelligent Information Technology Application, 2008. IITA '08. Volume 2, 20-22 Dec. 2008 Page(s):229 – 233.

[31] Popplewell, P.H.R.; Karam, V.; Shamim, A.; Rogers, J.; Plett, C.; "An Injection-Locked 5.2 GHz SoC Transceiver with On-Chip Antenna for Self-Powered RFID and Medical Sensor Applications," 2007 IEEE Symposium on VLSI Circuits, 14-16 June 2007 Page(s):88 – 89.

[32] De Toledo, P.; Lalinde, W.; del Pozo, F.; Thurber, D.; Jimenez-Fernandez, S., "Interoperability of a Mobile Health Care Solution with Electronic Healthcare Record Systems," Engineering in Medicine and Biology Society, 2006. EMBS '06. 28th Annual International Conference of the IEEE, Aug. 30 2006-Sept. 3 2006 Page(s):5214 – 5217.

[33] Yu, P.; Yu, H., "Lessons learned from the practice of mobile health application development," Proceedings of the 28th Annual International Computer Software and Applications Conference, 2004. COMPSAC 2004. Volume 2, 2004 Page(s):58 - 59 vol.2.

[34] Krco, S.; Kostic, S.; Sakac, D.; Lukic, Z.; "mSens Mobile Health Monitoring System," The International Conference on Computer as a Tool, 2005. EUROCON 2005. Volume 1, 21-24 Nov. 2005 Page(s):80 – 83.

[35] NSF CRI Project # 0709285, "CRI: IAD Infrastructure for Environmental Monitoring and Modeling using Large-Scale Sensor Networks," PI: Yan Huang, University of North Texas, Aug 2007.

[36] NSF CRI Project # 0709268, "CRI: A Heterogeneous Sensor Network Laboratory for Integrated Research and Education, " Xiaojiang Du, North Dakota State University Fargo, Sep 2007.

[37] NSF CRI project # 0830127, "CRI: Secure Wireless Ad-hoc Networking and Sensor Networking," PI: Sirisha Medidi, Boise State University, March 2008.

[38] NSF CRI Project # 0751101, CRI: Planning - A Testbed for Compiler-supported Scalable Error Monitoring and Diagnosis for Reliable and Secure Sensor Networks," PI: Zhiyuan Li, Purdue University, March 2008.

[39] NSF CRI project #0709249, "CRI: A Research Infrastructure for Investigation of Performance, Configuration, and Security Issues of Wireless Sensor and Ad Hoc Networks," PI: Feniosky Pena-Mora, University of Illinois at Urbana-Champaign, Sep 2007.

[40] NSF CRI project # 0751165, "Collaborative Research: CRI/IAD: Programmable and At-Scale Infrastructure for Wireless Access, Mobile Computing, and Health Sensing, " PI: Edward Knightly, William Marsh Rice University, May 2008.

[41] HP Agilent 8753A RF Network Analyzer 300 Khz to 3 Ghz:
http://www.valuetronics.com/Details.aspx?ProdID=1987&Model=Agilent%20HP_8753A . 2008.

[42] Tektronix Inc RSA3408A spectrum analyzer: http://www2.tek.com/cmsreplive/psrep/13392/37W_18380_4_2008.05.21.14.31.05_13392_EN.pdf. 2008.

[43] Tektronix Inc AWG7052 arbitrary signal/wave generator: http://www2.tek.com/cmsreplive/psrep/13568/76W_19779_3_2008.07.10.17.56.11_13568_EN.pdf , 2008.

[44] Crossbow Inc. motes (programmable tiny wireless sensors): http://www.xbow.com.

[45] Perrig, A., Szewczyk, R., Wen, V., Culler, D., and Tygar, J. D. 2001. SPINS: security protocols for sensor networks. In *Proceedings of the 7th Annual international Conference on Mobile Computing and Networking* (Rome, Italy). MobiCom '01. ACM, New York, NY, 189-199.

[46] *Boneh, Dan (1999). "*Twenty Years of attacks on the RSA Cryptosystem*". Notices of the American Mathematical Society (AMS)* ***46*** *(2): 203–213*. http://crypto.stanford.edu/~dabo/abstracts/RSAattack-survey.html*.*

[47] NTRU cipher: lots of details are in http://www.ntru.com.

[48] LFSR (Linear Feedback Shift Registers), see: http://homepage.mac.com/afj/lfsr.html.

[49] A. Klein, Attacks on the RC4 stream cipher, Designs, Codes and Cryptography (2008) 48:269-286

[50] DES cipher: http://www.tropsoft.com/strongenc/des.htm.

[51] Miyaguchi, S. 1991. The FEAL Cipher Family. In *Proceedings of the 10th Annual international Cryptology Conference on Advances in Cryptology* (August 11 - 15, 1990). A. Menezes and S. A. Vanstone, Eds. Lecture Notes In Computer Science, vol. 537. Springer-Verlag, London, 627-638.

[52] ECG types: http://www.ecglibrary.com/ecghome.html.

[53] Fei Hu, Meng Jiang, Mark Wagner and Decun Dong "Privacy-Preserving Tele-cardiology Sensor Networks: Towards A Low-cost, Portable Wireless Hardware / Software Co-design ", *IEEE Transactions on Information Technology in Biomedicine*, VOL. 11, NO. 6, NOVEMBER 2007, Pages 617-627.

[54] Fei Hu, Yu Wang, Hongyi Wu, *Mobile Telemedicine Sensor Networks with Low-energy Data Query and Network Lifetime Considerations*, IEEE Transactions on Mobile Computing, Vol 5(4), pp. 404-417, April 2006.

[55] Fei Hu and Yang Xiao, "Low-Power Circuit Design for *Cardiac* Data Mining in Medical Sensor Networks," Book chapter in "Handbook on Sensor networks," 2008.

[56] Fei Hu, Sumil Kumar, "*Multimedia Query with QoS Considerations for Wireless Sensor Networks in Telemedicine"*, Proceedings of International Conference on Internet Multimedia Management Systems (SPIE ITCom'03). September 2003, Orlando, Florida USA.

[57] Fei Hu, Michael Schab, and Xiaojun Cao, “Hardware-Based Confidential Data Transmission In *Telemedicine Sensor Networks,”* book chapter, “Security in Ad hoc and sensor Networks”, 2008.

[58] Fei Hu, Yang Xiao, and Qi Hao, "Congestion-aware, loss-resilient bio-monitoring sensor networking for mobile health applications," IEEE Journal on Selected Areas in Communications, to appear.

[59] Fei Hu, Shruti Lakdawala, Qi Hao, etc. "Low-power, low-cost sensor hardware interface for wireless telecardiology data pre-processing," IEEE Transactions on Information Technology in Biomedicine, to appear.

[60] Fei Hu, Meng Jiang, Yang Xiao, "Low-cost Wireless Sensor Networks for Remote Cardiac Patients Monitoring Applications ", *Wireless Communications and Mobile Computing (Wiley InterScience Journal)*, (to appear), March 2007.

[61] Fang, Jiang-Shuen and Hao, Qi, "A pyroelectric infrared biometric system for real-time walker recognition by use of a maximum likelihood principal components estimation (MLPCE) method," Optics Express, vol. 15, no. 6, pp. 3271-3284, Mar. 2007.

[62] Hao, Qi, "Multiple human tracking and identification with wireless distributed pyroelectric sensors," PhD Thesis, Duke University, May, 2006.

[63] Jing Liu, Yang Xiao, and Qi Hao, etc. "Bio-inspired visual attention in agile sensing for target detection," International Journal of Sensor Networks vol. 5, no. 2, pp. 98-111, 2009.

[64] Wang, Y., Liu, K., Hao, Qi and etc., "Multicamera phase measuring profilometry for accurate depth measurement," Proc. of SPIE Sensors and Systems for Space Applications, May 2007, pp. 655509(1-12).

[65] Li, N. and Hao, Qi, "Multiple human tracking with wireless distributed pyroelectric sensors," Proc. of SPIE Defense and Security, March 2008, pp. 694033(1-12).

[66] Li, N. and Hao, Qi, "Multiple walker recognition with wireless distributed pyroelectric sensors," Proc. of SPIE Defense and Security, March 2008, pp. 694034(1-12).

[67] Ember Inc., see http://www.ember.com.

[68] Zigbee wireless communication standard: see http://www.zigbee.org.

[69] VHDL tutorial, see http://www.seas.upenn.edu/~ese201/vhdl/vhdl_primer.html.

[70] Mobile 6 SDK download, see: http://www.microsoft.com/downloads/details.aspx?FamilyID=06111A3A-A651-4745-88EF-3D48091A390B&displaylang=en.

[71] Zigbee standard: http://www.zigbee.org.

[72] Fei Hu, Ankur Teredesai, "Establishing Strong Pervasive Computing Curriculum for Both Engineering and Science Students," *IEEE Pervasive Computing*, Vol. 6, No.1, Pages 88-91, Jan-March 2007.

[73] Xiaojun (Matt) Cao, see http://www.cs.gsu.edu/cao/.