A Distributed Cyber-based Information Distillation and Control Architecture for Wireless Healthcare Systems

Haiying Shen, Ze Li and Linlin Yang
Department of Computer Science and Computer Engineering
University of Arkansas, Fayetteville, AR 72701
{hshen, zxl008, lxy006}@uark.edu

ABSTRACT

Cyber-physical space, characterized by the seamless integration of wired and wireless networking technologies, embedded computer systems, sensor and actuator technologies, enable ordinary people to richly interact with their environment. The health-care domain presents many promising applications for cyber-physical space, such as patient information management, real-time emergency reporting, elder living assistance, etc. However, although many component technologies needed for realizing such a health-care based cyber-physical space are available, a robust and effective architecture with novel management protocols implemented which synthesizes these separated components to cooperatively work in a predicted way is missing. In this paper, we propose a distributed, and effective heterogeneous architecture to make up such a gap, emphasizing on patient information retrieval, real-time monitoring and instant reactions.

Categories and Subject Descriptors

C.1.3 [**Other Architecture Styles**]: Heterogeneous (hybrid) systems

General Terms

Design

Keywords

Cyber-physical system, Wireless sensor networks, Information management, Distributed hash table, Health care

1. INTRODUCTION

An efficient information management system is very important for health care agency. When a surgeon needs to easily fetch some similar case histories required for surgery to study how to improve operations, he/she has to go to the computer center or depository to find many cases; when a patient needs to be examined by the physician on regular basis, he/she has to go there frequently. However, the rapid growth of technology in wireless sensor networks offers a promising future for Cyber-Physical Space (CPS) systems, with which doctors and patients are not required to go to hospital but only need to type some words on computers or wireless devices.

The polluted environment and increasing aging population result more and more medical problems, especially chronic diseases for elders. Also people need to pay more and more to keep healthy. According to the CDC [1] (Centers for Disease Control and Prevention), in 2005, 133 million people, almost half of Americans lived with at least one chronic condition; chronic diseases account for 70% of all deaths in US; the medical care costs of people with chronic diseases account for more than 75% of the nation's 2 trillion medical care costs; chronic diseases account for one-third of the years of potential life before age 65. Most chronic diseases could be controlled if earlier treatment is adopted and a lot of death can be exempt if they can find unusual symptoms earlier. We live in an environment equipped with a network of sensors, computing devices and wireless devices, which can provide information from everywhere and process them to form a CPS system to support many applications and services. Obviously, adopting CPS would save lots of life and save a lot of money, since the symptoms could be found in home and most people do not need to live in hospitals, while living there is more expensive than living in the best hotels.

To realize a CPS system, a wireless sensor network is needed to collect all the information needed. Most of the wireless technologies could be used, including Radio Frequency (RF), WiFi, and Bluetooth, to construct the wireless sensor network. Users (doctors, nurses, patients) can hold a wireless device to monitor the medical status, based on the real-time measurement generated by the sensors attached on patients' bodies, and the patients' data are extremely useful for future research and experiments. Advanced technologies in manufacturing, computing and energy-saving are making the system more and more efficient, easier and safer. There have been considerable amount of research to build up a CPS system, but they are all with a centralized structure, owing a high computing capacity and large storage space to store most of the data. They also have excellent performance if used in a small hospital or a clinic; also it is high risk to keep all the data in a centralized space; furthermore, as the databases become increasingly larger, information retrieval will be more and more difficult to deploy. In this paper,

WiMD'09, May 18, 2009, New Orleans, Louisiana, USA.

we propose a Distributed CPS system (DCPS) architecture based on a Distributed Hash Table (DHT), focusing on real-time monitoring and instant reaction, information retrieval, object tracking and schedule noticing. In DCPS, every person associated with the hospital has a personal database for information management. Based on the DHT structure, the patients' databases are stored in the distributed base stations. The real-time health monitoring information of a person and his/her objects (e.g. keys, wallets, medicine) location information are stored in the database for emergency reaction and future reference.

The rest of the paper is presented as follows. Section 2 presents the related work. Section 3 specifies our DCPS system for medical health care. Section 4 discusses performance evaluation and Section 5 concludes the paper.

2. RELATED WORKS

The System for the health care can be traced back from simple pulse monitors [2], activity monitors [3], and portable Holter monitors [4]. However, these systems are just servers' static data collectors, which can provide real time data processing, analysis and emergency alarm. In [5], E. Javanov et. al. presented the system WISE, Wireless Intelligent SEnsors, in which the patient was equipped with a set of wireless sensors. Each sensor measures a specific vital signal and then sends the data to the personal server that communicates with a Telemedical server to report emergencies. T. Martin also presented a case study in [6] about a wearable electrocardiogram (ECG) and pointed out the issues they faced. However, in these systems, the individual sensors are operating separately, without the integration with third-party devices. Recent technology advances in embedded system, wireless sensor networking and micro-fabrication have enabled a new generation of wireless sensor networks for habitat monitoring [7, 8, 9]. In these system, the collected data can be continuously transmitted to sinks for further data process and analysis. But they failed to provide an interactive action. The WWBAN [10] consisting of inexpensive sensors provide a long-term health monitoring with instantaneous feedback to the user about their health status. Such instantaneous feedback can provide information for the nurse and doctor for a real time monitoring to avoid catastrophic events.

CPS provides a closed interaction with ordinary people with embedded systems. Health care system is also a main application of the CPS to enable patients and elders to receive real-time medical care from the doctors and nurses. Hou et al. in [11] proposed an example reference architecture for building cyber-physical space to assist elders for independent and assisted living. In [12] a three-tiered architecture was introduced to construct a CPS system for health monitoring, and similarly [13] also presented a more widely used three-tiered architecture in a strongly centralized way. Additionally, improvement and optimization are introduced to make CPS systems better and more robust. In [14] G. Virone et al. proposed a smart health care system targeting assisted-living residents and others who may benefit from continuous, remote health monitoring, while H. Baldus et al. in [15] realized a medical body sensor networking covering a set-up procedure to provide a reliable and easy system. ALARM-NET in [16] also showed a mature and robust system suitable for health care in a centralized way. H. Wang et al. presented a search engine named Snoogle to search for small objects labeled with small tags in [17], but it is still a centralized solution. In this paper we propose a three-tiered system to form a CPS system. Unlike the previous highly centralized CPS systems as [12, 13, 16], we use a fully distributed DHT-based system for efficient data management, emphasizing the real-time monitoring and reacting.

3. DISTRIBUTED CPS SYSTEM FOR MEDICAL HEALTHCARE

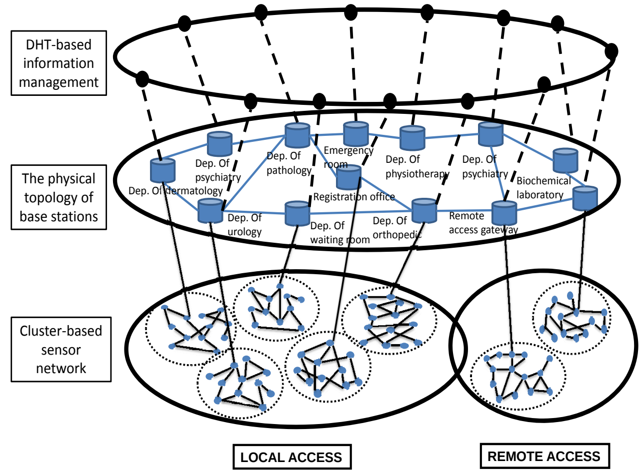

Figure 1: Network layers of DCPS.

3.1 Architectural requirements

To meet our application needs, the architecture has to fulfill the following architectural requirements:

(1) *DHT-based distributed computing*: The traditional server and client structure is easy to form a hot spot at the center server. Meanwhile, if a server crashes down, the real time monitoring and instant reacting requirement of the health care applications cannot be satisfied. The flooding based distributed system leads to high overhead and huge signal interference to medical devices. Our DHT-based solution organizes the computing and storage capacity of individual computers and clusters based sensing resources in an efficient way.

(2) *Instant reactions enabled*: The system should react instantly to some emergency and unexpected events. Our real-time data collecting, data processing, file indexing and database management guarantee the system to offer instant reactions.

(3) *Scalability and openness*: Our system is not only designed for small medical institutions, but also be easily incorporated into large scales and open to outside users who can connect with hostile's LAN via WLAN. With the help of DHT structure, scalability and openness features of CPS are easily realized.

3.2 System components

DCPS consists of sensors and base stations. Sensors in DCPS can be classified into two categories. One category is called medical sensors [2, 3, 4]. Such sensors are used for collecting physical and health information of the patients. Such medical sensors can configure with a RFID tag to uniquely identify the sensor hosts. Such ID can be host's consistent hash value of the email address and so on. Another kind of sensor is called communication sensor [18]. The communication sensors are implemented with two interfaces. One is the cellular interface which can receive the message from cellphone, while the other one is IEEE ad-hoc interface that can receive message from lap-top, WiFi, bluetooth. Such sensors are deployed around the hospital to receive the information collected by the medical sensors or information queries from users. The physically closed communication sensors are clustered together and can connect to a base station sink. These base station sinks construct a DHT for efficient information storage. Figure 1 shows the three-tiered architecture of DCPS system. The lower tier consists of sensors, which are classified into different clusters and each cluster connects to a Base Station (BS). On the upper layer, BSs receive data from sensors and constitute the DHT for efficient message storage and query. The people associated with hospital have their own database which store their profile, disease history or even real time medical monitoring information. Users, including patients, doctors, nurses and patients' relatives, in the system may use PDAs, cell phones or laptops to query, search or retrieve information.

3.3 Data processing and storage

Medical sensors attached on patients measure data about the patients' symptoms like body temperature and heart rate, and these data are then transmitted to nearby communication sensors. Communication sensors relay data to the corresponding BS. Then the BS processes these data and stores them in the space where the patient's ID is hashed. The medical sensors could be configured to transmit one value per minute, or ten values per minute, according to the condition of the patient. If the illness is severe, data could be sent more frequently. Additionally, we affix some description key words (metadata) on the ID, describing the patient's symptoms, such as headache, snivel and sneeze. These metadata are used to facilitate information retrieval.

For every patient, the doctor will make a schedule telling the patient to take pills or treatments on time. After the schedule file is created, it will be added in the patient's database. The patient will also tag his/her personal items with wireless sensors and create a personal item file in his/her database. BSs perform the following data operations in users' databases.

Creation: When a new patient comes to the hospital, a new ID is hashed from the email address or social security number. Then the user's database is created and stored in a BS according to this ID.

Insert: When receiving new medical data from sensors, the BS will process them and write them in the file. Then an "Insert" operation is performed to record the file into the patient's database.

Delete: The patient's personal items are changing from time to time. If the patient's personal items are discarded or given to others, the personal item file will be deleted. If the patient asks for deletion of sensitive information in the files, "Delete" will be used, too.

Update: When a doctor or nurse issues a new schedule, or when new descriptions need to be added in the metadata, a user's database is updated. When a new schedule is given, the previous one is updated. When this happens, BS will also send notice messages to the user, until the change is confirmed.

3.4 DHT-based information management

The DHT-based infrastructure comprised of base stations. It constitutes a reliable and stable backbone at the center of the heterogeneous network. To build a DHT-based infrastructure network for the efficient data management, we use the base station's IP address as its DHT ID, and assign an ID to a patient by hashing patient unique ID name (e.g. email-address) using consistent hash function. Since the hash function is collision-resistant, it would not result the same hashed value for a node and its reputation information. As a result, base stations are connected as nodes in DHT networks, in which each base station serves a sink to a clustered physically closed wireless sensors. This ID is the index (primary key) of patient's information.

After a base station receives sensed information from its underlying sensor cluster, the base station forwards the information to another base station which is responsible to store the information using `Insert(key,object)` function. The information of a patient is indexed using his RFID tag ID. Based on DHT key assignment policy, each patient's information will be stored in its owner database resided in the base station satisfies d:d=min(B.ID-N.ID) and d>0, where B.ID is the DHT ID of the base station and N.ID is the DHT ID of the node. Meanwhile, DCPS can also facilitate data query. For example, if a doctor wants to query for a patient's information, he/she can use a cell phone, PDA, lap top to issue a query message and send it to the closest sensor. The sensor sends the message to the cluster sink. The sink uses a `Lookup(key)` function to sent request with the hashed value of patient's ID. Using DHT routing algorithm, the request will be forwarded to the base station that stores the information database of the patient. In addition to the primary

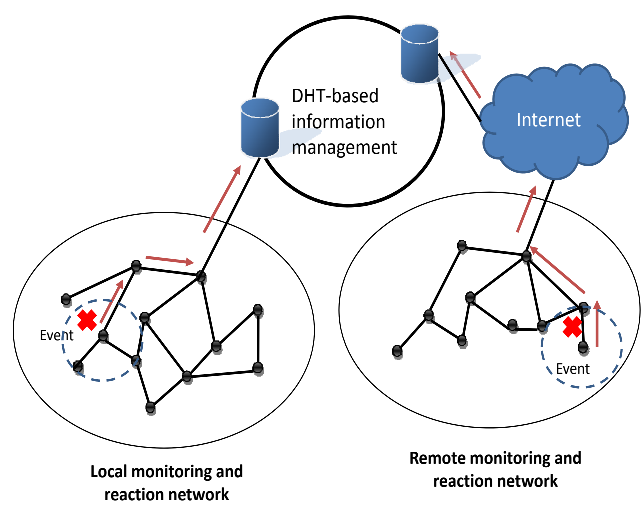

Figure 2: Event monitoring and reacting.

query, DCPS can also issue other DHT based queries. The intuitive idea is to store a replica of the original file based on another keyword. However, such a method brings other problems such as file consistency, file security and increased system storage. In order to solve this problem, a metadata is used to represent the patient's original file for efficient data search. A metadata has a form as `(keyword, primary key)`. The metadata is stored based on the keywords. After a query about the keywords is issued, the metadata can be found using `Lookup(keyword)` function. Based on the primary key in the metadata, the information of the patients can be retrieved using `Lookupkey` function again.

If a researcher wants to investigate the relationship between pneumonia and patients's case histories, he/she can input key words like 'pneumonia' to search in the system. The IDs whose metadata contain this word are found. The research could then search the ID in DHT and read the corresponding database.

3.5 Real-time monitoring

The medical sensors constantly generate new measurements. When a measurement is out of threshold, an event is evoked and is broadcasted to all nurses nearby. This message is also sent to BS and recorded in the file. BS also sends this message to the corresponding doctor. The nearest nurses are notified to check what happened and the doctor will also take actions if necessary. When an elder falls on the ground, the acceleration sensor on his/her body will sense an unusual value, and the horizon-vertical sensor senses a 'horizon' value. If the 'horizon' value lasts for a relatively long time, the sensors generate a 'fall' message and the message is immediately broadcasted to the nearest nurses. BS sends emergency messages to all wireless devices held by the nurses in this cluster and the patient to remind him/her.

Moreover, we provide a schedule noticing function to patients. It is quite common that a patient could not keep the schedule in mind all the time, especially for the elders. However, if they receive a notice every time they need to keep the schedule on treatment appointment or taking pills, it is not likely that they would miss them. The wireless portable device hold by a patient is able to provide voice, vision and vibration notice. Once a time point arrives, the patient is noticed to take actions until it is confirmed. If a patient needs to have a treatment at 2:00pm, the task will be stored in the schedule file and shown to the patient. When the time is approaching 2:00pm, the BS generates a noticing message and sends it to the patient. The wireless device hold by the patient receives the message and then alarm the patient to take actions until the alarm is confirmed.

4. PERFORMANCE EVALUATION

Since the DHT-based data management system is the central part of the system, in this section, we will evaluation this performance compared with snoogle [17], a centralized information management system. However, since the novelty and significant contributions of snoogle system are not the centralized data managements but the information retrieving technique, we do not claim our system is better than snoogle. However, our distributed data management can be an alternative choice to improve its data management efficiency.

We design and implement a simulator in Java to evaluate the DCPS based on Chord [19] with nodes as dimension 3, 4, 5, 6, 7, 8, respectively. A node with dimension n indicates the total number of nodes in the system is 2^n. We choose overhead in the application layer and network layer as the landmark for the performance evaluation, because the number of overhead can reflect the power consuming, resource consuming and routing efficiency. Meanwhile, since the communication devices may affect the ability of the medical devices to function properly and the resultant safety of patients and operators, because of the signal interference. Less overhead leads to less packet transmission which subsequently leads to less signal interference with the nearby medical devices.

Figure 3 shows the average destination routing hops of DCPS compared to the Snoogle in the application layer. The figure shows that since the Snoogle should query all the nodes nearby to get the information they need, the query hops are very high. On the other hand, based on the DHT structure, DCPS send the query message in a determined manner within O(log(n)) hops. Therefore, the number of query hops is much smaller.

Figure 4 shows the actual routing overhead of DCPS compared to Snoogle in the network layer. Although unlike the Snoogle which stores the information locally, DCPS should publish the file to another base station according to DHT routing algorithm, the routing overhead of DCPS is still much less than the flooding based Snoogle. More specifically, in the DCPS, although the DHT overlay is not consistent with underlying topology, that is the packet may transfer more hops than its shortest path to the destination. However, compared to the flooding based query, the total path length is still shorter.

5. CONCLUSION

CPS for medical healthcare promises a close interaction between the advancing computing technologies and people involved in to improve the working efficiency of the doctors and nurses and provides a ubiquitous medical healthcare for patients or disabled people. Although many component technologies needed for realizing such a CPS system are available, a central architecture to organize them together is missing. In this paper, we propose a distributed Cyber-based information distillation and control architectures for Wireless Healthcare System. This system provides, real-time monitoring and reacting and distributed data management.

Acknowledgments

The authors are grateful for the help of Baha Alsaify and Anirudh Ladha in writing this paper. This research was supported in part by U.S. NSF grants CNS-0834592 and CNS-0832109.

6. REFERENCES

[1] Chronic disease overview. http://www.cdc.gov/nccdphp/overview.htm.

[2] Seiko pulse graph wrist watch. http://www.seiko-pgt.or.jp/ (Japanese).

[3] Digi-Walker step counter. http://www.digiwalker.com.

[4] Holter systems. http://med-electronics.com/.

[5] E. Jovanov, D. Raskovic, J. Price, J. Chapman, A. Moore, and A. Krishnamurthy. Patient monitoring using personal area networks of wireless intelligent sensors. *Biomedical Sciences Instrumentation*, 37:2001, 2001.

[6] T. Martin, E. Jovanov, and D. Raskovic. Issues in wearable computing for medical monitoring

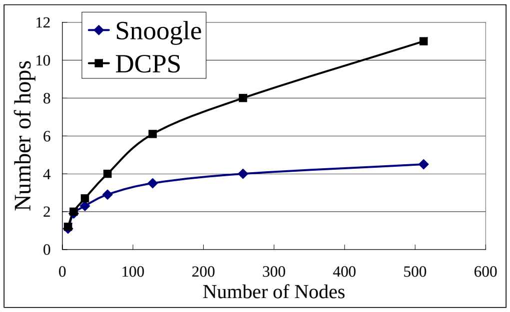

Figure 3: The number of transmission hops.

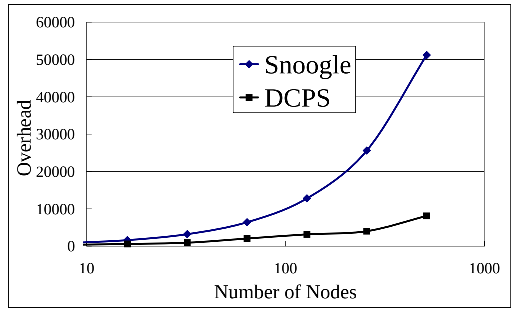

Figure 4: Transmission overhead.

applications: A case study of a wearable ecg monitoring device. *Wearable Computers, 2000. The Fourth International Symposium on*, pages 43–49, 2000.

[7] R. Szewczyk, E. Osterweil, J. Polastre, M. Hamilton, A. Mainwaring, and D. Estrin. Habitat monitoring with sensor networks. In *ACM communication*, 2004.

[8] Z. Li, H. Shen, and B. Alsaify. Integrating RFID with wireless sensor networks for inhabitant, environment and health monitoring. In *Proc. of IEEE International Conference on Parallel and Distributed Systems*, 2008.

[9] E. Jovanov, A. Lords, D. Raskovic, P. Cox, R. Adhami, and F. Andrasik. Stress monitoring using a distributed wireless intelligent sensor system. *IEEE Engineering in Medicine and Biology Magazine*, 2003.

[10] E. Jovanov, A. Milenkovic, C. Otto, and P. C. de Groen. A wireless body area network of intelligent motion sensors for computer assisted physical rehabilitation. *IEEE Engineering in Medicine and Biology MagazineJournal of NeuroEngineering and Rehabilitation*, 2005.

[11] J. C. Hou and L. Sha. A reference architecture for building cyber physical space for independent/assisted living. October 2006.

[12] A. Milenkovi, C. Otto, and E. Jovanov. Wireless sensor networks for personal health monitoring: Issues and an implementation. 29(13-14):2521, 2006.

[13] C. Otto, A. Milenkovi, C. Sanders, and E. Jovanov. System architecture of a wireless body area sensor network for ubiquitous health monitoring. *Mobile Multimedia*, 1(4):307–326, 2006.

[14] G. Virone, A. Wood, L. Selavo, Q. Cao, L. Fang, T. Doan, Z. He, and J. Stankovic. An advanced wireless sensor network for health monitoring. Distributed Diagnosis and Home Healthcare (D2H2), April 2006.

[15] H. Baldus, K. Klabunde, and G. Morch. *Wireless Sensor Networks*, volume 2920, Chapter Reliable Set-Up of Medical Body-Sensor Networks, pages 353–363. Springer Berlin / Heidelberg, January 2004.

[16] A. Wood, G. Virone, T. Doan, Q. Cao, L. Selavo, Y. Wu, L. Fang, Z. He, S. Lin, and J. Stankovic. Alarm-net: Wireless sensor networks for assisted-living and residential monitoring. Technical report, Department of Computer Science, University of Virginia, 2006.

[17] H. Wang, C. Tan, and Q. Li. Snoogle: A search engine for the physical world. *INFOCOM 2008. The 27th Conference on Computer Communications. IEEE*, pages 1382–1390, April 2008.

[18] RF characteristics of Mica-Z wireless sensor network motes. http://oai.dtic.mil/.

[19] I. Stoica, R. Morris, D.L. Nowell, D.R. Karger, F.F. Kaashoek, F. Dabek and H. Balakrishnan. Chord: A scalable peer-to-peer lookup protocol for Internet applications. *IEEE/ACM Trans. Netw.*, 1(1):17–32, 2003.