I-Living: An Open System Architecture for Assisted Living

Qixin Wang, Wook Shin, Xue Liu, Zheng Zeng, Cham Oh, Bedoor K. AlShebli,
Marco Caccamo, Carl A. Gunter, Elsa Gunter, Jennifer Hou, Karrie Karahalios, and Lui Sha

***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. This is a particular challenge for open and extensible systems that combine software and hardware from many vendors and provide information to diverse clinicians. In this paper we present the *I-Living* architecture for assisted living that allows independent parties work together in a dependable, secure, and low-cost fashion with predictable properties. Our approach is based on an Assisted Living Service Provider (ALSP) who provides a server that collects and maintains encrypted Assisted Persons (APs)' records. Our ALSP can be a third party distinct from APs, communication providers, and clinicians; or it can be part of an ISP, hospital or similar enterprise. We have explored the architecture by developing a collection of applications and implementing them in a prototype system. Our system shows the feasibility and opportunity of an open approach to assisted living systems.**

I. Introduction

The aging of baby boomers has become a social and economic challenge. According to MIT's magazine TECHNOLOGY REVIEW, July/August 2003, "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, and similar increases are expected worldwide". Along with the increase of population of elderly people, the expenditures of the United States for health-care will grow projecting to rise to 15.9% of the GDP ($2.6 trillion) by 2010 (Digital 4Sight's Health care Industry Study). Unless the cost of senior care can be significantly reduced by technological means, it could bankrupt the already shaky social security and medicare systems.

Another social trend that affects senior care is the move away from the nuclear family household and the increasingly youth-oriented society. This leaves many people to their own means in receiving health care and satisfaction from life. They are increasingly restricted to living alone or in assisted living facilities. According to a report by National Institute on Aging, only 10% of elderly people of age 65-85 and 25% of those of age 85 and above in the United States are institutionalized. Similarly, it has been reported that the numbers of elderly people living alone in Korea has increased 100% in the last ten years. Because of the deteriorating capabilities to sense and interact with the environment, such as memory, eye sight, hearing, dexterity and mobility, elderly people often live with significantly degraded life quality. Many also suffer from chronic diseases that require medication and clinic visits on a regular basis. Without assistance, they often cannot keep up with their schedule and at times are unable to call for help after a serious fall or illness.

Because of above reasons, researchers at the University of Illinois at Urbana-Champaign have been designing, implementing, and evaluating with testable hypothesis an assisted-living supportive software architecture that allows disparate technologies, software components, and wireless devices to work together in a low cost, dependable, and secure fashion and enables elderly people to regain their capability of independent living. We name the architecture *I-Living* (where "I" stands for Illinois, Independence and Information-Technology). Specifically, we designed I-Living architecture to meet the following requirements:

1) **Dependability**: 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) **Low Cost and Flexibility**: The assisted living infrastructure will be open with well defined interfaces, machine checkable QoS assumptions, and support the use of low-cost, third-party devices. As incompatible and incomplete assumptions have been reported to be a major source of unexpected interactions leading to high maintenance cost, these attributes will significantly reduce system integration and deployment time and promote industry standardization.
3) **Security and Privacy**: Medical and personal data will be protected with different levels of information disclosure to different roles (health care providers, medical team, relatives, and assisted persons). Also, with wireless networking being the predominant communication medium, security mechanisms will be built in in these communication facilities and associated information storage.
4) **Quality-of-Service Provisioning**: In spite of the existence of various forms of workload dynamics, ranging from transmission of reminder messages, monitoring information, audio commands, to time-critical multimedia streams supporting tele-medicine, Quality of Service (QoS) will be provided at different levels

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The authors are with Department of Computer Science, University of Illinois at Urbana-Champaign, Urbana, IL 61801 (Email: {qwang4, wookshin, xueliu, zzeng2, chamoh, alshebli, mcaccamo, cgunter, egunter, jhou, kkarahal, lrs}@uiuc.edu)

The last six authors are listed in alphabetical order.

to applications subject to their timing, reliability and criticality requirements.

5) **Wireless Interference Mitigation**: Different wireless devices of disparate protocol families can interfere with each other when they are in range, e.g., Bluetooth versus IEEE 802.11b, and IEEE 802.11a versus microwave. We will ensure that interference is mitigated to the maximal possible extent and QoS is provided even in the presence of wireless interference and medium contention.
6) **Light-Weight, Easy-to-Use HCIs**: The user interfaces will be easy-to-use, safe, accommodate with respect to user mistakes, and provide different control levels of information disclosure.
7) **Thorough Evaluation and User Group Studies**: The assisted living system will be evaluated in terms of the extent to which these technologies help elderly people with their independent living in the home or assisted living facilities, their attitudes toward deploying these technologies in the environment. Different hypotheses that are amenable to theoretically-grounded tests will be established, and a detailed, comprehensive evaluation will be carried out by professional, quality-of-care experts to (in-)validate the hypotheses.

In what follows, we begin in Section II with a discussion of example applications that are enabled with the proposed I-Living architecture. Then we elaborate on the designs of various components in the architecture in Section III. Following that, we summarize our implementation status of the architecture and its associated applications in Section IV, and give a succinct summary of related work in Section V. Finally we conclude the paper in Section VI.

II. Example Scenarios

We envision an assisted living supportive environment in which various embedded devices (sensors, actuators, displays, and bluetooth-enabled medical devices) either operate independently or are coordinated under the local intelligence node, called the *Assisted Living Hub* (ALH). The ALH can be a specialized PC, PDA, or a black box equipped with one or more wireless interface cards (IEEE 802.11, Bluetooth, Ultra Wide Band, or Infrared). Independent devices (also called smart devices) and the ALH can communicate with the *Assisted Living Service Provider* (ALSP) server over the Internet. The ALSP server also provides web-based interfaces to allow caregivers, health care providers and medical experts, to monitor the environment, retrieve/analyze measurement data, and issue instructions/feedback. Under the assisted living system architecture, we envision the following assisted living application scenarios:

1) **Activity Reminder**: The ALH obtains from the ALSP server (to which health care providers have access) updated prescription and appointment records of the *Assisted Person* (AP) through secure channels. When it is time for the AP to carry out his/her time driven routines, such as taking medicine or taking vital signs, the ALH locates active wireless-enabled devices (e.g., TVs, cell phones, wearable headsets, and/or active badges [1]) in range, and sends reminder messages to one or more devices that are in the proximity of the AP. (The AP can also prioritize the order in which devices will be used.) For example, if the AP is watching TV at the time when the reminder message is scheduled, the TV will be switched to an information channel (with the use of Infrared remote control) and a reminder message will be displayed. In this manner, the AP can be reminded of his/her time driven routines. Whether or not these routines are followed as advised is detected in a non-intrusive manner by exploiting sensor localization technologies such as RFID [2] or Ubisense [3] – the prescription bottles can be attached with light-weight RFID or Ubisense tags (with unique barcodes) and one or more RFID/Ubisense readers in the environment are activated (by the ALH) to track location changes (if any) of these bottles. Note that each RFID tag costs approximately 40 cents today, and the cost is expected to further decrease in the future.
2) **Vital Sign Measurement**: In the current practice of glucose monitoring for diabetics patients, a patient measures his/her glucose level on a daily basis, and brings the OneTouch [4] device to his/her monthly clinic visits where the measurements are retrieved and interpreted by health care providers. With the proposed environment in place, vital signs (such as the glucose level, blood pressure, heart bit rate, arterial oxyhemoglobin saturation level) can be measured and transmitted by Bluetooth-enabled meters [5][6][7] to the ALH and then to the ALSP server (through the secure channels established between the ALH and the server). In this fashion, health care providers can monitor various vital signs at desirable time granularity. Should the readings suggest any abnormal health situations, medical instructions can be given before the situations deteriorate.
3) **Personal Belonging Localization**: Personal belongings such as eyeglasses, hearing aids, and key chains can be attached with tags, and located through the use of RFID/Ubisense readers. When a person cannot find his/her belongings (because of forgetfulness), he/she can issue a simple vocal command (through, for example, a light-weight, Bluetooth-enabled headset) to the ALH which then schedules the RFID/Ubisense readers to scan the environment and help locate the object.
4) **Personal Behavior Profiling**: With the same set of sensor localization techniques, the assisted living environment can profile the movement of APs in a privacy preserving manner (e.g., without the use of surveillance video cameras) and detect early warning signs for depression (no longer taking medicine regularly, giving up routine activities, or staying in bed for long periods of time) and/or other chronic diseases such as Parkinson's disease and Alzheimer's disease. The AP wears a RFID tag or an active badge (turned into, for example, a bracelet or a button on his clothes). The

RFID readers installed in the environment will keep track of his location, and hence will be able to detect abnormal spatio-temporal movement, without intrusion of privacy.

5) **Emergency Detection**: In case of the need for emergency attention (e.g., the blood pressure/sugar has been dangerously high/low, and/or the person has been detected via localization techniques to be immobile on the floor for an unreasonably long time), real-time communication channels can be established to notify on-site caregivers (in the case of assisted living), health care providers (in the case of clinical use), and/or designated relatives, and facilitate transmission of electrocardiogram (EKG) and other measures in real-time.

To realize the above scenarios, we have to consider several design issues. First, the various application scenarios require effective communication and coordination of disparate embedded hardware, software and communication components. For example, in the reminder application, the ALH has to coordinate, and effectively transport messages, among a Bluetooth earplug, Infrared TV, cable-connected projector, and localization systems such as Ubisense (e.g., to verify the person has taken the medicine). What makes things more complicated is that as the system evolves, different embedded components may be brought into the environment. Therefore, the assisted living architecture must be flexible enough to accommodate hybrid embedded systems. Second, several assisted living applications, such as daily reminder of taking medicines for chronical diseases, monitoring vital signs, and detecting emergencies and abnormal situations, must operate all-year-around without disruption. Availability is thus another important design requirement. Moreover, this requirement has to be met even when the ALH is down or when the AP is away from home. Finally, as a large amount of medical data is transported in the proposed infrastructure, security and privacy is another indispensable concern. The system must provide means to authenticate distributed entities, protect communication resources, and preserve user privacy. We have laid out an open system architecture called I-Living, to meet the above design requirements. The next section presents the various components of the I-Living architecture.

III. I-Living System Architecture

A. Overall Architecture

The basic system architecture is depicted in Figure 1. The home environment of the *Assisted Person* (AP) is covered by a *Wireless Local Area Network* (WLAN). Devices in the WLAN connect to the Internet via the *gateway router*. One important device in the WLAN is the *Assisted Living Hub* (ALH), which acts as the local intelligence and manages *peripheral* devices (most of which pertain to activity reminder and localization services) through its own peripheral network (e.g., Bluetooth). Several assisted living client applications reside on the ALH and use its various peripheral devices. A *smart* or *independent* device, on the other hand, can also act as an autonomous WLAN node, and does not rely on the ALH. In particular, if the smart device is equipped with the internet stack, it can connect to the *Assisted Living Service Provider* (ALSP) server directly. Incorporating such smart devices in the infrastructure promotes end-to-end security and reduces the number of intermediate control entities that are subject to potential security leaks. Moreover, with the peer smart devices in place in addition to the ALH, the system availability will be overally improved, because the ALH will not become a potential single point-of-failure.

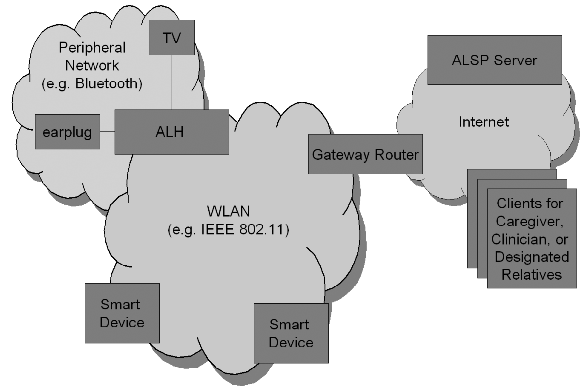

Fig. 1. Overall System Architecture – Gateway Mode

The design in Figure 1 may still suffer from a single point-of-failure: the gateway router. To ensure high availability, we propose a backup alternative (Figure 2) in which a Bluetooth-enabled cellphone (that the AP owns) serves as the replacement when the gateway router fails or is absent (e.g., when the AP is away from home). Specifically, upon detection of the failure/absence of the gateway router, a smart device (or the ALH) triggers the Bluetooth *Dial-Up Networking Profile* (DUN) mechanism[8] to turn the cellphone into a wireless modem for Internet access. For convenience of discussion, we call the former system architecture the "gateway mode", and the latter the "cellphone mode". Introducing the cellphone and its associated DUN mechanism enhances availability.

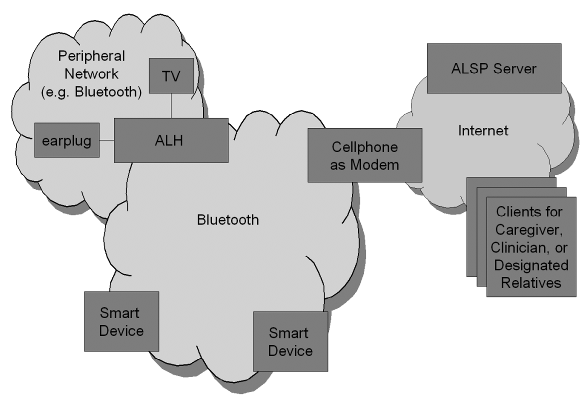

Fig. 2. Overall System Architecture – Cellphone Mode

B. System Architecture of ALH Node

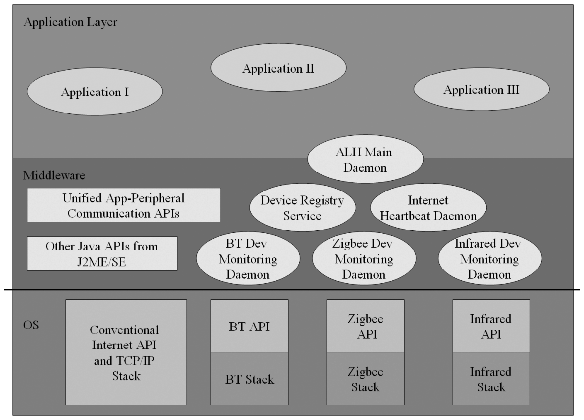

Fig. 3. System Architecture of ALH Node

The ALH node 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, the other stacks and APIs may include Bluetooth, ZigBee[9], Infrared etc.

The middleware layer wrapps platform-dependent APIs with unified Java APIs, and provides standard services to assisted living applications. From middleware layer above, the runnables are Java [10] byte codes, which are platform-independent. Specifically, the middleware consists of following components:

1) **Device Monitoring Daemons**: These daemons monitors the join/leave of peripheral devices in the environment, and registers/de-registers the devices in the Device Registry Service.
2) **Device Registry Service**: This maintains a database of peripherals available in the environment. Each entry is an XML [11] file describing the device. The XML file specifies at least the following properties: *Device Communication Paradigm*, *Address*, and *Application Protocol*. The *Device Communication Paradigm* can be (but not limited to): Bluetooth, ZigBee, Wifi, USB, and Infrared. *Address* is the unique address of the device under its communication paradigm. *Application Protocol* specifies the application layer protocol that should be used to interact with the device, for example, "mp3 player", "text message display". Different devices may comply with the same application layer protocols. Use of XML allows the standard, human-readable, and machine-checkable specifications of the above properties. Note also that with the Device Monitoring Daemons and the Device Registry Service, applications do not have to bind with specific devices, but rather locate proper devices at runtime by querying the Device Registry Service.
3) **Unified Application-Peripheral Communication APIs**: Specific programming APIs under various communication paradigms are different. For example, the Java API for Wifi is the standard java.net.* package [12], while the API for Bluetooth is JSR-82 [13]. The Unified Application-Peripheral Communication APIs abstracts different communication APIs in a consistent paradigm, which basically follows the well-known java.net.* APIs. This allows applications to be developed independently of specific communication APIs. Another feature of the Unified Application-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.
4) **Other APIs from J2ME/J2SE**: Either J2ME[14] (if the ALH is a PDA) or J2SE[15] (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.
5) **Internet Heartbeat Daemon**: This daemon periodically checks the availability of Internet access through gateway router (see Figure 1). When the gateway router fails/recovers, this daemon activates/deactivates the Bluetooth cellphone as a wireless modem (by invoking/terminating the DUN mechanism) for Internet access.
6) **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.

The application layer is where various applications resides. They are built on top of the unified APIs and services provided by the middleware. Many of them can be daemons that runs all-year-around. At the time of writing this article, we have designed and implemented two applications: daily reminder of taking medication and vital sign measurement, and will discuss them in Section IV.

C. Security and Privacy Mechanism

The security mechanism in the assisted living infrastructure concerns two aspects:

1) protecting information confidentiality;
2) ensuring data integrity in the home WLAN with link-level authentication and encryption.

Protection of information confidentiality implies the need to differentiate information visibility to different entities. For example, when the smart medical device sends a message that contains vital sign meansurements to the ALSP server, the content of the message is meant to be interpreted only by designated clinicians. The ALSP server itself should not be able to read the vital sign measurement. Rather, it should only be able to read *administrative* information contained in the message such as the ID of the AP. This requirement can be realized by the *partial encryption* mechanism [16] of *Simple Object Access Protocol* (SOAP) [17], an XML-based message format for interoperable message communication among heterogeneous systems. For example, we can encrypt administrative information and vital sign measurements separately: we first encrypt only the vital sign measurements using the encryption key between the smart medical device and the clinician, and then the entire message (that includes both the administrative information and the encrypted vital sign measurements) using another encryption key known to the smart device, the ALSP server, and the clinician. In this fashion, a third-party cannot decrypt the message, the ALSP server can only decrypt the administrative information (and knows to which AP the corresponding vital sign measurement belongs), and the designated clinician can decrypt the entire message.

To protect communication in the home WLAN with link-level authentication and encryption, all the devices in the home WLAN share an authentication token (a specialized encryption key). The gateway router uses this token to authenticate a device before allowing it to use the home WLAN. The authentication scheme follows Wi-Fi Protected Access 2 (WPA2) [18], a subset of IEEE 802.11i[19] security standard. WPA2 has two authentication modes: *WPA2 Enterprise* (WPA2-EAP) and *WPA2 Personal* (WPA2-PSK). WPA2-EAP leverages IEEE 802.1x framework and authenticates network nodes using *Extensible Authentication Protocol* (EAP). In spite of its powerfulness, this mode is, however, too heavy-weight due to the use of high-cost servers such as *Remote Authentication Dial-In User Service* (RADIUS) server and *Certification Authority* (CA). WPA2-PSK, on the other hand, authenticates nodes using a token called the *Pre-Shared Key* (PSK). It offers a light-weight solution that fits the need for authenticating devices in the home WLAN. As such, we adopt the latter in the software architecture.

Encryption is required for both preserving privacy and protecting wireless communication from unauthorized use. Context information such as encryption keys or certificates have to be delivered to the involved devices. We propose the use of a specialized USB memory stick, called *Authentication Manager for You* (AMY), for configuring and managing encryption contexts. A device (the gateway router, the ALH, or a smart device) is equipped with AMY software to automatically recognize and install the context information when an AMY is pluged into the device.

IV. Implementation of Applications on Top of Proposed System Architecture

With the software architecture in place, numerous applications can be built to facilitate elderly people with their independent/assisted living. At the time of writing the article, We have designed and implemented two demo applications: daily reminder of taking medication and vital sign measurement.

In the reminder application, events are scheduled by clinicians and caregivers for the AP (see Figure 4) 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 APs 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 cellphone.

In the vital sign measurement application, the AP measures his vital signs (such as glucose level, blood pressure, heart bit rate, arterial oxyhemoglobin saturation level) with Bluetooth enabled medical meters at home (see Figure 5)[1]. The measurement results are then encrypted (either by the device or by the ALH if the device is not smart), and sent to the ALSP server. In the clinic, an authorized clinician can retrieve the vital sign measurements of the AP at any time. This mimics the drop-box workflow in real-world hospitals: patient put their blood samples in a drop-box, the drop-box stores the samples temporarily until the doctor picks up the blood samples. Also, note that the personal behavior profiling application can be readily implemented with the same set of code, except that Bluetooth-enabled medical devices have to be replaced by RFID or Ubisense readers.

V. Related Work

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

At the *Center for Future Health* (CFH) at University of Rochester [20] the smart medical home prototype consists of infrared sensors, computers, bio-sensors, and video cameras. The key services to be provided are medical advisory which provides a natural conversational interface between the patient and health care expert, motion and activity monitoring, pathogen detection and skin care, and personal health care 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 aims to develop middleware solutions to adapt applications to a changing set of available resources in the smart medical home environment. Our research complements CFH in two aspects. At the application level, the application domain of CFH is health care settings such as nursing homes and hospitals. In contrast, we focus on improving the quality of living in an assisted living environment. At the infrastructure level, we focus on laying a robust, dependable, and secure software infrastructure that allows disparate technologies,

[1]The current implementation involves Nonin 4100 Oximeter[5]. Integration with A&D UC-321PBT Scale[6] and LifeWatch blood pressure meter[7] is underway.

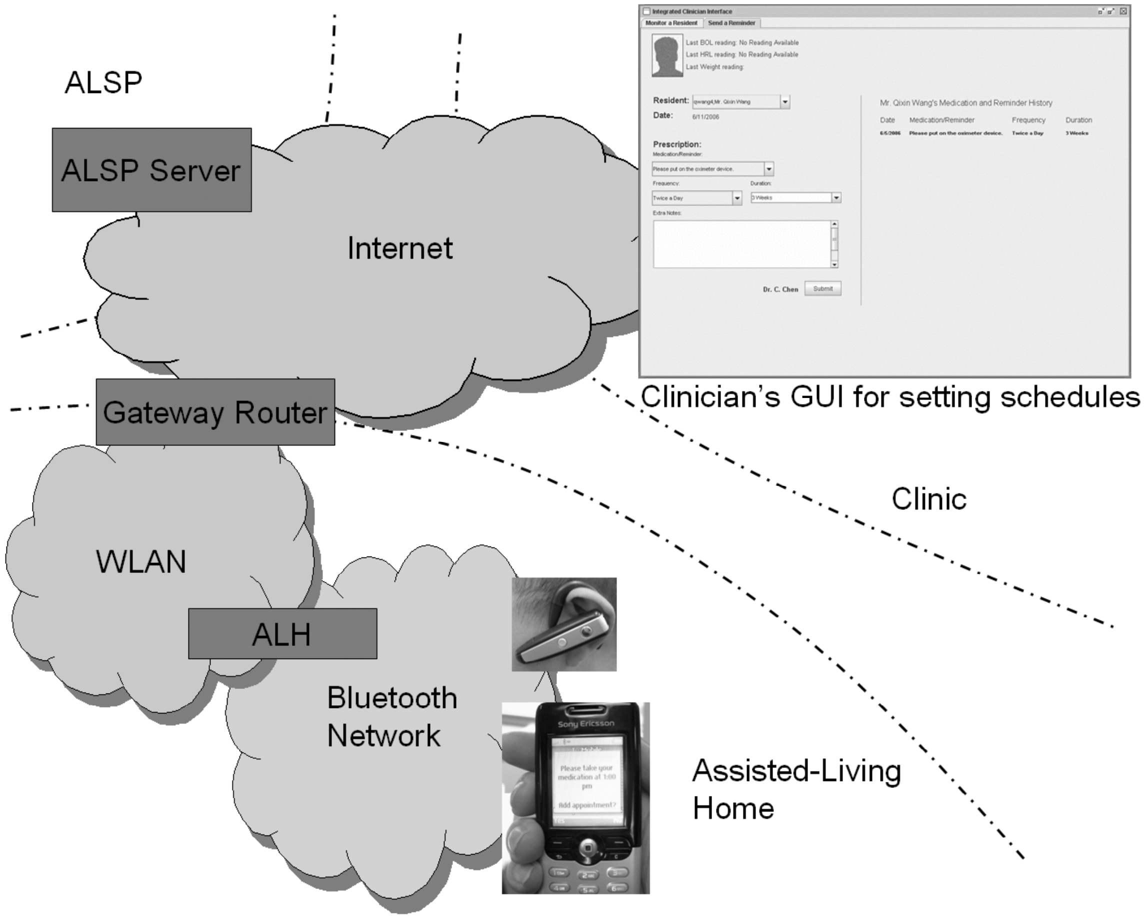

Fig. 4. Reminder Application Scenario

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 have also deliberately chosen, for privacy reasons, not to use video cameras for monitoring.) We leverage low-cost, non-intrusive technologies such as RFID and Ubisense technologies and diverse wireless devices to help elderly people to interact, and make sense, with the environment. Moreover, we will carry out ethnography-based studies and user group assessment with clear testable hypotheses.

The *Aware Home* project at Georgia Tech [21] targets to create a home environment that is aware of its occupants' whereabouts and activities. The services provided by "aware home" range from enhancing social communication such as providing digital portrait of elderly people to their family members, to memory aids that assist users in resuming interrupted activities based on playbacks of past events recorded by video camera. At the system level, the "aware home" project focuses on context-aware computing to support rapid prototyping of home applications. It does not, however, address QoS provisioning, wireless networking, security/privacy, human-computer interface issues in a dynamic environment that allows integration of various hardware, software, and wireless technologies in a plug-and-play fashion. A clinical study that explores potential clinical utilities is also lacking.

The smart in-home monitoring system at University of Virginia [22] 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 elderly people. The data management system is complementary to our research, as the behavior profile gathered by the RFID/Ubisense components in our assisted living infrastructure can be fed into their server for early diagnosis of behavior changes and/or elderly diseases.

The major industry research effort is perhaps led by the age-in-place advanced smart-home system at Intel [23]. It aims to help elderly people with Alzheimer's diseases, 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 people 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. Again the focus of this project is not on systems reliability, robustness, security, and wireless

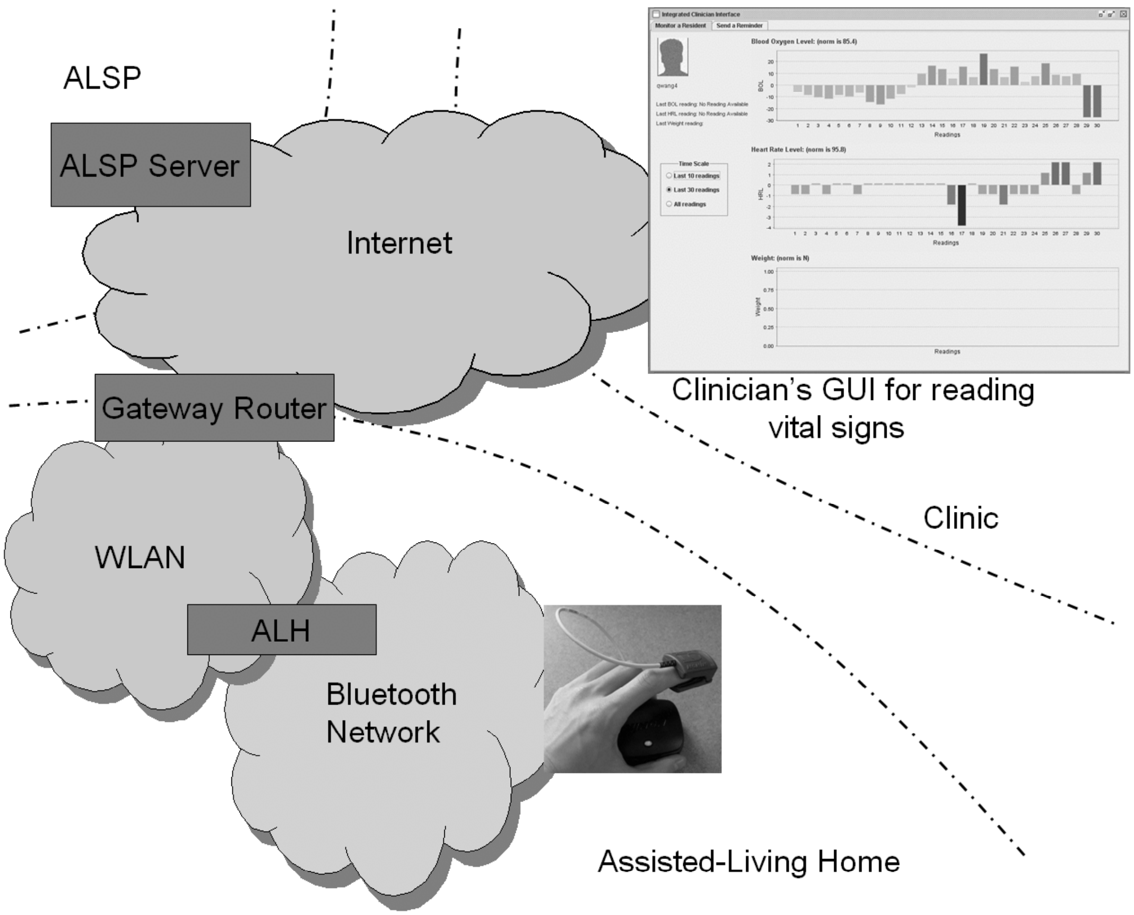

Fig. 5. Vital Sign Measurement Scenario

device coexistence issues.

We expect our research will complement existing projects at the application level by developing new applications (such as time-driven, event-driven and situational reminders, services for locating personal belongings, services for transporting AP-measured vital signs to health care providers and medical experts); and at the infrastructure level by addressing research issues on laying an open, dependable, and secure software infrastructure that allows elderly people to interact with the environment with low-cost localization and wireless technologies. In addition, we are the first to advocate an open environment that provides well-defined, QoS-annotated APIs and allows devices of different vendors to co-exist and collaboratively improve the quality of life of elderly people. This is the key to industry standardization, and wide deployment, of these devices. We are also in the process of working with experienced medical and health care experts at Washington University in Saint Louis, in employing a comprehensive, systematic HCI-based methodology for evaluating how elderly feel about leveraging new technologies to facilitate their independent living.

VI. Conclusion

The need for the assisted living supportive environment is compelling, due to the increasing economic and social problems posed by aging. In this article, we have proposed I-Living, an open assisted living system arhitecture that allows integration of various, hybrid embedded devices in a flexible, secure, and highly available fashion with predictable properties. Flexibility is provided by deploying the Device Registry Service, Unified Application-Peripheral Communication APIs, XML, and Java technology. Availability is ensured by enabling the system to operate both in the gateway mode and in the cellphone mode. When the gateway router is unavailable, the environment will activate the cellphone to act as a wireless modem for Internet access. Security and privacy are addressed in the context of protecting information confidentiality and providing link-level authentication. We propose the use of SOAP to provide information confidentiality and differentiated privacy, and AMY based authentication to protect home WLAN resource from unauthorized accesses. For proof-of-concept, we have also implemented two representative applications: daily reminder application and vital sign measurement application to demonstrate the usefullness of the proposed system.

As part of our future work, we will add more functionality, such as QoS provisioning, wireless interference mitigation, and a rich set of easy-to-use and error-accommodating HCI components into the assisted living system. We are incorporating role-based trust management in the HCI components so as to provide different levels of information disclosure to different people. We are also in the process of working with medical experts at Washington University in Saint Louis to define testable hypotheses, identify a group of volunteers from elderly people and clincians, and carry out user group studies.

VII. Acknowledgements

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