An Advanced Wireless Sensor Network for Health Monitoring

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***Abstract*—In this paper we propose a system architecture for smart healthcare based on an advanced Wireless Sensor Network (WSN). It specifically targets assisted-living residents and others who may benefit from continuous, remote health monitoring. We present the advantages, objectives, and status of the design. An experimental living space has been constructed at the Department of Computer Science at UVA for evaluation. Early results suggest a strong potential for WSNs to open new research perspectives for low-cost, ad hoc deployment of multimodal sensors for an improved quality of medical care.**

I. INTRODUCTION

As the world's population ages, those suffering from diseases of the elderly will increase. In-home and nursing-home pervasive networks may assist residents and their caregivers by providing continuous medical monitoring, memory enhancement, control of home appliances, medical data access, and emergency communication.

Researchers in computer, networking, and medical fields are working to make the broad vision of smart healthcare possible [1-8]. For example, some of them are devoted to continuous medical monitoring for degenerative diseases like Alzheimer's, Parkinson's or similar cognitive disorders [6]. Other projects such as "CodeBlue" at Harvard extend WSNs for medical applications in disasters [7]. Some focus on high-bandwidth, sensor-rich environments [2].

This paper presents an emerging system design oriented around remote, continuous medical monitoring using wireless sensor networks. Its advantages for in-home monitoring are described in the next section. Parts II and III deal with our long-term objectives and final architecture, whereas parts IV and V describe our current implementation and preliminary results. Section VI discusses a variety of ongoing research topics.

II. OUR MAIN GOALS

We are developing a network architecture for smart healthcare that will open up new opportunities for continuous monitoring of assisted and independent-living residents [9, 10]. While preserving resident comfort and privacy, the network manages a continuous medical history. Unobtrusive area and environmental sensors combine with wearable interactive devices to evaluate the health of spaces and the people who inhabit them. Authorized care providers may monitor residents' health and life habits and watch for chronic pathologies. Multiple patients and their resident family members as well as visitors are differentiated for sensing tasks and access privileges.

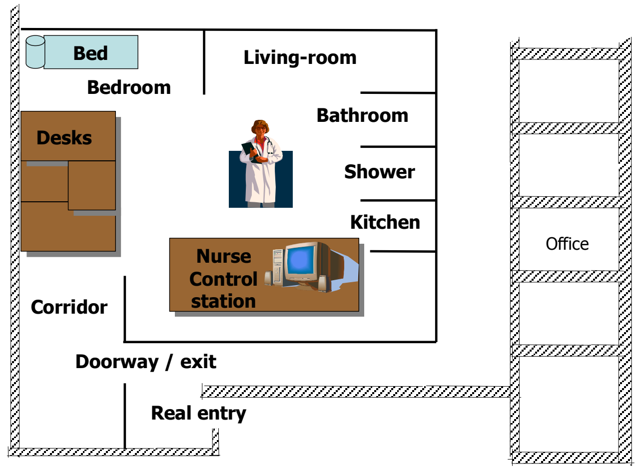

Figure 1: Layout of the experimental smart health home at UVA.

High costs of installation and retrofit are avoided by using ad hoc, self-managing networks. Based on the fundamental elements of future medical applications (integration with existing medical practice and technology, real-time and long-term monitoring, wearable sensors and assistance to chronic patients, elders or handicapped people), our wireless system will extend healthcare from the traditional clinical hospital setting to nursing and retirement homes, enabling telecare without the prohibitive costs of retrofitting existing structures. Figure 1 shows the layout of the experimental laboratory.

The architecture is multi-tiered, with heterogeneous devices ranging from lightweight sensors, to mobile components, and more powerful stationary devices. Figure 2 shows a MicaZ device from Crossbow with an environmental sensor board mounted on it.

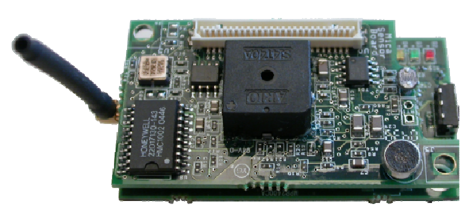

Figure 2: MicaZ with MTS310 sensor board.

The advantages of a WSN are numerous for smart healthcare, as it provides the following important properties:

1. **Portability and unobtrusiveness**. Small devices collect data and communicate wirelessly, operating with minimal patient input. They may be carried on the body or deeply embedded in the environment. Unobtrusiveness helps with patient acceptance and minimizes confounding measurement effects. Since monitoring is done in the living space, the patient travels less often, which is safer and more convenient.
2. **Ease of deployment and scalability**. Devices can be deployed in potentially large quantities with dramatically less complexity and cost compared to wired networks. Existing structures, particularly dilapidated ones, can be easily augmented with a WSN network whereas wired installations would be expensive and impractical. Devices are placed in the living space and turned on, self-organizing and calibrating automatically.
3. **Real-time and always-on**. Physiological and environmental data can be monitored continuously, allowing real-time response by emergency or healthcare workers. The data collected form a health journal, and are valuable for filling in gaps in the traditional patient history. Even though the network as a whole is always-on, individual sensors still must conserve energy through smart power management and on-demand activation.
4. **Reconfiguration and self-organization**. Since there is no fixed installation, adding and removing sensors instantly reconfigures the network. Doctors may re-target the mission of the network as medical needs change. Sensors self-organize to form routing paths, collaborate on data processing, and establish hierarchies.

III. HIGH LEVEL SYSTEM ARCHITECTURE

A. System overview

The medical sensor network system integrates heterogeneous devices, some wearable on the patient and some placed inside the living space. Together they inform the healthcare provider about the health status of the resident. Data is collected, aggregated, pre-processed, stored, and acted upon using a variety of sensors and devices in the architecture (pressure sensor, RFID tags, floor sensor, environmental sensor, dust sensor, etc.). Multiple body networks may be present in a single system. Traditional healthcare provider networks may connect to the system by a gateway, or directly to its database. Some elements of the network are mobile, while others are stationary. Some can use line power, but others depend on batteries. If any fixed computing or communications infrastructure is present it can be used, but the system can be deployed into existing structures without retrofitting.

The components of the architecture are shown in Figure 3, dividing devices into strata based on their roles and physical interconnect. Each tier of the architecture is described below.

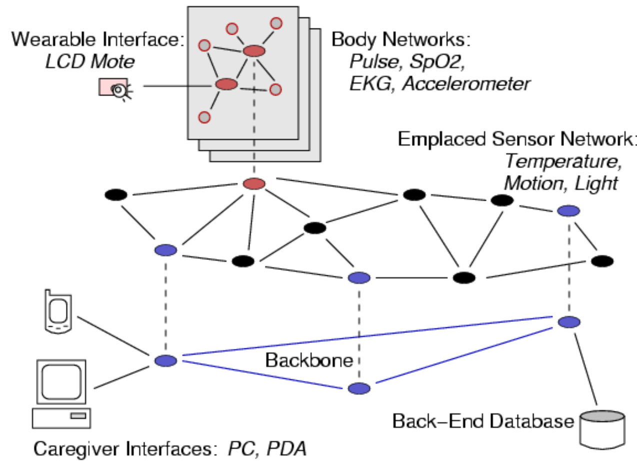

Figure 3: Multi-tiered system architecture, showing physical connectivity.

1. **Body Network and Subsystems**. This network comprises tiny portable devices equipped with a variety of sensors (such as heart-rate, heart-rhythm, temperature, oximeter, accelerometer), and performs biophysical monitoring, patient identification, location detection, and other desired tasks. These devices are small enough to be worn comfortably for a long time. Their energy consumption should also be optimized so that the battery is not required to be changed regularly. They may use “kinetic” recharging. Actuators notify the wearer of important messages from an external entity. For example, an actuator can remind an early Alzheimer patient to check the oven because sensors detect an abnormally high temperature. Or, a tone may indicate that it is time to take medication. The sensors and actuators in the body network are able to communicate among themselves. A node in the body network is designated as the gateway to the emplaced sensor network. Due to size and energy constraints, nodes in this network have little processing and storage capabilities. More details about the particular body networks we have developed are available [10].
2. **Emplaced Sensor Network**. This network includes sensor devices deployed in the environment (rooms, hallways, furniture) to support sensing and monitoring, including: temperature, humidity, motion, acoustic, camera, etc. It also provides a spatial context for data association and analysis. All devices are connected to a more resourceful backbone. Sensors communicate wirelessly using multi-hop routing and may use either wired or battery power. Nodes in this network may vary in their capabilities, but generally do not perform extensive calculation or store much data. The sensor network interfaces to multiple body networks, seamlessly managing handoff of reported data and maintaining patient presence information.
3. **Backbone**. A backbone network connects traditional systems, such as PDAs, PCs, and databases, to the emplaced sensor network. It also connects discontiguous

sensor nodes by a high-speed relay for efficient routing. The backbone may communicate wirelessly or may overlay onto an existing wired infrastructure. Nodes possess significant storage and computation capability, for query processing and location services. Yet, their number is minimized to reduce cost.

4. **Back-end Databases**. One or more nodes connected to the backbone are dedicated databases for long-term archiving and data mining. If unavailable, nodes on the backbone may serve as in-network databases.
5. **Human Interfaces**. Patients and caregivers interface with the network using PDAs, PCs, or wearable devices. These are used for data management, querying, object location, memory aids, and configuration, depending on who is accessing the system and for what purpose. Limited interactions are supported with the on-body sensors and control aids. These may provide memory aids, alerts, and an emergency communication channel. PDAs and PCs provide richer interfaces to real-time and historical data. Caregivers use these to specify medical sensing tasks and to view important data.

IV. Current Status

Here we describe the current implementation of the medical WSN system, a summary of which is shown in Table I.

TABLE I
SYSTEM REQUIREMENTS

Requirements	Operational Yes/No
Query management	Yes
Power management	No
Authentication	Yes
Data privacy	No
Multiple patients	No
Real-time (delays < 0.3sec)	Yes

A. Data acquisition

1. **Motion sensor**. We have adapted a low-cost sensor module that is capable of detecting motion and ambient light levels. The module also has a simple one-button and LED user interface for testing and diagnostics. It is interfaced to a MicaZ wireless sensor node that processes the sensor data and forwards the information through the wireless network. A set of such modules is used to track human presence in every room of the simulated smart health home.
2. **Body network**. We have implemented a wearable WSN service with MicaZ motes embedded in a jacket, which can record human activities and location using a 2-axis accelerometer and GPS. The recorded activity data is subsequently uploaded through an access point for archiving, from which past human activities and locations can be reconstructed.
3. **Indoor temperature and luminosity sensor**. These sensors give the environmental conditions of the habitat and are also connected to the backbone via MicaZ.
4. **Bed sensor**. The bed sensor, developed by the Medical Automation Research Center (MARC), is based on an air bladder strip located on the bed, which measures the breathing rate, heart rate and agitation of a patient.
5. **Pulse-oximeter and EKG**. These sensors were developed by Harvard University [7]. They are wearable, connecting to MicaZ and Telos devices, and collect patient vital signs. Heart rate (HR), heartbeat events, oxygen saturation (SpO2), and electrocardiogram (EKG) are available.

B. Current backbone infrastructure

The current backbone is a single Stargate serving as a gateway between the motes deployed in the home environment and the nurse control station. Motes use a Zigbee-compliant (802.15.4) wireless protocol for communication. The Stargate runs Embedded Linux and possesses more power and capabilities than the motes.

C. Database management and data mining

A MySQL database serves as a backend data store for the entire system. It is located in a PC connected to the backbone, and stores all the information coming from the infrastructure for longitudinal studies and offline analysis.

D. Graphical user interfaces

Interfaces with residents, healthcare providers, and technicians have different requirements. Each must present an appropriate interface for performing the intended tasks, while conforming to the constraints imposed by form factor and usability. Currently, the system offers four different GUIs. The first is located on the local nurse control station, and it tracks the motion of the resident using motion activations.

A second GUI (see Figure 4), which can run on a PDA, permits a caregiver to request real-time environmental conditions of the living space and the vital signs of the resident. It uses a query management system distributed among the PDA, Stargate and the sensor devices. The interface graphically presents requested data for clear consumption by the user.

Figure 4: A GUI displays accelerometer data, patient pulse-rate, and environmental temperature.

An LCD interface board was also de-signed for the MicaZ for wearable applications. It presents sensor readings, reminders and queries, and can accept rudimentary input from the wearer.

A final GUI, from a direct medical application based on motion sensors, exists to study the behavioral profile of the user's sleep/wake patterns and life habits, and to detect some pathologies in the early stages.

V. FIRST RESULTS

The system is single hop, as the radio range covers all of the facility. A multi-hop protocol will be necessary for access of multiple floors, or if transmission power is reduced. Data communication is bi-directional between the motes and the Stargate. Time-stamping is done by the PC when motion events are received. Figure 5 shows the current acquisition chain.

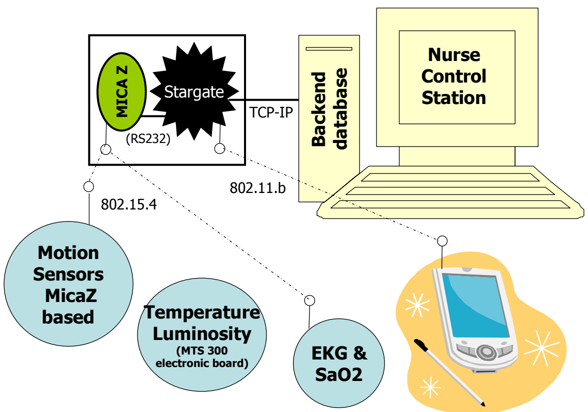

Figure 5: Current configuration of the medical testbed.

A first experiment based on seven MicaZ motes, programmed to send motion events over the network containing the location of the user, was performed with no activity in the lab for one week. We observed no false detections in the system under these conditions. However, this experiment showed the necessity of enhancing the power management scheme to prolong the lifetime of the sensors. In another experiment, the supervision program located at the control station correctly displays the location of a mobile resident by polling the MySQL database for motion events.

VI. ONGOING RESEARCH TOPICS

1. **Multi-modal data association and multiple residents**. Data association is a way to know "who is doing what?" in a system without biometric identification and with multiple actors present, such as an assisted-living community. It permits us to recognize the right person among others when he is responsible for a triggered event. This is indispensable for avoiding medical errors in the future and properly attributing diagnostics. Consequently, dedicated sensors and data association algorithms must be developed to increase quality of data.
2. **Data integrity**. When the data association mechanisms are not sufficient, or integrity is considered critically important, some functionalities of the system can be disabled. This preserves only the data which can claim a high degree of confidence. In an environment where false alarms cannot be tolerated, there is a tradeoff between accuracy and availability.
3. **Security and privacy**. The system is monitoring and collecting patient data that is subject to privacy policies. For example, the patient may decide not to reveal the monitored data of certain sensors until it is vital to determine a diagnosis and therefore authorized by the patient at the time of a visit to a doctor. Security and privacy mechanisms must be throughout the system.

VII. CONCLUSION

The baseline of the system is implemented. A one week experiment showed a robust system with some straightforward communications from front to backend of the system. The modularity of this system should enable progressive development of the research areas described in Part VI. We believe this system design will greatly enhance quality of life, health, and security for those in assisted-living communities.

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