PAS: A Wireless-Enabled, Sensor-Integrated Personal Assistance System for Independent and Assisted Living

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Abstract

Advances in networking, sensors, and embedded devices have made it feasible to monitor and provide medical and other assistance to people in their homes. Aging populations will benefit from reduced costs and improved healthcare through assisted living based on these technologies. However, these systems challenge current state-of-the-art techniques for usability, reliability, and security. In this paper we present the PAS open architecture for assisted living, which allows independently developed third party components to collaborate. We discuss key technological issues in assisted living systems, such as tracking, fall detection, security and privacy; and results from our pilot study in a real assisted living facility are presented.

1. Introduction

The aging of baby boomers is creating social and economic challenges. In the United States alone, the number of people over age 65 is expected to hit 70 million by 2030, doubling from 35 million in 2000. As the population ages there will be an increasing demand on health care resources. Approximately one-third of the health care expenditures are directed to the population over age 65. The fastest growing segment of the older adult population is those over age 85. This population will also double by 2030[13]. Almost 25% of this population have one or more deficits in their activities necessary for successful daily living (i.e., dressing and bathing) and resides in a skilled or assisted living facility. Because of the increasing demands of our aging population on the health care system, expenditures in the United States for health-care will grow to 15.9% of the GDP ($2.6 trillion) by 2010 (Digital 4Sight's Healthcare Industry Study)[5] . The ability of the current system to shift the burden of care to the family members will become increasingly limited, as a result of the decrease in the birth rate and the increasing number of adults surviving to old age without living children. These same demographics contribute to the declining proportion of our society in the work force that must support the increasing health care costs of those who have retired [19]. Clearly the current system of health care delivery is not sustainable. Innovative strategies will be needed to avoid the impending crisis.

Fortunately advances in sensing, object localization, event monitoring, wireless communications technologies make possible the unobtrusive supervision of basic needs of frail elderly and thereby replicate services of on-site health care providers. It is postulated that implementation of a cost-effective, reliable, secure, and open personal system that provides real-time interaction between elderly people and remote care providers can delay their transfers to skilled nursing facilities (SNFs) and improve the quality of their lives (by preserving independence). It is further postulated that the money saved by delaying transfers to SNFs will significantly offset the deployment cost of PAS. Supported in part by National Science Foundation and Motorola Labs, we have been in the process of designing, developing, and deploying such a wireless-based software infrastructure, called the Personal Assistant System (PAS), with sensing, localization, monitoring, wireless communication, and event/data management that facilitates preservation of independence and quality of life of frail elderly. In a nutshell, PAS exploits inexpensive, "off the shelf" technologies to assist elderly people to maintain the capability of independent living through time-based reminders of daily activities, non-intrusive monitoring of physiological functions and mobility profiles, and real-time communications with remote care providers and clinicians. Specifically, we

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have carried out the following engineering R&D tasks to realize sensing, monitoring, and wireless transmission functionalities in PAS:

1) We have established in PAS a network of small, low-power devices that integrates off-the-shelf radio-frequency identification (RFID) readers/tags, MicaZ-based sensors, and bluetooth-enabled medical devices.

2) We have equipped PAS with an enhanced Cricket system[26] and hence the capability of tracking in real-time (in addition to locating) humans and objects with the combination of ultrasonic and RFID technologies.

3) We are in the process of enhancing the robustness and ubiquity of PAS by exploring the use of cell phones as both the wireless modem and the local intelligence for data aggregation and acquisition.

4) We have incorporated into PAS a MicaZ Motes [11] -based fall detection and response system to track impact/orientation of residents and to provide audio communications with the health care provider in case of need.

To ensure that the security, privacy, trust, reliability, and user-friendliness requirements are met, we have also carried out the following R&D tasks:

5) We enhance system robustness and reliability by managing and controlling dependency relations between software components in multiple devices of the system.

6) We develop a rigorous security framework to support security and privacy in a wide range of operational context.

We are currently working with geriatricians at Washington University in Saint Louis in evaluating operations of PAS in Nazareth Living Center for Assisted Living with patients with diverse medical needs. Note that although the population targeted is home-bound elderly people, most of the PAS development and evaluation has been (and will be) made in assisted living facilities with 24 hour nursing supervision and redundant monitoring and communication to ensure the safety of the participating residents. Based on responses by patients and care providers, we are in the process of modifying the system's functionality in a synergistic design-evaluation-redesign loop. PAS is also being evaluated with respect to the delay achieved in transitioning from independent living to a higher level of skill nursing care or institutionalization by a randomized clinical trial comparing PAS to standard of care.

Our ultimate goal is to (in-)validate the postulation that with PAS, the frequency of home nurse visits can be greatly reduced while the intensity of supervision can be enhanced at a lower cost. As such, PAS should be able to extend the period of time a patient remains in the home environment, and represents a major potential financial savings in senior care. From a social perspective, PAS increases not only the ability of elder people to live independently, but the opportunity to remain at home and in contact with their social network and support system. The later has its advantages that go beyond patient satisfaction.

The rest of the article is organized as follows. In Section 2, we give an overview of the overall software architecture of PAS and several example applications that are made possible under this architecture. In Section 3, we describe in detail the systems architecture of PAS. In Section 4, we discuss the underlying sensing and tracking techniques used to realize the applications. We also discuss how we leverage cell phones to enhance the robustness and ubiquity of PAS. In Section 5, we discuss how we ensure PAS is secure and privacy-preserving. Finally, we report our pilot study results in Section 6 and highlight how PAS complements several R&D efforts in the literature in Section 7.

2. PAS Overview

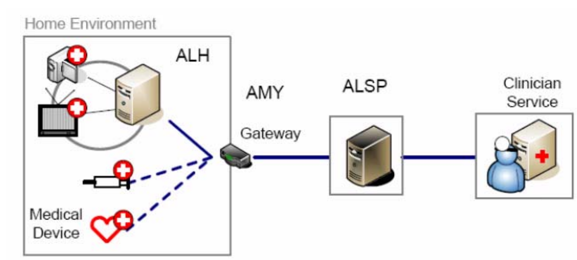

Figure 1. The overall architecture of PAS (note, in the future, some intelligent medical devices may be able to connect to ALSP directly without going through ALH)

Figure 1 shows the overall architecture of PAS. In the figure, we envision an open environment in which a security-enhanced, assisted-living device called Authentication Manager for You (AMY), co-exists with a system (a home PC or specialized device) called the Assisted-Living Hub (ALH). Equipped with one or more wireless interface cards (IEEE 802.11, Bluetooth, Ultra Wide Band, and Infrared), the ALH hosts the PAS software infrastructure and serves as the intelligence for the environment. It also communicates over the Internet with the Assisted Living Service Provider (ALSP) at which healthcare providers and medical experts can retrieve/analyze data, monitor the environment, and give instructions, if necessary, to the resident. In some sense, we follow the ADT security systems model in which a black box (i.e., the ALH) is installed in the home environment, is responsible for coordinating all the services, and communicates with the ALSP where caregivers and/or healthcare providers monitor the resident and their environment. Such ALH devices are nascent today but will be commonplace in future years. Finally, wireless-enabled medical meters, consumer electronics, and/or RFID tags/readers are introduced into the environment after being appropriately authenticated. They are responsible for collecting various physiological functions, mobility profiles of residents, and/or giving proper reminders and instructions to residents. With this architecture, several applications can be provided:

Application 1: PAS can help residents with performing daily activities. For example, the ALH can obtain from the ALSP (through secure IP tunnels) updated prescription and appointment records of residents. When it is time for the resident to carry out their time driven routines, the ALH locates active wireless-enabled devices (e.g., PDAs, digital frames, cell phones, wearable headsets) and sends reminder messages to one or more devices that are in the proximity of the resident. Whether or not these routines are followed as advised is detected in a non-intrusive manner by exploiting sensor localization and tracking technologies.

Application 2: A number of physiological functions critical to maintaining homeostasis for different medical conditions can be measured by Bluetooth-enabled medical meters, transmitted to the ALH and then to the ALSP to be evaluated by healthcare providers. These physiological functions include blood glucose in the management of diabetes, daily body weights in the management of congestive heart failure, O_2 saturation in the management of pulmonary disease, and blood pressure in the management of hypertension. Measures will have a prescribed desired range and deviations from that range will generate an alert from the ALSP to the health care provider. This alert system enables prompt intervention before the situation deteriorates to a point requiring hospitalization or may simply be in the form of additional instructions to the resident to increase or decrease a medication.

Application 3: With the combination of ultrasonic/RFID technologies as the underlying sensing mechanism for real-time tracking of objects, PAS is able to locate personal belongings attached with tags, such as eyeglasses, hearing aids, key chains, and purses/wallets. When a resident cannot find their belongings, they can issue a simple vocal command to the ALH which then helps locate the object.

Application 4: PAS can profile elderly people's movement in a privacy preserving manner (e.g., without the use of surveillance video cameras) and detect falls and early warning signs of illness. Residents wear sensors equipped with accelerometer converted to bracelets/watches or pendants. The spatio-temporal movement data can be collected without intrusion of privacy, and transmitted to the ALSP.

At the time of writing this article, we have designed and implemented four applications: time-based reminder service, vital sign measurement service, human and object tracking service, and fall detection and emergency help service, three of which leverage either medical sensors (i.e., Bluetooth-enabled medical meters) or MicaZ motes. The

Table 1. Factors contributing to the loss of independence and institutionalization

Need	% of Residents with Need	% of Residents as Primary Cause
Needs prompting to take medications	95	42
Risk of injury due to falls	42	17
Unable to get up after a fall	20	17
Monitoring of vital signs too labor intensive	12	20
Needs physical assistance with Activities of Daily Living	90	67
Needs prompting to toilet on a schedule	67	17
Needs prompting to go to meals	33	10
Needs prompting to bathe	75	0
Gets lost in apartment	17	0
May wander out of facility	12	10
Needs monitoring of blood sugar frequently	20	8
Needs monitoring of weight daily/weekly	25	0

decision of realizing the four applications is made based on a clinic survey conducted at Washington University in Saint Louis. The survey was conducted among 6 geriatricians, 3 nurse administrators of assisted living facilities, and 3 home health clinicians, with the objective of understanding the factors contributing to the loss of independence and institutionalization. As shown in Table 1, there is indeed a need to prompt elder patient to take medication (by 95% of residents) and to monitor their blood sugar (20%) and weight (25%), and the risk of injury due to falls is high (42%). The applications developed in PAS intend to address these needs.

On the other hand, in order to ensure PAS being widely deployed and utilized, we believe that PAS has to *i*) deal robustly with a wide range of failure scenarios; *ii*) be very reliable in diverse operating conditions; *iii*) communicate securely with well-specified parties; and *iv*) respect the privacy of its users. To this end, we are in the process of equipping PAS with the following (due to the page limit, interested reader shall refer to http://lion.cs.uiuc.edu/assistedliving/index.html for more details):

1) Safety, robustness and availability: Critical services will be failure safe, and delivered in spite of the failures of useful but non-critical services. Moreover, the system as a whole will have high availability and robustness.

2) Security and privacy: Medical and personal data will be protected with different levels of information disclosure to different users (healthcare providers, medical team, relatives, and residents) in PAS. Because wireless networking will be the predominant communication medium, security

mechanisms will be built in both information storage and communication facilities.

3) Light-weight, easy-to-use HCIs for elderly residents: The user interfaces will be unobtrusive, easy-to-use, safe, accommodating with respect to user mistakes.

3. Description of the System Architecture

Figure 2 gives the software architecture of PAS. To implement the time-driven reminder service (Application 1), a reminder application that resides at the ALH finds, at scheduled time instants, a proper wireless device in range and issues reminders (e.g., time to take medicine). The reminder application will also schedule the mini-RFID reader (worn on the resident's wrist) to keep track of the resident's response (e.g., whether or not the medicine has been taken). Similarly, the object localization service (Application 3) can be provided by having an object localization application receive vocal commands (e.g., through a light-weight, Bluetooth-enabled headset of a resident). Upon receipt of a vocal command, the application queries the device/object location DDB to find the whereabouts of the requested object. Then the application can send a response message to a proper wireless device that is either in range or specified by the resident.

The ALH serves an important role in the home environment. Its detailed internal architecture is depicted in Figure 3. The architecture consists of three layers: OS, middleware, and application.

The OS layer is equipped with various communication stacks and corresponding platform-dependent Application Programming Interfaces (APIs). The TCP/IP API and stack is installed by default, so that the ALH can access the Internet. Depending on the family of peripherals to support, other stacks and APIs may, for example, include Bluetooth, ZigBee [2], and Infrared.

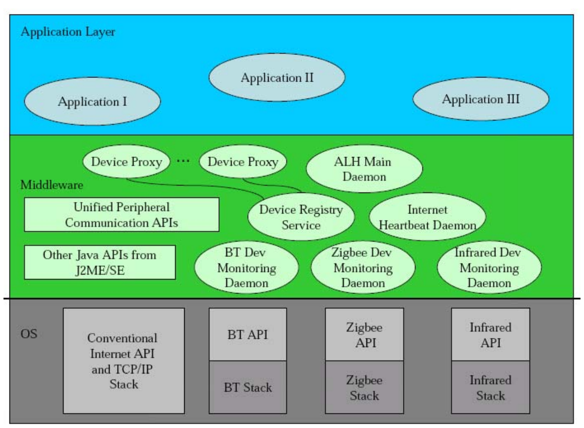

Figure 3. Systems architecture of the ALH

The middleware layer wraps platform-dependent APIs with unified Java APIs, and provides standard services to assisted living applications. In both middleware and application layer, the runnables are Java byte codes, which are platform-independent. Specifically, the middleware consists of following components:

1) Device Monitoring Daemons: These daemons monitor the join/leave of peripheral devices in the environment, and registers/de-registers the devices in the Device Registry Service. The register/de-register process includes creating/destroying proxy or singular proxy stub objects (explained later) for the device, and inserting/deleting the proxy/proxy-stub into/from Device Registry Service (explained later).

2) Proxy (and Proxy Stub): A proxy object shields vendor-dependent communication semantics from the applications. Specifically, there are a set of well-known APIs to access certain types of devices, e.g., APIs to access blood-pressure meters, oximeters, and weighing scales, just to name a few. The vendor of a medical device of certain type (e.g., a blood-pressure meter) should provide proxy code that complies with the well-known APIs of that specific type. The vendor can either write the proxy code him/herself, or assign a third party software developer to do that. Each proxy uses the underlying *Unified Peripheral Communication* APIs (explained later) to access its device. The "proxy-layer" protocol (i.e., the semantics communicated between the proxy and its device), however, is vendor dependent. The main purpose of proxies is to provide another layer of flexibility: On the one hand, applications can now be built upon well-known device APIs instead of vendor specific APIs/semantics. On the other hand, any off-the-shelf devices (especially those manufactured without knowing the PAS system programming interfaces) can be integrated into the PAS system, as long as the vendor provides the semantics specifications on how to communicate with the device.

There are two communication patterns between an application and a proxy: application polls proxy, or proxy signals application. An application can poll a proxy by calling proxy functions. For a proxy to signal an application, the application must register as a listener of the proxy in advance.

There are also two communication patterns between a proxy and a device: proxy polls device, or device signals proxy. In the first case, the device is on the server socket side, and the proxy is on the client socket side. In the second case, the device is on the client socket side, and the proxy is on the server socket side. While there may be several proxies for the same device, each proxy for a different application, there can only be *one* server socket. To deal with this problem, we have a singular Proxy Stub object run the server socket in the ALH, and all proxies register as lis-

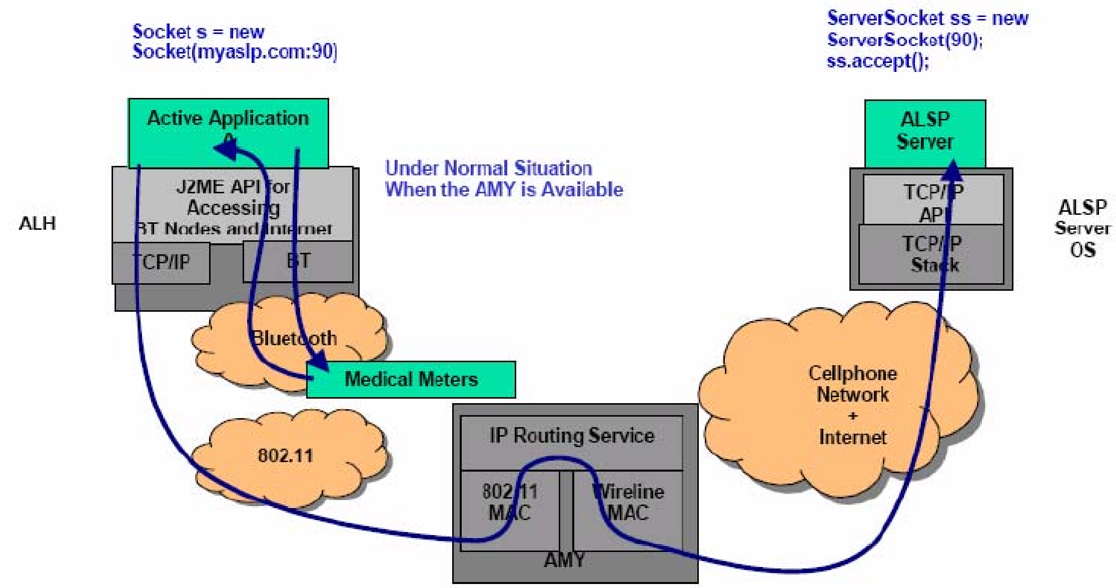

Figure 2. A technical view of the PAS software architecture for assisted/independent living

teners to this proxy stub. Whenever a device fires an event to the proxy stub, the proxy stub notifies every registered proxy.

3) Device Registry Service: This maintains a database of peripherals available in the environment. Each entry of the database is a proxy (or proxy stub) object created for a specific peripheral device. Applications will query this service for appropriate proxies. When an appropriate proxy is found, a clone of the proxy migrates to the application.

4) Unified Peripheral Communication APIs: Programming interfaces for different network stacks are different. For example, the Java API for Wifi is the standard java.net.* package, while the API for Bluetooth is JSR-82. The Unified Peripheral Communication APIs abstracts different network stack programming interfaces into a consistent paradigm, which basically follows the well-known java.net.* APIs. This allows proxies to be developed independently of specific network stack programming interfaces. Another feature of the Unified Peripheral Communication APIs is the adoption of QoS request parameters. Users can specify their QoS demands when establishing communication links, and the middleware returns approved QoS guarantees. All QoS related parameters conform to a predefined extensible XML schema.

5) Other APIs from J2ME/J2SE: Either J2ME (if the ALH is a PDA) or J2SE (if the ALH is a PC) is installed on the ALH as the runtime environment. This means the J2ME/SE APIs are also available to applications.

6) Internet Heartbeat Daemon: This daemon periodically checks the availability of Internet access through gateway router (Figure 1). When the gateway router fails/recovers, this daemon activates/deactivates the Bluetooth cell phone as a wireless modem (Section 4.3) for maintaining access to the ALSP.

7) ALH Main Daemon: This daemon is in charge of managing (start, suspend, stop, restart etc.) all the application daemons and middleware daemons on the ALH.

8) Soft States: Proxies, proxy stubs, and Bluetooth cell phone connections are maintained as soft states. They are destroyed and garbage collected if not renewed by their users. The concept of soft state makes the PAS system robust to Device Monitoring Daemon and Internet Heartbeat Daemon failures (e.g. fail to realize the device is turned off, fail to realize the Gateway router is available again).

We plan to purely use message passing (instead of function calls) for services, daemons, and applications to communicate each other (e.g. proxies are serialized between applications and the device registry service). This allows services, daemons, and applications to run on segregated Java Virtual Machines, even on different computers, which will enhance flexibility and fault-containment.

The application layer is where various applications reside. They are built on top of the unified APIs and services provided by the middleware. Many of them can be daemons that run all-year-around. It should be clear that numerous applications can be supported under this PAS ALH architecture, and new wireless devices can be plugged in to provide new capabilities.

4. PAS Applications and Underlying Technologies Used to Realize Theses Applications

4.1. Time-based Reminder and Physiological Function Monitoring Services and Their Robustness/Ubiquity with Use of Cell Phones

As mentioned in Section 2, we have designed and implemented four applications. We discuss in this subsection the first two applications, and will defer the discussion of the latter two application to Sections 4.2 and 4.3.

In the reminder service, events are scheduled by clinicians and caregivers for the resident through interfaces provided by the ALSP server. In the home environment, the reminder daemon that resides on the ALH periodically polls the ASLP server. When it is time for reminding residents of certain events, the reminder daemon picks the most appropriate device and sends the reminding message. For example, if the reminding message is an audio clip, it may be forwarded to a Bluetooth earplug. On the other hand, if it is a text message, it may be forwarded to a cell phone or a bluetooth-enabled (or IEEE 802.11-enabled) digital frame.

In the vital sign measurement application, the resident measures his vital signs (such as glucose level, blood pressure, heart beat rate, arterial oxyhemoglobin saturation level) with Bluetooth enabled medical meters at home. The measurement results are then encrypted (either by the device or by the ALH if the device is dumb, Section 5), and sent to the ALSP server. In the clinic, an authorized clinician can retrieve the vital sign measurements of the resident at any time. At the time of writing this article, we have integrated a digital pulse oximeter by Nonin Medical, Inc., a personal scale by A&D Medical, Inc. and a blood pressure meter by LifeWatch, Inc.

One major deficiency of PAS in Figure 2 is that both vital sign measurement and reminder message transport are through the gateway, which becomes unavailable when it fails or when the resident is away from home. To deal with this deficiency, we have used cell phones (transparent to users) as both a backup and the local intelligence for data aggregation and acquisition. Figure 4 depicts the architecture of a portable gateway based on the dial-up networking profile (DUN) service available with Motorola cell phones. In particular, we have leveraged the programming capability of Motorola EZX platforms (mainly the A780, E680 and E680i phones) to incorporate the following novel features that are not currently present in any cell phones:

1) Enabling cell phones to serve as local data storage/fusion intelligence: Because of the energy constraint of battery-powered cell phones, transport of a large amount of data using cell phones may become prohibitively energy inefficient. We are investigating intelligent data fusion and acquisition applications on a cell phone. Instead of passively relaying all the measurement data, the cell phone is instrumented to infer the status of the resident based on a set of pre-specified rules, and only transports readings to the ALSP when abnormal situations are identified. The set of pre-specified rules can be downloaded from the ALSP to the phones, and can be either simply threshold-based or derived based on a more complicated correlation between readings from different devices. These rules also need to be personalized based on medical records, current health status, and medical prescriptions for the resident.

2) Enabling cell phones as a delivery endpoint for reminder messages: Recall that at scheduled times (of performing daily activities), the ALH detects wireless devices in range and sends reminder messages to them. If the cell phone is selected but is not accessible to the resident (e.g., the phone is in a handbag), the resident may miss critical reminder messages. To solve this problem, we have exploited the Lightweight Remote Displays (LRD) technology by Motorola. With LRD, the phone transparently locates nearby alternative displays (e.g., digital picture frame in the environment) and sends alerts to them, tailored specifically to suit the capabilities of each display.

4.2. Monitoring and Real-time Tracking Service in PAS

In PAS, real-time indoor tracking of humans and objects is an important baseline service for realizing many useful high-level services such as finding personal belongings and objects, keeping track of whether or not instructions have been followed as advised, and resident mobility profiling for early detection of diseases from behavioral change. Visual tracking is not attractive because of high cost and privacy issues. The IR (Infra Red) signals as in Active Badge [27] and RF signal strength as in Microsoft RADAR [4] and SpotON [15] can be used for non-intrusive sensing of target positions. However, due to the inherent limitation of their sensing technologies, their positioning accuracy is several meters at best [18]. The UWB (Ultra Wide Band) based systems such as Ubisense and Multispectral Solution Inc. PAL650 [16] can provide a good positioning accuracy but they are currently quite expensive ($8,000 for a suite of 4 sensors and tags).

We have built a system that uses a combination of ultrasonic and RFID technologies as the underlying sensing mechanism for real-time tracking of both human and objects. Figure 5 shows the overall system configuration. Ultrasonic transmitters, called beacons and denoted by B_i, occasionally sends out an ultrasonic pulse and a short RF signal at the same time (marked as (1) in Figure 5). Due to the speed difference between an RF signal (speed of light) and an ultrasonic signal (speed of sound), the listener denoted

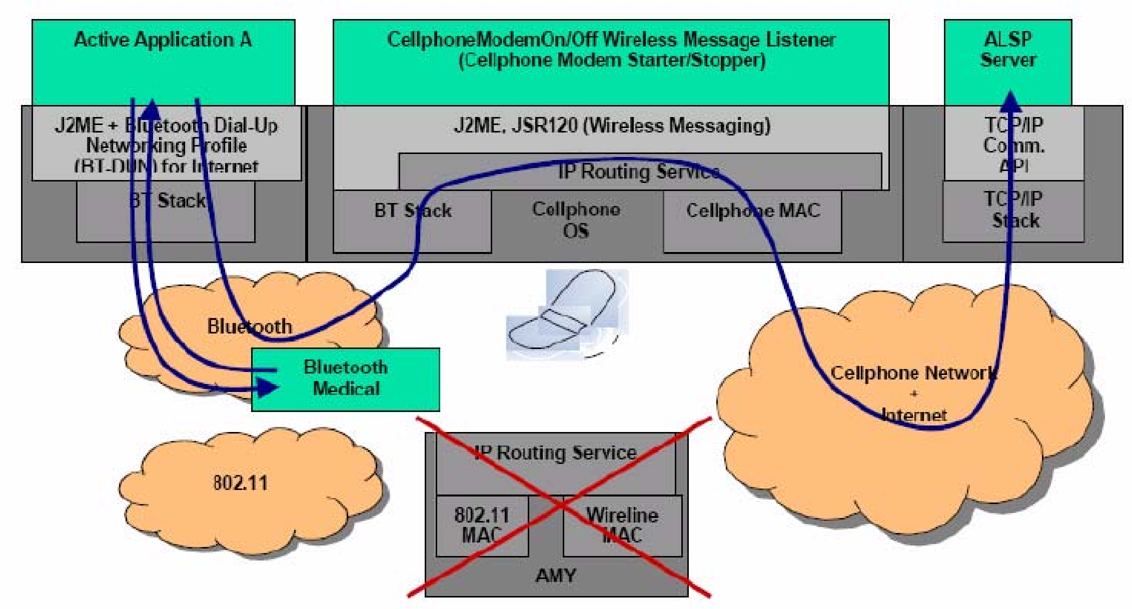

Figure 4. A technical view of how medical data is transported to the monitoring center through cell phone

by L_j on the wristband of the resident can infer its distance from the beacon using the TDOA (Time Difference Of Arrivals) of the two signals. This distance measurement can be reported to the ALH for real-time tracking of the use (marked as (2) and (3)). Also, the RFID (radio frequency identification) reader attached on the same wristband can read RFID tags of objects touched by the user. Thus, we can track the objects as well, whenever the user touches and/or carries them.

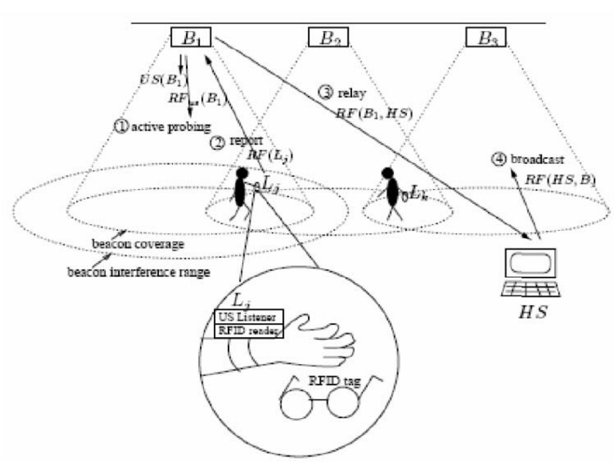

Figure 5. System configuration for the localization and tracking system

With this underlying sensing mechanism, one challenge is how to schedule ultrasonic pulses and RF signals to ensure a high sampling frequency of the listener location for real-time tracking. Since the beacons use active probing signals, i.e., ultrasonic pulse and RF signal, if two beacons within the interference range transmit the active signals at the same time, they collide. The state-of-the-art ultrasonic based location systems, Active Bat [14] and Cricket [26], address the collision problem based on carrier sensing and random arbitration. However, it cannot ensure high-quality and predictable tracking performance. To enable high frequency, collision-free sampling, we have devised a novel scheduling algorithm [21] that leverages the following ideas:

1) Harmonizing sensing and communication: The system should schedule active ultrasonic signals (i.e., sensing) while exchanging RF messages (i.e., communication) among beacons, listeners, and the ALH. We maximally overlap the duration of ultrasonic signals and RF transmissions, since they do not collide. The overlapping allows us to build a more packed schedule and hence realize a high rate of collision-free sampling.

2) Location-aware scheduling: Two beacons may or may not collide depending on the listener location. We form a feedback loop between the scheduler and tracking tasks, and build a better transmission schedule of ultrasonic signals and RF transmissions with an even higher sampling rate by utilizing the information of listener locations.

3) Mobility-conscious scheduling: We adaptively control the sampling frequencies of beacons depending on the mobility of users—low rate for low mobility and high rate for high mobility. In this fashion, we can significantly save energy without compromising tracking accuracy.

We have quantitatively evaluated the performance of the real-time tracking algorithm by measuring its time-average of tracking error. For experimental repeatability, we have used a speed-controllable train as shown in Figure 6(a). To track the train, we deploy four beacons on the ceiling and one listener on the train. Figure 6(b) shows the measured tracking error of the random arbitration algorithm used in Cricket as we increase the random wake-up frequency for three train speeds, i.e., slow = 28 sec lap time, medium = 14 sec lap time, and high = 7 sec lap time. These lap times correspond to the average speeds of 28.5 cm/sec, 57 cm/sec, and 114 cm/sec, respectively, considering the 800 cm length of the rails. The measured performance of the Cricket algorithm improves to a certain extent as the wake-up frequency increases but any further increase in the frequency starts degrading the performance due to severe collisions. On the other hand, the proposed algorithm can guarantee 5 Hz collision-free sampling for each beacon and hence significantly improve the tracking error for all train speeds. The time-average of tracking error is around 20 cm for older adults (whose moving speed is usually close to that of medium speed train).

4.3. Robust and Accurate Fall Detection Service

We have also incorporated into PAS a novel fall detection and response service for 24/7 monitoring of older adults. The subsystem that realizes the service is composed of fixed embedded Crossbow MicaZ motes [1] that provide the communication infrastructure (packet relay), the ALH for collecting and processing sensing information, and sensing nodes (also MicaZ motes, each carried by a resident). Each mote device includes a 2-axis accelerometer and a microphone. We have implemented a fall detection algorithm [9] utilizing the accelerometer on its sensor board to track impact as well as orientation. The algorithm is based on observation that when an individual falls, there is a combination of a large impact or impacts followed by a large change in orientation. A common occurrence would be a person falling to the ground, while another would be a person falling down the stairs before landing on the ground. Both involve single or multiple impacts and change of orientation. Thus, by keeping track of a window of orientation values, we can compare for instance, the orientation of the wearer just before the detection of an impact and immediately after it.

Whenever an event of interest (e.g., a potential fall) is detected by a sensor node, a communication channel between the sensing node and the ALH is established using geographic routing [17]. Note that a prioritized multi-hop MAC protocol is needed to deliver time-critical data from the sensing node to the ALH within a bounded delay; as a consequence, real-time multi-hop wireless communications is crucial for the deployment of a fall detection and response service. In particular, we have considered two problems: *i*) packet collisions on a wireless channel and *ii*) priority inversions when accessing the wireless medium. To avoid packet collisions and mitigate the priority inversion problem caused by the multi-hop nature of sensor networks, we exploit a prioritized medium access scheme based on the Black-Burst (BB) protocol [1], and propose a new notion of Real-Time Chain (RTC) [8]: a multi-hop real-time data flow that is characterized by a real-time priority and can be established on demand. RTC will also allow good spatial reuse of the wireless medium by exploiting multiple channels, be less susceptible to wireless interference caused by best effort (non real-time) traffic and be compatible with IEEE 802.15.4 (after minor modifications to the IEEE standard).

Upon detection of a fall, the sensing mote requests for a chain to be opened. When the chain is successfully opened, the mote begins sampling the voice of the wearer (through the microphone) at 2kHz and at the same time performs an 8 bit ADPCM encoding before transmitting the packet to the next node. The current packet length used to carry voice is 30 bytes: this allows for future extensions since the sensor node can transmit up to 20 more bytes per packet while still remaining within the real-time chain's specifications. Note that audio monitoring is triggered by the accelerometer (due to detection of a falling pattern) and is an effective way of gathering additional information in real-time. The ALH also issues an alarm notifying care providers that the wearer may be injured. This automatic transmission of voice and information circumvents the problem with current med-alert systems which rely on the competence of the patient at the time of the accident to activate the system.

5. Enhancing PAS with Security and Privacy

The ALSP for the PAS provides technology-naive residents and clinicians with help in configuring security tokens such as passwords, encryption keys, and certificates so adequate security can be assured. The ALSP also provides reliable storage and holds collected vital status information from assisted-persons so that residents, clinicians, families and other authorized personnels can retrieve the stored information. Since ALSP requires sophisticated networking and storage service administration, it is likely to be supplied by an Information Technology (IT) specialist such as an Internet Service Provider (ISP) rather than a healthcare

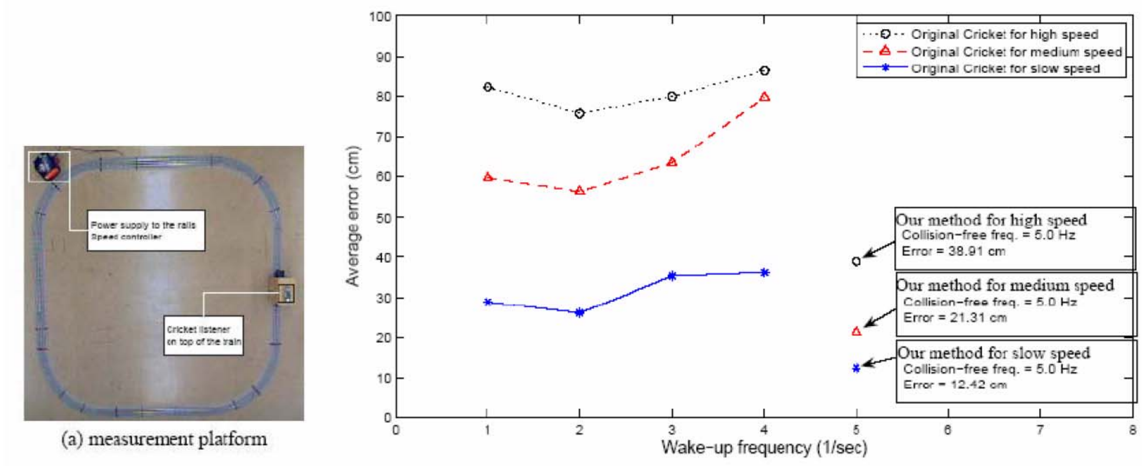

Figure 6. Performance of the real-time tracking algorithm

provider.

The ALSP and the protocols to communicate with it must satisfy basic security requirements, like protecting passwords. Since the ALSP is primarily an IT entity, it is desirable that it does not “know” the private medical information that it is relaying. Therefore, our security requirements include two major goals. First, we must preserve privacy of medical data even when the ALSP is compromised and leaks all of the information it has. The other is to protect all information from an attacker who can inject, intercept, and construct message transmissions. Since such an attacker can inject a false message, we also have to show *message correspondence*, which guarantees that a delivered legitimate message originates from an authorized participant. We attain these security requirements using a combination of authentication, signature, encryption, and access control. In summary, we separately encrypt a resident’s medical information and administrative information (such as a timestamp and from/to tags), so that ALSP will deliver and hold the private information without decrypting the contents. Details appear in [20] and we will not repeat them here. In summary, we introduced the requirements and security architecture of our system, developed bootstrapping workflows, and described protocols for transmitting report and alarm messages over the PAS architecture. Moreover, we gave a proof of a correspondence theorem and showed security of our transmission protocols with the assumption of the partially trusted intermediate entity. We used the TulaFale [6] formal specification language and the ProVerif protocol verifier [7] to prove the security properties. Currently, the PAS architecture is implemented based on standards for web services to enhance extensibility and interoperability. The messages are delivered in Simple Object Access Protocol (SOAP) message format. They are encrypted and signed using XML encryption and signature standards (XML-Enc and XML-Sig, respectively). The functions of the ALSP are described in Web Service Definition Language (WSDL).

For the link-level security of wireless home networks, we rely on Wi-Fi Protected Access 2 (WPA2), a subset of IEEE 802.11i. WPA2 Personal (WPA2-PSK) mode is more appropriate to our PAS environment than WPA2 Enterprise (WPA2-EAP) since the latter needs an authentication server, which is not typically affordable for SOHO environments. WPA2 is expected to screen out unauthorized bandwidth usage and to guarantee the availability of wireless network resources under the application level security architecture. Access to the network requires users to install a secret on each device. USB memory tokens can sometimes be used for the installation, but we are investigating a device called an AMY to get an easy-to-use solution based on RFID tags.

6. Pilot Study Results

With the help of geriatricians at Washington University in Saint Louis, we have carried out a pilot study at the Nazareth Living Center for Assisted Living in June-July 2006. We deployed two PAS prototypes (because of budget constraints) during a three-week pilot study at Nazareth Living Center in Saint Louis MO. This facility houses 110 well-educated, predominantly female residents, whose average age was 88. Of 30 residents who attended a presentation, 14 agreed to participate. After administering a standard cognitive assessment, two residents were consented to test the PAS prototypes and ten residents to carry/wear a placeholder device for a period of two weeks.

The working PAS consisted of a handheld blood oximeter and an IBM Thinkpad T43 (with WindowsXP

Home Edition, Java Runtime Environment Standard Edition 1.5.0_06, Bluetooth stack: Avetana) placed in the resident's room. The two residents received alert messages on a flat computer screen twice a day, reminding them to take an oximeter reading. Alert times were collaboratively set by the residents and the staff. When the resident had taken the oximeter reading, she would tap the computer to acknowledge the alert message. The oximeter reading was then sent wirelessly (and transparently to the resident) to an IBM Thinkpad T41 (with WindowsXP Professional, Java Runtime Environment Standard Edition 1.5.0_09, MySQL Server 5.0, WebServer: Apache-Tomcat version 5.5.20) in the nurse's station. A monitoring interface, installed at the nurse's station, provided a history of alert adherences and oximeter readings. To assess whether, and to what extent, older adults are willing to carry sensors and medical meters on a daily basis, 10 residents carried a placeholder device. The placeholder device was a pedometer of the similar size to an oximeter, and residents were encouraged to wear it as they wished. The twelve residents and their nurses were interviewed prior to and after their interaction with PAS. During the study they were also given journals to make comments and/or ideas they had about the interfaces.

Pilot Results: The qualitative and quantitative data from the pilot study comprise several hundred pages. Summarized below are several of our major findings that pertain to the issues considered in this article:

1) The systems performance is reasonably fast: We have calibrated the performance of PAS with respect to several parameters. The (mean, std) values of the measured results are given in units of milliseconds: *i*) the time it takes for the ALH to poll reminders from the database of the ALSP: (323,.3, 124.51); *ii*) the time it takes for the ALH to discover the Bluetooth-enabled oximeter: (15195.0,190.86); *iii*) the time to read the oximeter measurement and upload it to the database of the ALSP (6948.2,201.67); *iv*) the time it takes for the clinician's computer to retrieve 170 cardinal vascular data entries from the database of the ALSP (655.8,76.31); and *v*) the time it takes for the clinician's computer to upload the reminder schedule into the database of the ALSP (212.4,195.66) . The performance bottleneck is the time ($\sim$ 15 sec) it takes the ALH to detect the Bluetooth-enabled oximeter (i.e., the time the resident has to wait in order for the system to take the measurement).

2) Residents found PAS useful and were willing to wear the sensing apparatus: *i*) The two residents using the PAS prototype found it to be quite useful. Residents not chosen to use the working prototype expressed their desire to use the working version as well, suggesting that PAS was, in general, well received by residents. *ii*) Nine of the ten residents with placeholder devices said they wore the device every day in the two week study. During five random checks, we found 100% adherence in 11 of the 12 residents. The 12th resident had dropped her device in water and stopped wearing it for fear the device would be giving inaccurate information.

3) Residents lack in confidence in PAS when it did not work properly: Wireless connectivity is made possible by a low-end Linksys WRT54G wireless router. During the study, this, coupled with concrete walls between residents' rooms and the nurse station, led to intermittent connectivity. Whenever the wireless connection was down, the host operating system (Window XP) attempted to reset the connection. For reasons currently under inspection, this often resulted in the entire system being inoperative. Residents, as a result, were not confident in relying solely on PAS for medical monitoring. This indicated both *i*) the reliability of PAS software and *ii*) the connectivity and QoS of the underlying wireless communication have to be improved before redeployment. To address this problem for the time being, we will add a wireless repeater (i.e., an additional Linksys WRT54G router configured in the client-mode and forwarding all packets to another, master router) between residents' rooms and the nurse station.

4) Nurses/caretakers desire interfaces that provide security/privacy. With a high resident-to-nurse ratio, nurses were usually very busy and could not ensure that the information being displayed would not be viewed by unauthorized personnel. The need for privacy should be addressed by designing adequate access control to PAS. Also, nurses inquired whether or not medical data could be securely transmitted via wireless technology. This implies they also had concerns about PAS security.

In summary, while PAS was quite well-received by the residents, we have identified several technical directions to pursue. In particular, PAS will need to *i*) deal robustly with a wide range of failure scenarios, *ii*) be very reliable in diverse operating conditions, *iii*) communicate securely with well-authenticated parties who are granted proper access to the information, *iv*) respect the privacy of its users, and *v*) provide QoS even in the presence of wireless interference and other environmental effects. We are continuing working on these issues.

7. Related Work

The need for new technologies to facilitate assisted living has recently received increasing attention both in industry and academic research. In what follows, we summarize existing R&D projects, and discuss the difference between the proposed and existing research.

At the Center for Future Health (CFH) at University of Rochester [22], the Smart Medical Home prototype consists of infrared sensors, computers, bio-sensors, and video cameras. The key services to be provided are *i*) medical advisory which provides a natural conversational interface between the patient and healthcare expert, *ii*) motion and activity monitoring, *iii*) pathogen detection and skin care, and *iv*) personal healthcare record for consumer-provider decision support. The core supporting technology to achieve the above services is a visual system for object recognition and tracking. The component project that comes closest to ours is called Middleware Linking Applications and Networks (MiLAN) and proposes to develop middleware solutions to adapt applications to a changing set of available resources in the smart medical home environment. PAS complements CFH in the fact that we focus on laying a robust, dependable, and secure software infrastructure that allows disparate technologies, software, and wireless devices (of different protocol families) to be plugged in a plug-and-play manner and operate with predictability and privacy preservation. We leverage low-cost, non-intrusive technologies such as sensors and diverse wireless devices to help elderly people to interact with, and make sense of, their environment. We have also deliberately chosen, for privacy reason, not to use video cameras for monitoring. Moreover, we are evaluating (with clear testable hypotheses) PAS by deploying units in a medically diverse group of ALF residents identified at risk of transition.

The Smart in-home Monitoring System at University of Virginia [23] focuses on data collection with the use of a suite of low-cost, non-intrusive sensors. The information collected is logged and analyzed in an integrated data management system (that is linked to the Internet). The system essentially collects information in a passive manner and does not directly interact with the resident. PAS is complementary to the data management, as the behavior profile gathered by the real-time monitoring and tracking system in PAS (Section 4.2) can be fed into the health care provider's server for early detection of behavior change and/or elderly disease.

The Assisted Cognition project at University of Washington [25] aims to create a computer system that will enhance the quality of life of people suffering from Alzheimer's disease and similar cognitive disorders. The system provides proactive memory and problem solving aids that help an individual perform the tasks of day-to-day life. It senses aspects of an individual's location and environment, both outdoors and at home, relying on a wide range of sensors such as GPS, active badges, motion detectors, and other ubiquitous computing infrastructure. It then learns to interpret patterns of everyday behavior and recognizes signs of distress, disorientation, or confusion, using techniques from state estimation, plan recognition, and machine learning. Finally the system offers help to patients through various verbal/physical interventions, and alerts caregivers in case of danger. Again PAS focuses on building a software infrastructure that allows integration of various wireless devices and sensors in a robust, secure, and cost-effective manner, rather than cognitive interpretation of the behavior profile gathered. In another University of Washington project, Opportunity Knocks [24] a cell phone serves as an intelligent navigational assistant, and *i*) helps people with memory problems to find their way around town and use public transportation, *ii*) learns the pattern of user's daily movements throughout the town.; and *iii*) attempts to call user if decides that user is lost. It complements our efforts of employing cell phones as local intelligence for reminders of daily activities and non-intrusive monitoring of physiological functions and mobility profiles.

The two major industry research efforts are perhaps the Age-in-Place Advanced Smart-Home system at Intel [10], and the Motohealth project at Motorola. The Intel effort aims to help elderly people with Alzheimer's disease, by integrating four major technologies: sensors, home networks, activity tracking, and ambient displays. The sensors located in the home environment sense the locations of the resident and the objects in the home. The home network uses a combination of motion sensors, cameras, contact switches, and magnetic switches to keep track of activities and to display the environment. At the system infrastructure level, the focus of this project is not on systems reliability, robustness, security/privacy, and wireless device coexistence issues; at the application level, it does not address the monitoring of medical conditions. The Motorola effort, on the other hand, uses FDA-approved body sensors to transmit data about the patient's condition to the healthcare provider via the patient's mobile phone. This convenient and discreet way of monitoring patients in the mobile environment can replace in-home monitoring devices, and give patients with chronic diseases more independence to continue their daily activities outside their homes. We share the same view of employing cell phones as wireless modems, but will augment its functionality to act as a local data repository and intelligence. Moreover, the set of data to be transmitted and managed includes not only vital sign data but also resident mobility profiles and instructions from healthcare providers.

PAS complements existing projects at the application level by developing new applications (such as time-/event-driven reminders of important daily activities, services for locating personal belongings, services for transporting resident-measured vital signs to healthcare providers and medical experts); and at the infrastructure level by laying an open, robust, and secure software infrastructure that allows residents to interact with the environment with low-cost localization, monitoring and wireless communications technologies.

8. Conclusion

Advances in networking, sensors, and embedded devices have made it feasible to monitor and provide medical and other assistance to people in their homes. Aging populations will benefit from reduced costs and improved healthcare through assisted living based on these technologies. However, these systems challenge current state-of-the-art techniques for usability, reliability, and security. Our PAS open architecture for assisted living allows independently developed third party components to collaborate. Key technologies, such as tracking, fall detection, security and privacy are partially addressed in our primary implementation. Results from our pilot study in a real assisted living facility shows the feasibility of our system.

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