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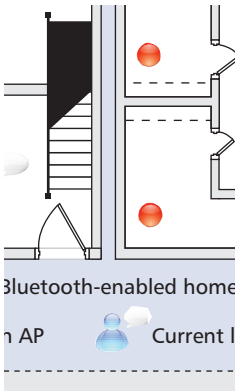
BLUETOOTH-ENABLED IN-HOME PATIENT MONITORING SYSTEM: EARLY DETECTION OF ALZHEIMER'S DISEASE

HO TING CHENG AND WEIHUA ZHUANG, UNIVERSITY OF WATERLOO



The authors propose a Bluetooth-enabled in-home patient monitoring system, facilitating early detection of Alzheimer's disease. They take advantage of short-range Bluetooth for in-home patient location tracking, and the location information can then be recorded in a local database.

ABSTRACT

As the baby boom generation is aging, more and more people are diagnosed with Alzheimer's disease, early detection of which is shown to be vital and necessary for better medical treatments and prolonging life expectancies. In this article we propose a Bluetooth-enabled in-home patient monitoring system, facilitating early detection of Alzheimer's disease. We take advantage of short-range Bluetooth communications for in-home patient location tracking, and the location information can then be recorded in a local database. With knowledge of the movement pattern of a patient, a medical practitioner is more likely to be able to determine whether a target patient is developing Alzheimer's disease. We also conduct a feasibility study, and our study shows that the proposed in-home patient monitoring system is feasible and can be applied in practice. Our proposed e-healthcare solution is expected to facilitate medical treatments, improve the quality of life of senior people, and reduce healthcare costs.

INTRODUCTION

Healthcare costs have been skyrocketing as the baby boom generation continues to grey. The rapidly aging population not only causes long hospital waiting times and expensive hospital stays, but also increases the workload of doctors and medical practitioners. Managing the cost and quality of treatment and caring for seniors are fast becoming key pressing issues in both developed and developing countries [1]. On the other hand, this global phenomenon has stimulated a drastic demand for electronic healthcare (e-healthcare). The Industrial Technology Research Institute reported that the global e-healthcare market is growing at a rate of 20 percent every year. In particular, patient monitoring in out-of-hospital conditions has been attracting a plethora of attention from researchers and healthcare practitioners in hopes of reducing the medical costs and enabling elderly independence (i.e., enable seniors to age with dignity in their own homes). In recent studies home-based monitoring has been shown to be promising for decreasing emergency room visits and/or hospitalizations compared to standard traditional healthcare [2]. In this work we focus on an e-healthcare solution for early detection of Alzheimer's disease, allowing senior citizens to have extended independent living at home and improved quality of life.

According to the Alzheimer's Association [3], there are more than 5 million people in the United States living with Alzheimer's disease. The direct and indirect costs ascribed to Alzheimer's disease amount to more than $148 billion each year. Despite the fact that there is no known cure for Alzheimer's disease yet, early detection of Alzheimer's disease is considered crucial in slowing the progression of Alzheimer's disease and compiling better treatment of patients. In other words, the earlier the treatment, the better the chance of a favorable response to treatment and the less financial costs overall for patients and their caregivers. However, many research studies have also shown that the early signs of Alzheimer's disease such as memory loss are not apparent to family members or evident even during a medical examination. A thorough clinical diagnosis of a patient, including observing the patient's movement and behavior, can take up to a few months or even years. Furthermore, patients clinically diagnosed with Alzheimer's disease are likely to be in the final stages of Alzheimer's disease, shortening their life expectancy. Therefore, an efficient and effective methodology for early detection of Alzheimer's disease is imperative.

In this article we propose a Bluetooth-enabled in-home patient monitoring system, facilitating early detection of Alzheimer's disease. Our proposed e-healthcare solution consists of two main components, in-home patient monitoring and telediagnosis. With the virtue of short-range Bluetooth communications, the location and hence the movement of a patient can be tracked and reported to a local database. The collected data is then transmitted via the Internet to a decision engine (on a remote site). A corresponding medical practitioner makes use of this intelligent decision engine to analyze and

determine whether the patient of interest is developing Alzheimer's disease. In a nutshell, our proposed Bluetooth-enabled in-home patient monitoring system decouples the processes of patient monitoring and diagnosis. This novel e-healthcare solution is expected to facilitate medical treatments, reduce overall healthcare costs, and plausibly improve the quality of life of seniors.

In the following we first give the rationale for employing Bluetooth for in-home patient monitoring, and describe our proposed Bluetooth-enabled in-home patient monitoring system. A feasibility study is then presented, followed by discussion and conclusions of this research.

Why Bluetooth?

To devise an efficient and effective strategy for in-home patient monitoring, capturing the location and hence the movement of a patient is fundamental. Concerning the ability to determine the location where computation takes place, the global positioning system (GPS) has been developed and widely employed. Despite its popularity, GPS works well only in outdoor environments with unobstructed views. In indoor environments such as homes, however, GPS becomes futile [4], giving rise to the necessity for new approaches to indoor localization. For all intents and purposes, a desired in-home patient monitoring system should be able to track the daily movement of a patient in his home.[1] For instance, when does a target patient go from one room to another, and how frequently does that transition happen? In general, there are a number of key criteria to determine the success of an in-home patient monitoring system:

- *Convenience* — The technology on which a patient monitoring system depends should be in use today and readily available on the market. Also, the deployment of such a system should be economical.
- *Bulkiness* — Since unobtrusive patient monitoring is desired, a monitoring device a patient carries should be small enough so that his normal day-to-day activities are not affected.
- *Accuracy* — Ideally, the resolution of a monitoring system should be as high as possible. In practice, a monitoring system should be at least able to determine in which room a patient is currently located.
- *Durability* — Since we anticipate that a monitoring device is battery operated, the technology should be of low power and last long, reducing the hassle of recharging the monitoring device constantly.

With the necessity of the aforementioned features for an in-home patient monitoring system, we study a number of possible candidates for practical implementation, including Active Bat and Cricket, Ascension Technology's tracking, wireless local area networks (WLANs), and Bluetooth.

Active Bat and Cricket

Active Bat [5] and Cricket [6] employ the notion of ultrasound time-of-flight technology to track the location of an object. Despite the fact that they can provide fine-grained accuracy on location tracking, a coarse clock calibration in timing would lead to a few meter error in distance estimation. Furthermore, these two technologies are not widely used in commercial products; therefore, applying these technologies to an in-home patient monitoring system can be prohibitively expensive.

Ascension Technology's Tracking

Ascension Technology proposes a location tracking system based on magnetic sensors. The system is demonstrated to be effective, providing a very high accuracy on the location of an object. However, the major drawback is that this system requires very expensive hardware. Other magnetic objects in the home might compromise the performance of this location tracking system. Moreover, how durable the Ascension Technology's tracking system can be is still an open question.

Wireless LANs

Recently, WLANs have been widely used, providing an economical solution for both peer-to-peer applications and Internet access. In fact, with the help of signal strength estimation, wireless LANs can be employed in object positioning and location-aware applications, and the resolution can be up to 1 m. However, the main disadvantage of using WLANs as an indoor monitoring system is rigorous device calibration. A monitoring device has to be trained and calibrated at every possible location before the monitoring system can function properly. In addition, the power consumption of a signal transmission over a few meters can be up to 1 W, possibly leading to a less durable monitoring device.

Bluetooth

Bluetooth has been specifically designed as a low-cost, low-power, and small-size radio technology, which is particularly dedicated to short-range communications. Specifically, the maximum power consumption of a Bluetooth signal transmission over 10 m is only 1 mW. A single 3 V battery cell can function up to a few years, leading to a viable solution for convenient yet unobtrusive patient monitoring. For safety considerations, low power requirements are also indispensable in an in-home patient monitoring system since such systems run near the body. To justify the aspect of convenience, Bluetooth has been shown as a stable, economical, and mature wireless technology [7]. Nowadays, Bluetooth devices for personal use can be made commercially available for under US$10. Besides, more than 1 billion Bluetooth integrated circuits were estimated to manufacture and ship in 2008 [8]. Due to its small size, Bluetooth can also easily be integrated into small personal belongings such as cell phones or Lifeline devices for seniors [9]. With the virtue of its short communication range (i.e., approximately 10 m), the location of a patient can be tracked with ease.

As discussed, Bluetooth wireless technology has enormous potential in e-healthcare for in-home patient tracking, monitoring, and medical data collection. In this article we make use of the unique features of Bluetooth technology to

Despite its popularity, GPS works well only in outdoor environments with unobstructed views. In indoor environments such as homes, however, GPS becomes futile, giving rise to the necessity for new approaches to indoor localization.

[1] *Even though we use masculine pronouns and nouns to describe a patient and a doctor throughout this article, both the patient and the doctor can be male or female.*

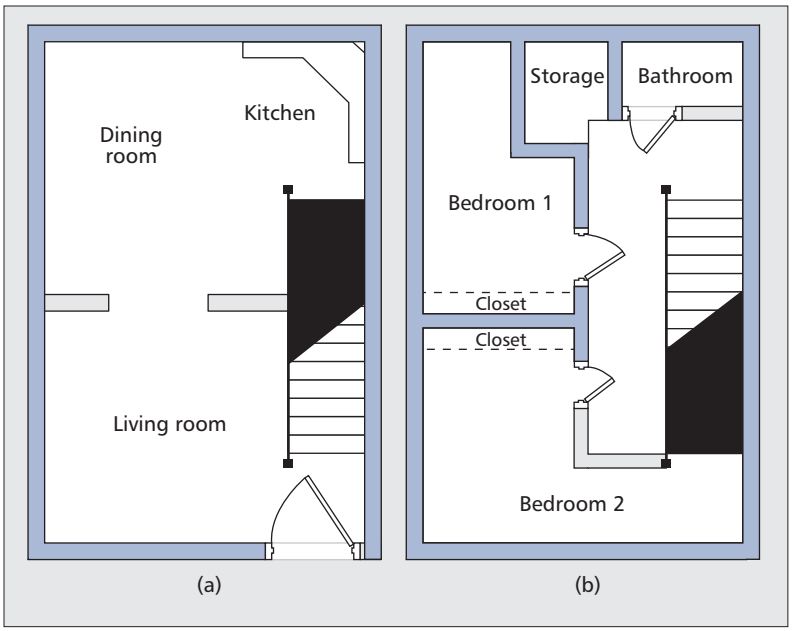


Figure 1. *Floor plan of a typical townhouse in North American suburban residential areas: a) first floor; b) second floor.*

devise an effective in-home patient monitoring system, whereby early detection of Alzheimer's disease and appropriate treatments by medical practitioners can be facilitated.

Bluetooth-Enabled In-Home Patient Monitoring System

In this section we propose a novel e-healthcare solution: a Bluetooth-enabled in-home patient monitoring system, aiming at an efficient and effective method for early detection of Alzheimer's disease. The gist of our proposed e-healthcare methodology is to separate the process of medical data assembly from the process of medical diagnosis. To be precise, the process of medical data assembly is autonomous, continuous, and unobtrusive, while a medical practitioner performs remote diagnosis assisted by an intelligent decision engine through the Internet. With faster early detection of Alzheimer's disease, not only can we foster better treatment of patients, but time and money can also be well spent on finding a cure for Alzheimer's disease.

Unlike clinical examinations in a conventional setting, our proposed e-healthcare solution consists of two main steps: in-home patient monitoring and telediagnosis through the Internet.

In-Home Patient Monitoring

Consider a typical two-story two-bedroom townhouse in a North American suburban residential area. The floor plan of the home under consideration is shown in Fig. 1. Since the daily routine of a person is contingent on his surrounding objects and environment (e.g., clothes in the closet, coffee pots in the kitchen), in our case the pattern of the movement of a senior hinges on the layout of his home. As time goes by, abnormally sporadic movements can indicate an early sign of Alzheimer's disease.

The system architecture of our proposed in-home patient monitoring is depicted in Fig. 2. We consider a Bluetooth-enabled home, where a Bluetooth access point (AP) is situated in every room of the house, and all Bluetooth APs are connected to a local database. A Bluetooth-enabled monitoring device is carried by the patient. Due to the virtue of short-range Bluetooth communications, the location of the target patient and hence the direction of his movement can be tracked. In particular, when the subject enters a room (e.g., a bathroom), a Bluetooth-enabled monitoring device performs an *inquiry* to find a Bluetooth AP to which to connect. In the presence of multiple available Bluetooth APs, the monitoring device chooses the one with the strongest signal strength. In this work we assume that Bluetooth APs are opportunistically deployed such that a single Bluetooth AP is sufficient to provide the wireless coverage for a room. After the connection is established, the Bluetooth AP to which the monitoring device is connected forwards a timestamp to a local database. Since only one Bluetooth AP is set up in each room, the location of the patient and the time instant he is at this location can be captured and stored in the local database. Notice that the process of inquiry by a Bluetooth-enabled monitoring device is performed regularly (e.g., once a minute). When the subject moves from one room to another, the monitoring device will then connect to the Bluetooth AP located in the latter room due to a stronger Bluetooth signal strength. With this approach, the movement pattern of a senior can be acquired, and the corresponding information can be recorded in the local database.

Telediagnosis

The raw data obtained from the Bluetooth APs is forwarded to a local database along with timestamps. The stored location information of a patient is to be transmitted from the local database via the Internet to his medical practitioner for remote diagnosis, and this information transfer is performed on a daily basis. The medical practitioner can then compile the information of the patterns of the target patient's daily routine, and a set of desired behavioral patterns can be procured. Here, we make use of a decision engine for the process of medical data assembly and compilation. This autonomous decision engine also warns both the patient and his medical practitioner of any early signs of Alzheimer's disease. We assume that the decision engine is empowered by intelligent movement pattern recognition software and programmed by a medical practitioner with respect to the unique conditions of the target patient; however, how to design such a movement pattern recognition program is beyond the scope of this research work. Since one of the early symptoms of Alzheimer's disease is memory loss, with the knowledge of the floor plan of a patient's home, his medical history, and the recorded information of his movement patterns, a diagnostic analysis through the Internet can be carried out to determine if the target senior is developing Alzheimer's disease. For example,

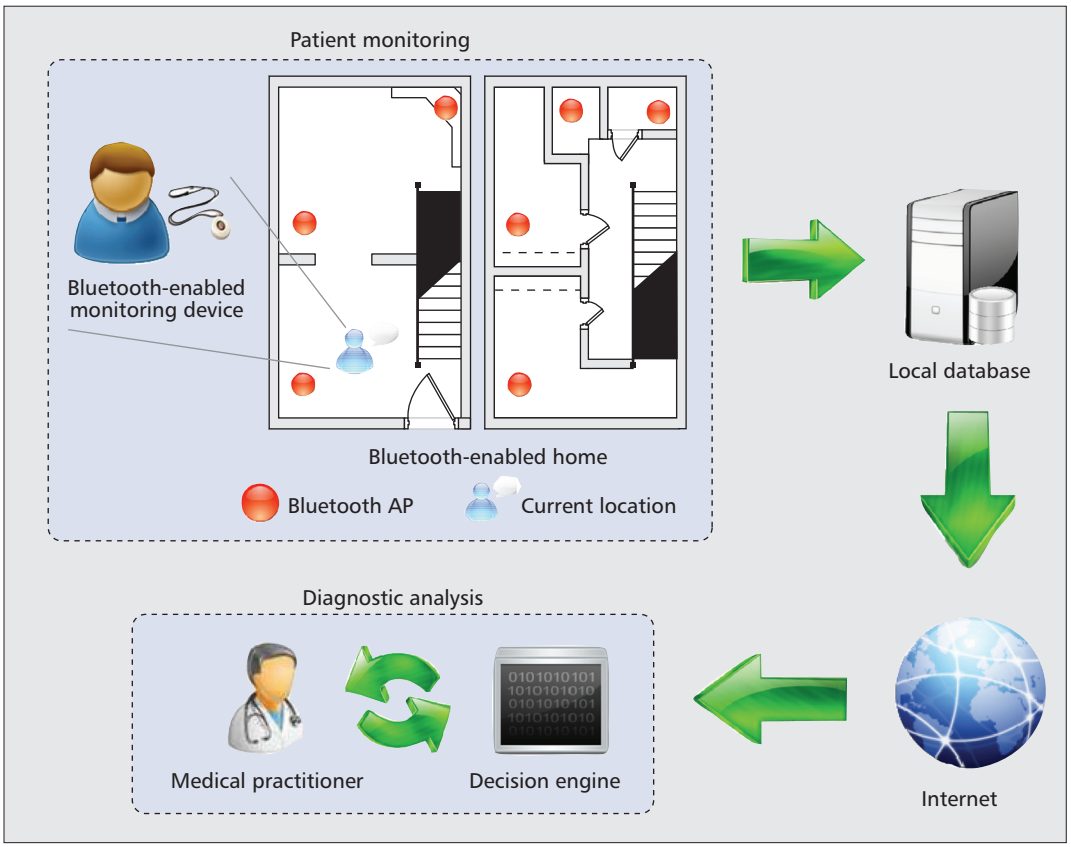


Figure 2. *An illustration of the proposed Bluetooth-enabled in-home patient monitoring system.*

With the help of early detection facilitated by the proposed e-healthcare solution, a doctor will plausibly be able to offer better treatments to the patient, thereby prolonging his life expectancy and enabling him to gain independence with dignity in his own home.

a target senior used to leave his bedroom for the kitchen around 12 p.m. and 5 p.m. every day. Recently, he has instead been going to the kitchen more often than usual (e.g., five times) sporadically, and this irregular pattern persists for some time. That could be an early sign of Alzheimer's disease. With the help of early detection facilitated by the proposed e-healthcare solution, a doctor may be able to offer better treatment to the patient, thereby prolonging his life expectancy and enabling him to gain independence with dignity in his own home.

Feasibility Study

We carry out an experiment to undertake a feasibility study for our proposed Bluetooth-enabled in-home patient monitoring system. The main purpose of this feasibility study is to determine the likelihood of using the Bluetooth wireless technology for in-home patient monitoring. The experiment is conducted in a two-story two-bedroom townhouse in the city of Waterloo, Ontario, Canada. The layout of the townhouse under experiment is similar to the one shown in Fig. 1. Our study focuses on the movement from a bedroom on the upper floor (about 18 m^2 in size) to a living/dining room on the main floor (about 40 m^2 in size), and vice versa. The equipment involved in this feasibility study includes two AXIS 9010 Bluetooth APs (Fig. 3a), an HP iPAQ hx2790c Pocket PC (Fig. 3b), and a laptop. The two Bluetooth APs, situated in the bedroom and living/dining room, are connected to the laptop, which resembles a local database in our proposed e-healthcare solution. We develop a tailored database program empowered by a Microsoft SQL Server to record the location and time of our Pocket PC over a 24-hour period of time. The HP iPAQ hx2790c Pocket PC is Bluetooth-enabled. This Bluetooth-enabled handheld, mimicking a monitoring device in the proposed e-healthcare approach, is carried by a volunteer who moves from one room to another in the townhouse under experiment. We also devise a custom-made Bluetooth application program using the Broadcom-WidComm Bluetooth SDK [10] for the handheld. This application first checks the availability of any Bluetooth AP on a regular basis (Fig. 4a), and then the handheld connects to the Bluetooth AP with the stronger signal strength (Fig. 4b). Once the handheld connects to a Bluetooth AP, the laptop is notified, and the location and timestamp are recorded in the database. Our study shows that in our Bluetooth-enabled home environment, the location and hence the movement pattern of the handheld can be captured, where the information is recorded in the local database. We also notice that the presence of WiFi has almost no impact on the outcome of our experiment. The implication is that the proposed Bluetooth-enabled in-home patient monitoring system is feasible, and can be applied to homes with WiFi users. The next step is to design an intelligent decision engine, facilitating the process of telediagnosis; however, addressing this issue is beyond the scope of this research.

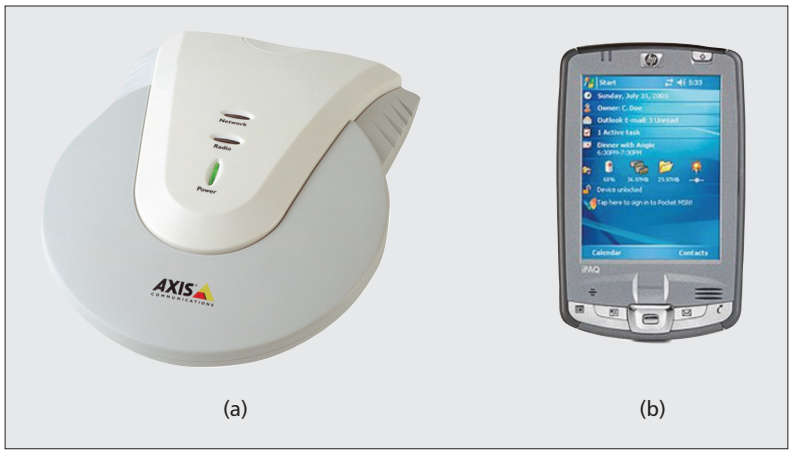


Figure 3. *Main equipment for the experiment in our feasibility study: a) an AXIS 9010 Bluetooth™ AP; b) an HP iPAQ hx2790c Pocket PC.*

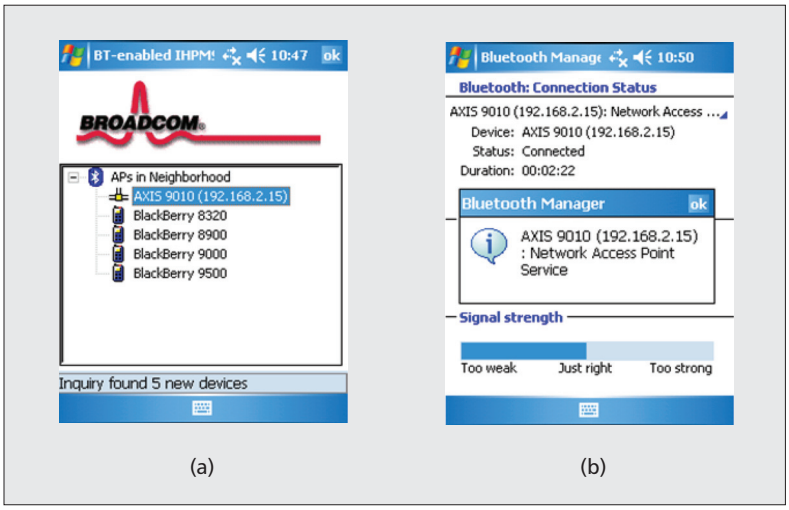


Figure 4. *Key steps of our feasibility study: a) discovery of Bluetooth APs; b) Bluetooth signal strength monitoring.*

Discussion

By exploring the merits of Bluetooth communications, unobtrusive patient monitoring can be made more convenient, efficient, and effective. In particular, our novel e-healthcare solution decouples patient monitoring and medical diagnosis, thereby reducing hospital stays and possibly lowering overall healthcare costs. Since the diagnosis is performed remotely (i.e., through the Internet), more people can have access to high-quality healthcare. Doctors and other medical practitioners from around the globe can collaboratively contribute to any individual case, possibly lowering the chance of false treatments and improving the quality of healthcare. With the location information and daily movement pattern of a target patient, the proposed Bluetooth-enabled in-home patient monitoring system provides a feasible and promising platform for early detection of Alzheimer's disease. Nevertheless, in order for this e-healthcare solution to be successful, there are a number of issues such as security and privacy we need to address with vigilance.

The notion of electronic health records has been discussed for decades. Recently, the U.S. government has invested almost $20 billion on the digitization of patient files and creation of electronic healthcare tracking systems. In our proposed e-healthcare solution, the health data of a target patient is sent via the Internet to his medical practitioner (and an intelligent decision engine) for diagnosis, where the problem of privacy can arise. Some of a patient's health information might be eavesdropped during the data transfer; thus, his health records can be compromised. Personal healthcare information should be kept secure, and only authorized parties (e.g., his doctor and his caregivers) able to access those medical records. As a result, secure and reliable health data transfer is imperative and needs further investigation.

In our feasibility study we notice that the deployment of a Bluetooth AP is crucial to the success of our proposed in-home patient monitoring system. We observe that in some cases the strength of a Bluetooth signal is too strong (Fig. 5a). The implication is that we can opportunistically adjust the transmit power of a Bluetooth signal and/or strategically deploy a Bluetooth AP, thereby prolonging network lifetime and lowering implementation costs. On the other hand, if a room is quite large compared to the coverage area of a Bluetooth AP, the signal reception can be very weak (Fig. 5b), and the location of a target patient can be misconstrued. One possible solution is to set up multiple Bluetooth APs to cover such relatively spacious rooms at the expense of deployment costs. Nonetheless, configuring a cost-effective Bluetooth-enabled home network is imperative for practical implementation.

Despite the fact that elderly people are more likely to get Alzheimer's disease, Alzheimer's disease can also strike people in their 30s, 40s, and 50s [3], and those people are not expected to stay home most of the time every day. In an outdoor environment we can monitor a target patient by means of other location tracking technologies such as GPS, and location information can be captured and forwarded to a database (at a remote site) via a wireless mesh backbone [11]. As a consequence, integrating a GPS-based outdoor monitoring system and our proposed Bluetooth-enabled in-home monitoring system into a single platform is essential.

Although our proposed e-healthcare solution provides continuous and unobtrusive patient monitoring, there is no real-time interaction or *context awareness*[2] between a patient and his medical practitioner. As a matter of fact, our work can be extended to encompass the notion of context-aware interactive communications between both parties. In the extension, real-time feedback from an intelligent decision engine to a target patient is required. Besides, an alertable agent implemented in the decision engine responsible for context-aware computing is necessary. The basic function of this alertable agent is to interpret the currently received movement information of a patient with his medical/behavioral history, and execute a corresponding service. For example, the data collected by our in-home patient monitoring system shows that a target patient is currently in the bathroom, and

[2] *Context awareness is the capability of an application to be aware of the existence and characteristics of a person's activities and/or his surrounding ambience [2].*

there has been no movement for an abnormally long time (e.g., two hours). The patient is likely in need of urgent care (e.g., due to a stroke or heart attack). An alertable agent would trigger a command and execute a service autonomously such as disseminating emergency messages to his medical practitioner, his caregivers, and the closest hospital. All in all, designing such an autonomous alertable agent is fundamental to the success of any interactive e-healthcare solution.

Conclusions

With technological advances, e-healthcare solutions are expected to be prevalent in the near future, providing affordable, high-quality, and accessible healthcare to every person. In this article we propose a Bluetooth-enabled in-home patient monitoring system to facilitate early detection of Alzheimer's disease. With the help of short-range Bluetooth communications, the location and movement pattern of a patient can be tracked and recorded in a database. Thus, a medical practitioner is able to perform remote diagnosis via the Internet. Any persistent sporadic and irregular movements of a patient can be noticed and analyzed by an intelligent decision engine. Moreover, our feasibility study demonstrates that the proposed Bluetooth-enabled in-home patient monitoring system can be applied in practice. Further work and potential challenges of our proposed e-healthcare methodology are also discussed.

References

[1] I. Korhonen, J. Parkka, and M. Van Gils, "Health Monitoring in the Home of the Future," *IEEE Eng. Med. Bio.*, vol. 22, no. 3, May–June 2003, pp. 66–73.

[2] C. Doukas and I. Maglogiannis, "Intelligent Pervasive Healthcare Systems," *Studies Comp. Intelligence*, vol. 107, 2008, pp. 95–115.

[3] Alzheimer's Association; http://www.alz.org/

[4] L. D. Vittorini and B. Robinson, "Optimizing Indoor GPS Performance: Receiver Frequency Standards," *GPS World*, Nov. 2003, pp. 40–48.

[5] A. Harter *et al.*, "The Anatomy of a Context-Aware Application," *Wireless Net.*, vol. 8, no. 2, Mar. 2002, pp. 187–97.

[6] N. B. Priyantha *et al.*, "The Cricket Compass for Context-Aware Mobile Applications," *Proc. MobiCom '01*, July 2001, pp. 1–14.

[7] Bluetooth; http://www.bluetooth.com/

[8] In-Stat/MDR, "Bluetooth 2008: New Standards Signify an Increasingly Complex Market"; http://www.researchandmarkets.com/

[9] Lifeline; http://www.lifeline.ca/

[10] WidComm; http://www.widcomm.com/

[11] H. T. Cheng, H. Jiang, and W. Zhuang, "Distributed Medium Access Control for Wireless Mesh Networks," *Wireless Commun. Mobile Comp.*, vol. 6, no. 6, Sept. 2006, pp. 845–64.

Biographies

HO TING CHENG [S'05] (fhtcheng@bbcr.uwaterloo.ca) received his B.Eng. and M.Phil. degrees in information engineering from the Chinese University of Hong Kong in 2003 and 2005, respectively. He is a research assistant and currently working toward his Ph.D. degree at the Department of Electrical and Computer Engineering, University of Waterloo, Canada. His research interests include distributed resource allocation, quality-of-service provisioning, Medium access control, scheduling, call admission control, cross-layer design, wireless mesh networking, vehicular networking, and communication theory. He was the system administrator of *IEEE Transactions on Vehicular Technology* from April 2008 to December 2009.

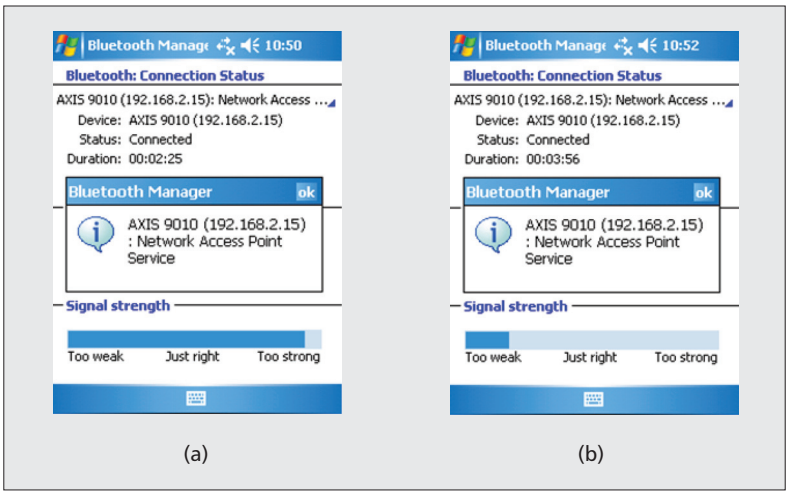


Figure 5. *Bluetooth signal reception: a) too strong; b) too weak.*

WEIHUA ZHUANG [M'93, SM'01, F'08] (wzhuang@bbcr.uwaterloo.ca) received her B.Sc. and M.Sc. degrees from Dalian Maritime University, China, and her Ph.D. degree from the University of New Brunswick, Canada, all in electrical engineering. In October 1993 she joined the Department of Electrical and Computer Engineering, University of Waterloo, as an assistant professor. She was promoted to the rank of associate professor with tenure in July 1997, and then to full professor in July 2002. Her current research focuses on resource allocation and QoS provisioning in wireless networks. She is a co-author of the textbook *Wireless Communications and Networking*, which has been published by Prentice Hall since 2003, and has been translated to Chinese and published by the Publishing House of Electronics Industry in China since 2004. She is a co-recipient of a Best Paper Award from IEEE ICC 2007, a Best Student Paper Award from IEEE WCNC 2007, and the Best Paper Awards from the International Conference on Heterogeneous Networking for Quality, Reliability, Security, and Robustness (QShine 2007 and 2008). She received the Outstanding Performance Award in 2005, 2006, and 2008 from the University of Waterloo for outstanding achievements in teaching, research, and service, and the Premier's Research Excellence Award in 2001 from the Ontario Government for demonstrated excellence of scientific and academic contributions. She is the Editor-in-Chief of *IEEE Transactions on Vehicular Technology*, and an Editor of *IEEE Transactions on Wireless Communications*, *EURASIP Journal on Wireless Communications and Networking*, and *International Journal of Sensor Networks*. She was TPC Co-Chair for the Wireless Networks Symposium of IEEE GLOBECOM 2008, Cross Layer Designs and Protocols Symposium of the International Wireless Communications and Mobile Computing Conference (IWCMC) 2007 and 2006, and the ACM Workshop on Wireless Multimedia Networking and Performance Modeling 2005. She is an IEEE Communications Society Distinguished Lecturer. She is a licensed Professional Engineer in the Province of Ontario, Canada. She is the Chair of the Vehicular Technology Chapter, IEEE Kitchener-Waterloo Section.