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Wireless Sensor Network for Healthcare Application

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Abstract: **In healthcare, there is a strong need to collect physiological data and sensor networking; this paper reviews recent studies and points to the needfor future research.Driven by the confluence between the need tocollect data about people's physical, physiological, psychological, cognitive, and behavioral processes in spaces ranging from personal to urban and the recent availability of the technologies that enable this data collection, wireless sensor networks for healthcare have emerged in the recent years. In this review, we present some representative applications in the healthcare domain and describe the challenges they introduce to wireless sensor networks due to the required level of trustworthiness and the need to ensure the privacy and security of medical data. These challenges are exacerbated by the resource scarcity that is inherent with wireless sensor network platforms. We outline prototype systems spanning application domains from physiological and activity monitoring to large-scale physiological and behavioral studies and emphasize ongoing research challenges**

***Keywords*—Healthcare monitoring; medical informationsystems; wireless sensor networks**

I. INTRODUCTION

Driven by technology advances in low-power networked systems and medical sensors, we have witnessed in recent years the emergence of wireless sensor networks (WSNs) in healthcare. These WSNs carry the promise of drastically improving and expanding the quality of care across a wide variety of settings and for different segments of the population. For example, early system prototypes have demonstrated the potential of WSNs to enable early detection of clinical deterioration through real-time patient monitoring in hospitals [13], enhance first responders' capability to provide emergency care in large disasters through automatic electronic triage [6] improve the life quality of the elderly through smart environments [9], and enable large-scale field studies of human behavior and chronic diseases [9], [13].

At the same time, meeting the potential of WSNs in healthcare requires addressing a multitude of technical challenges. These challenges reach above and beyond the resource limitations that all WSNs face in terms of limited network capacity, processing and memory constraints, as well as scarce energy reserves. Specifically, unlike applications in other domains, healthcare applications impose stringent requirements on system reliability, quality of service, and particularly privacy and security. In this review paper, we expand on these challenges and provide examples of initial attempts to confront them.

These examples include: 1) network systems for vital sign monitoring that show that it is possible to achieve highly reliable data delivery over multihop wireless networks deployed in clinical environments [13], 2) systems that overcome energy and bandwidth limitations by intelligent preprocessing of measurements collected by high data rate medical applications such as motion analysis for Parkinson's disease [19]; 3) an analysis of privacy and security challenges and potential solutionsin assisted living environments [12]; and 4) technologies for dealing with the large-scale and inherent data quality challenges associated with in-field studies [5], [8].

The remainder of the paper is structured as follows. The next section reviews background material in medical sensing and wireless sensor networks, while Section III describes several promising healthcare applications for wireless sensor networks. We highlight the key technical challenges that wireless sensor networks face in the healthcare domains in Section IV and describe representative research projects that address different aspects of these challenges in Section V. We conclude with an outline of the remaining challenges and future directions for wireless sensor networks in healthcare.

II. BACKGROUND

A. Medical Sensing

There is a long history of using sensors in medicine and public health [2], [4]. Embedded in a variety of medical instruments for use at hospitals, clinics, and homes, sensors provide patients and their healthcare provider's insight into physiological and physical health states that are critical to the detection, diagnosis, treatment, and management of ailments. Much of modern medicine would simply not be possible nor be cost effective without sensors such as thermometers, blood pressure monitors, glucose monitors, electrocardiography (EKG), photoplethysmogram (PPG), electroencephalography (EEG), and various forms of imaging sensors. The ability to measure physiological state is also essential for interventional devices such as pacemakers and insulin pumps.

Medical sensors combine transducers for detecting electrical, thermal, optical, chemical, genetic, and other signals with physiological origin with signal processing algorithms to estimate features indicative of a person's health status. Sensors beyond those that directly measure health state have also found use in the practice of medicine. For example, location and proximity sensing technologies [11] are being used for improving the delivery of patient care and workflow efficiency in hospitals [4], tracking the spread of diseases by public health agencies [8], and monitoring people's health-related behaviors (e.g., activity levels) and exposure to negative environmental factors, such as pollution [8].

There are three distinct dimensions along which advances in medical sensing technologies are taking place. We elaborate on each of the three in the paragraphs that follow.

1. Sensing modality: Advances in technologies such as microelectromechanical systems (MEMS), imaging, and microfluidic and Nano fluidic lab-on-chip are leading to new forms of chemical, biological, and genomic sensing and analyses available outside the confines of a laboratory at the point of care. By enabling new inexpensive diagnostic capabilities, these sensing technologies promise to revolutionize healthcare both in terms of resolving public health crisis due to infectious diseases and also enabling early detection and personalized treatments.

2. Size and cost: Most medical sensors have traditionally been too costly and complex to be used outside of clinical environments. However, recent advances in microelectronics and computing have made many forms of medical sensing more widely accessible to individuals at their homes, work places, and other living spaces.

3. The first to emerge [2] were portable medical sensors for home use (e.g., blood pressure and blood glucose monitors). By enabling frequent measurements of critical physiological data without requiring visits to the doctor, these instruments revolutionized the management of diseases such as hypertension and diabetes.

4. Next, ambulatory medical sensors, whose small form factor allowed them to be worn or carried by a person, emerged [2]. Such sensors enable individuals to continuously measure physiological parameters while engaged routine life activities. Examples include wearable heart rate and physical activity monitors and Holter monitors. These devices target fitness enthusiasts, health conscious individuals, and observe cardiac or neural events that may not manifest during a short visit to the doctor.

5. More recently, embedded medical sensors built into assistive and prosthetic devices for geriatrics and orthotics [18] have emerged.

6. Finally, we are seeing the emergence of implantable medical sensors for continuously measuring internal health status and physiological signals. In some cases, the purpose is to continuously monitor health parameters that are not externally available, such as intraocular pressure in glaucoma patients [20]. The goal in other cases is to use the measurements as triggers for physiological interventions that prevent impending adverse events (e.g., epi-leptic seizures [8]) and for physical assistance (e.g., brain-controlled motor prosthetics [7]). Given their implantable nature, these devices face severe size constraints and need to communicate and receive power wirelessly.

7. Connectivity: Driven by advances in information technology, medical sensors have become increasingly interconnected with other devices. Early medical sensors were largely isolated with integrated user interfaces for displaying their measure-ments. Subsequently, sensors became capable of interfacing to external devices via wired interfaces such as RS 232, USB, and Ethernet. More recently, medical sensors have incorporated wireless connections, both short range, such as Bluetooth, Zigbee, and near-field radios to communicate wirelessly to nearby computers, personal digital assistants, or smartphones, and long range, such as WiFi or cellular communications, to communicate directly with cloud computing services. Besides the convenience of tetherless operation, such wireless connections permit sensor measurements to be sent to caregivers while patients go through their daily work life away from home, thus heralding an age of ubiquitous real-time medical sensing. We note that with portable and ambulatory sensors, the wired or wireless connectivity to cloud computing resources is intermittent (e.g., connectivity may be available only when the sensor is in cellular coverage area or docked to the user's home computer). Therefore, such sensors can also record measurements in nonvolatile memory for uploading at a later time when they can be shared with healthcare personnel and further analyzed.

B. Wireless Sensor Platforms

Recent years have witnessed the emergence of various embedded computing platforms that integrate processing, storage, wireless networking, and sensors. These embedded computing platforms offer the ability to sense physical phenomena at temporal and spatial fidelities that were previously impractical. Embedded computing platforms used for healthcare applications range from smartphones to specialized wireless sensing platforms, known as motes, which have much more stringent resource constraints in terms of available computing power, memory, network bandwidth, and available energy.

Existing motes typically use 8- or 16-b microcontrollers with tens of kilobytes of RAM, hundreds of kilobytes of ROM for program storage, and external storage in the form of Flash memory. These devices operate at a few milliwatts while running at about 10 MHz [1]. Most of the circuits can be powered off, so the standby power can be about 1 W. If such a device is active for 1% of the time, its average power consumption is just a few microwatts enabling long-term operation with two AA batteries. Motes are usually equipped with low-power radios such as those compliant with the IEEE 802.15.4 standard for wireless sensor networks [3]. Such radios usually transmit at rates between 10 and 250 Kb/s, consume about 20–60 mW, and their communication range is typically measured in tens of meters [6]. Finally, motes include multiple analog and digital interfaces that enable them to connect to a wide variety of commodity sensors.

1. These hardware innovations are paralleled by advances in embedded operating systems [11], component-based programming languages [15], and networking protocols [9], [16].
2. In contrast to resource-constrained motes, smartphones provide more powerful microprocessors, larger data storage, and higher network bandwidth through cellular andIEEE 802.11 wireless interfaces at the expense of higher energy consumption. Their complementary characteristics make smartphones and motes complementary platforms suitable for different categories of healthcare applications, which we discuss in the section that follows.

III. HEALTHCARE APPLICATIONS

Wirelessly networked sensors enable dense spatiotemporal sampling of physical, physiological, psychological, cognitive, and behavioral processes in spaces ranging from personal to buildings to even larger scale ones. Such dense sampling across spaces of different scales is resulting in sensory information based healthcare applications which, unlike those described in Section II-A, fuse and aggregate information collected from multiple distributed sensors. Moreover, the sophistication of sensing has increased tremendously with the advances in cheap and miniature, but high-quality sensors for home and personal use, the development of sophisticated machine learning algorithms that enable complex conditions such as stress, depression, and addiction to be inferred from sensory information, and finally the emergence of pervasive Internet connectivity facilitating timely dissemination of sensor information to caregivers.

In what follows, we introduce a list of healthcare applications enabled by these technologies.

a) Monitoring in mass-casualty disasters: While triage protocols for emergency medical services already exist [11], their effectiveness can quickly degrade with increasing number of victims. More-over, there is a need to improve the assessment of the first responders' health status during such mass-casualty disasters. The increased portability, scalability, and rapidly deployable nature of wireless sensing systems can be used to automatically report the triage levels of numerous victims and continuously track the health status of first responders at the disaster scene more effectively.

b) Vital sign monitoring in hospitals: Wireless sensing technology helps address various drawbacks associated with wired sensors that are commonly used in hospitals and emergency rooms to monitor patients [13]. The all too familiar jumble of wires attached to a patient is not only uncomfortable for patients leading to restricted mobility and more anxiety, but is also hard to manage for the staff. Quite common are deliberate disconnections of sensors by tired patients and failures to reattach sensors properly as patients are moved around in a hospital and handed off across different units. Wireless sensing hardware that are less noticeable and have persistent network connectivity to back-end medical record systems help reduce the tangles of wires and patient anxiety, while also reducing the occurrence of errors.

c) At-home and mobile aging: As people age, they experience a variety of cognitive, physical, and social changes that challenge their health, independence, and quality of life. Diseases such as diabetes, asthma, chronic obstructive pulmonary disease, congestive heart failure, and memory decline are challenging to monitor and treat. These diseases can benefit from patients taking an active role in the monitoring process. Wirelessly net-worked sensors embedded in people's living spaces or carried on the person can collect information about personal physical, physiological, and behavioral states and patterns in real-time and every-where. Such data can also be correlated with social and environmental context. From such Believingrecords, useful inferences about health and well-being can be drawn. This can be used for self-awareness and individual analysis to assist in making behavior changes, and to share with caregivers for early detection and intervention.

At the same time such procedures are effective and economic ways of monitoring age-related illnesses.

As the examplesabove show, the applications enabled by wireless networked sensing technologies are distributed across multiple dimensions. One dimension is the spatial and temporal scope of distributed sensing. The spatial scope can range from sensory observations of health status made when an individual is confined to a building (e.g., home, hospital) or a well-defined region (e.g., disaster site) to observations made as an individual moves around during the course of daily life. The temporal scope can range from observations made for the duration of an illness or an event to long-term observations made for managing a long-term disease or for public health purposes. Different spatial and temporal scopes place different constraints on the availability of energy and communications infrastructure, and different requirements on ergonomics.

A second dimension is that of the group size, which can range from an individual patient at home, to groups of patients at a hospital and victims at disaster sites, and all the way to large dispersed population of subjects in a medical study or an epidemic.

IV. TECHNICAL CHALLENGES

In the paragraphs that follow, we describe some of the core challenges in designing wireless sensor networks forhealthcare applications. While not exhaustive, the challenges in this list span a wide range of topics, from core computer systems themes such as scalability, reliability, and efficiency, to large-scale data mining and data association problems, and even legal issues.

A. *Trustworthiness*

Healthcare applications impose strict requirements on end-to-end system reliability and data delivery. For example, pulse oximetryapplications, which measure the levels of oxygen in a person's blood, must deliver at least one measurement every 30 s [17]. Furthermore, end users require measurements that are accurate enough to be used in medical research. Using the same pulse oximetry example, measurements must deviate at most 4% from the actual oxygen concentrations in the blood [17]. Finally, applications that combine measurements with actuation, such as control of infusion pumps and patient controlled analgesia (PCA) devices, impose constraints on the end-to-end delivery latency. We term the combination of data delivery and quality properties the trustworthiness of the system and claim that medical sensing applications require high levels of trustworthiness.

B. *Privacy and Security*

Wireless sensor networks in healthcare are used to determine the activities of daily living (ADL) and provide data for longitudinal studies. It is then easy to see that such WSNs also pose opportunities to violate privacy. Further-more, the importance of securing such systems will continue to rise as their adoption rate increases.

The first privacy challenge encountered is the vague specification of privacy. The Health Insurance Portability and Accountability Act (HIPPA) by the U.S. Government is one attempt to define this term [1]. One issue is that HIPPA as well as other laws define privacy using human language (e.g., English), thus, creating a semantic night-mare. Nevertheless, privacy specification languages have been developed to specify privacy policies for a system in a formal way. Once the privacy specifications are specified, healthcare systems must enforce this privacy and also be able to express users' requests for data access and the system's policies.These requests should be evaluated against the predefined policies in order to decide if they should be granted or denied. This framework gives rise to many new research challenges.

C. *Resource Scarcity*

In order to enable small device sizes with reasonable battery lifetimes, typical wireless sensor nodes make use of low-power components with modest resources. Fig. 1 shows a typical wearable sensor node for medical applications, the SHIMMER platform [14]. The SHIMMER comprises an embedded microcontroller (TI MSP430; 8-MHz clock speed; 10-KB RAM; 48-KB ROM) and a low-power radio (Chipcon CC2420; IEEE 802.15.4; 2.4 GHz; 250-Kb/s PHY data rate). The total device power budget is approximately 60 mW when active, with a sleep power drain of a few microwatts. This design permits small, rechargeable batteries to maintain device lifetimes of hours or days, depending on the application's duty cycles.

The extremely limited computation, communication, and energy resources of wireless sensor nodes lead to a number of challenges for system design. Software must be designed carefully with these resource constraints in mind. The scant memory necessitates the use of lean, event-driven concurrency models, and precludes conventional OS designs. Computational horsepower and radio band-width are both limited, requiring that sensor nodes trade off computation and communication overheads, for example, by performing a modest amount of on-board processing to reduce data transmission requirements. Finally, application code must be

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extremely careful with the node's limited energy budget, limiting radio communication and data processing to extend the battery lifetime. While smartphone-based systems typically enjoy more processing power and wireless bandwidth, the fact thatthey are less flexible compared to customizable mote platforms limits their capability to aggressively conserve energy. This leads to shorter recharge cycles and can limit the types of applications that smartphones can support.

Fig. 1. The SHIMMER wearable sensor platform. SHIMMERincorporates a TI MSP430 processor, a CC2420 IEEE 802.15.4 radio, a triaxial accelerometer, and a rechargeable Li-polymer battery. The platform also includes a Micro SD slot

supporting up to 2 GB of Flash memory

V. SYSTEMS

Next, we present several wireless sensing system proto-types developed and deployed to evaluate the efficacy of WSNs in some of the healthcare applications described in Section III. While wireless healthcare systems using various wireless technologies exist, this work focuses on systems based on low-power wireless platforms for physiological and motion monitoring studies, and smartphone-based large-scale studies.

A. *Physiological Monitoring*

In physiological monitoring applications, low-power sensors measure and report a person's vital signs (e.g., pulse oximetry, respiration rate, and temperature). These applications can be developed and deployed in different contexts ranging from disaster response, to in-hospital patient monitoring, and long-term remote monitoring for the elderly.

While triage protocols for disaster response already exist (e.g., [11] and [7]), multiple studies have found that they can be ineffectual in terms of accuracy and the time to transport as the number of victims

increases in multicasualty incidents [5]. Furthermore, studies in hospitals report that patients are left under monitored [15] and emergency departments today operate at or over capacity [4]. Finally, anecdotal evidence suggest that this lack of patient monitoring can lead to fatalities [14].

Ko et al. proposed MEDiSN to address similar goals as Code Blue (e.g., improve the monitoring process of hospital patients and disaster victims as well as first responders), but using a different network architecture [3]. Specifically, unlike the ad hoc network used in Code Blue, MEDiSN employs a wireless backbone network of easily deployable relay points (RPs). RPs are positioned at fixed locations and they self-organize into a forest rooted at one or more gateways (i.e., PC-class devices that connect to the Internet) using a variant of the collection tree protocol (CTP) [20] tailored to high data rates.

Fig. 2. Medical information tag, or miTag for short, used in MEDiSN [14]. The miTag is a Tmote mini-based [20] patient monitor that includes a pulse oximetry sensor with LEDs, buttons and an LCD screen. The miTag is powered using a rechargeable 1200-mAh

B. Motion and Activity Monitoring

Another application domain for WSNs in healthcare is high-resolution monitoring of movement and activity levels. Wearable sensors can measure limb movements, posture, and muscular activity, and can be applied to a range of clinical settings including gait [12], activity classification,athletic performance [3], [1], and neuromotor disease rehabilitation. In a typical scenario, a patient wears up to eight sensors (one on each limb segment) equipped with MEMS accelerometers and gyroscopes. A base station, such as a PC-class device in the patient's home, collects data from the network. Data analysis can be performed to recover the patient's motor coordination and activity level, which is in turn used to measure the effect of treatments

C. Large-Scale Physiological and Behavioral Studies

The final application of WSNs in healthcare that we discuss is their use in conducting large-scale physiological and behavioral studies. The confluence of body-area net-works of miniature wireless sensors (such as the previously mentioned miTag and SHIMMER platforms), always-connected sensor-equipped smartphones, and cloud-based data storage and processing services is leading to a newparadigm in population-scale medical research studies, particularly on ailments whose causes and manifestations relate to human behavior and living environments.

One example of such systems is AutoSense [19], in which objective measurements of personal exposure to psychosocial stress and alcohol are collected in the study participant's natural environments. A field-deployable suite of wireless sensors form a body-area wireless network and measure heart rate, heart rate variability, respiration rate, skin conductance, skin temperature, arterial blood pressure, and blood alcohol concentration. From these sensor readings, which after initial validation and cleansing at the sensor are sent to a smartphone, features of interest indicating onset of psychosocial stress and occurrence of alcoholism are computed in real time. The collected information is then disseminated to researchers answering behavioral research questions about stress, addiction, and the relationship between the two. Moreover, by also capturing time-synchronized information about a subject's physical activity, social context, and location, factors that lead to stress can also be inferred, and this information can potentially be used to provide personalized guidance about stress reduction.

One answer to these problems can be to allow the study subjects and patients to retain control over their raw sensor data throughout its life cycle: its capture, sharing, retention, and reuse [7], [4]. However, giving study subjects control over data raises concern about quality of data for researchers. As it is, ensuring high-quality trustworthy information from sensors out in the real world is hard due to malfunctions, misbehaviors, and lack of compliance. Letting subjects selectively hide or perturb data raises the issue of bias and availability, and thus utility. Quoting P. Ohm from a recent article: BData can either be useful or perfectly anonymous, but never both [5]. Technology assists such as automated validation procedures, audit traces, and incentive mechanisms to ensure compliance and encourage sharing may provide further help.

VI. FUTURE DIRECTIONS

Driven by user demand and fueled by recent advances in hardware and software, the first generation of wireless sensor networks for healthcare has shown their potential to alter the practice of medicine. Looking into the future, the tussle between trustworthiness and privacy and the ability to deploy large-scale systems that meet the applications' requirements even when deployed and operated in unsupervised environments is going to determine the extent that wireless sensor networks will be successfully integrated in healthcare practice and research.

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