Cloud-Enabled Wireless Body Area Networks for Pervasive Healthcare

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Abstract

With the support of mobile cloud computing, wireless body area networks can be significantly enhanced for massive deployment of pervasive healthcare applications. However, several technical issues and challenges are associated with the integration of WBANs and MCC. In this article, we study a cloud-enabled WBAN architecture and its applications in pervasive healthcare systems. We highlight the methodologies for transmitting vital sign data to the cloud by using energy-efficient routing, cloud resource allocation, semantic interactions, and data security mechanisms.

Due to several recent technological advances and new concepts, such as wireless body area networks (WBANs) and low-power wireless communications, pervasive health monitoring and management services are becoming increasingly popular. However, efficient management of the large number of monitored data collected from various WBANs is an important issue for their large-scale adoption in pervasive healthcare services. Since WBANs have limited memory, energy, computation, and communication capabilities, they require a powerful and scalable high-performance computing and massive storage infrastructure for real-time processing and data storage, as well as for online and offline data analysis [1]. Mobile cloud computing (MCC) is gradually becoming a promising technology, which provides a flexible stack of massive computing, storage, and software services in a scalable and virtualized manner at low cost [2]. The integration of WBANs and MCC is expected to facilitate the development of cost-effective, scalable, and data-driven pervasive healthcare systems, which must be able to realize long-term health monitoring and data analysis of patients in different environments.

In MCC, mobile devices do not need a powerful configuration, such as high CPU speed or large memory capacity, since their data and complicated computing modules can be stored and processed in the cloud. The seamless integration of WBANs and MCC introduces several advantages, which include:

- *Richer functionalities and services*: With MCC capabilities, a wider range of services, including more medical video streaming and medical data mining (MDM) can be provided to meet richer application requirements.
- *Performance efficiency*: Since the resource constraints mobile devices and network bandwidth limitations in WBANs have hampered further improvement of service quality and large deployment of mobile pervasive services, the mobile services and cloud servers are considered as a whole to enhance the performance efficiency of pervasive healthcare applications in terms of computation, storage, communications, and energy.
- *Patient-centric services*: Since WBANs are evolving to enable a highly flexible and scalable infrastructure for mobile services assisted by cloud computing, MCC applications can be designed in such a way that patients can control their own data and activities with strong privacy and security protection.
- *Reinforced reliability*: Since medical data from a patient is stored on multiple servers in the cloud, even if some data is lost in the mobile device there are still backup copies in the cloud. Furthermore, when the battery of a mobile device dies, the applications can still continue running in the cloud without interruption.

Nevertheless, the research into cloud-enabled WBAN platforms (also called wMCC platforms) is still in its infancy, several technical issues and challenges are to be addressed in order to fulfill the research promises. For example, the supporting functionalities of cloud services need deliberate categories and designs according to application requirements in different environments. Current studies related to wMCC platforms focus on architectural design to realize a health monitoring and analysis system.

The remainder of this article is organized as follows. We first discuss the importance of WBANs with MCC support. We then study WBAs architecture with MCC capability, which must be able to provide convenient, reliable, and richer cloud services. We further emphasize the crucial methodologies for improving the quality of service (QoS) of the wMCC platform. Finally, we offer concluding remarks and suggestions for future research.

Developing WBANs with MCC Capability

WBANs have emerged as an indispensable technology for pervasive healthcare. They collect patients' vital signs and movements using miniaturized wearable or implantable sen-

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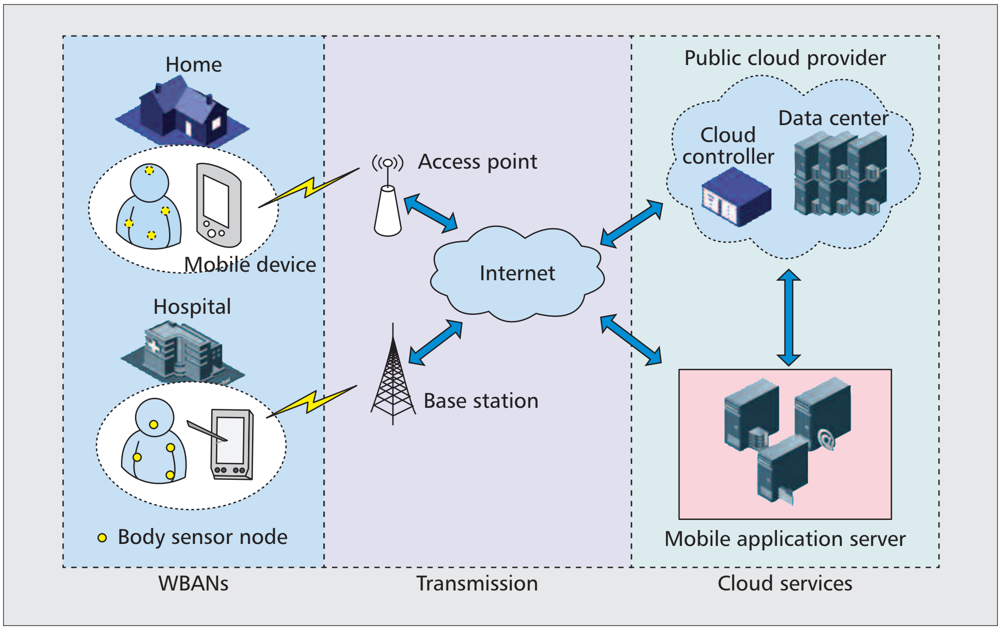

Figure 1. *Conceptual architecture for WBANs with MCC capability.*

sors and forward this information to medical servers or physicians [3]. Because of MCC's elasticity, scalability, and pay-as-you-go pricing model, it can potentially provide huge cost savings, flexible high throughput, and ease of use of WBAN services.

New mobile applications for pervasive healthcare can be rapidly provisioned and released using MCC with minimal effort. We consider MCC technology to highlight some innovative applications, including mass medical data storage and MDM for pervasive healthcare with richer mobile video streaming, more supporting functionalities, and more reliable QoS. The development of WBANs with MCC capability is based on two observations as follows:

- *MCC benefits*: MCC inherits many benefits of cloud computing such as dynamic provisioning, scalability, and ease of integration, as well as of a mobile network, such as seamless mobility. We can develop and deploy numerous mobile applications for pervasive healthcare, which can access larger and faster data storage services and processing power from the cloud. Furthermore, MCC can improve the reliability and security of mobile applications, where the data and computation can be backed up in the medical cloud.
- *MCC applications*: Many mobile applications including mobile commerce, mobile learning, and mobile gaming have been developed for diverse MCC environments. As an example, a prototype of a mobile healthcare information management system based on cloud computing and a mobile terminal running an Android operating system is being implemented. This prototype platform is developing services that utilize the Amazon S3 cloud storage service to manage patient health records and medical images [4]. All these examples have provided some useful references, and have established the foundation for incorporating MCC capabilities into WBANs.

Figure 1 shows the conceptual architecture of WBANs with MCC capability. The mobile devices serve as gateways for WBANs, and access the Internet via WiFi or cellular networks to coordinate with application servers or locally make decisions on the offloading strategy. The mobile devices will then offload the healthcare tasks to the cloud accordingly. Once the requests from patients or mobile application servers have been received, the cloud controllers will schedule the healthcare tasks on virtual machines (VM), which are rented by application service providers, and return the results. In some situations, the application servers can also be deployed in the cloud.

A Pervasive Healthcare System with MCC Capability

This article designs cloud-enabled WBANs to provide three types of scenarios (home, hospital, or outdoor environment) for ambulatory monitoring, and support a point of care to patients, the elderly, and infants in different environments. In this section, we propose a framework for a pervasive healthcare system with MCC capability, and focus on cloud-enabled WBAN architecture and system functionalities.

Cloud-Enabled WBAN Architecture

Figure 2 depicts a framework for a pervasive healthcare system with MCC capability. This system is composed of four main components: WBANs, wired/wireless transmission, cloud services, and users. WBANs collect various vital signals such as body temperature or heart rate information from wearable or implantable sensors. The collected monitored data are processed in the cloud and then selectively transmitted to the users. The medical video streaming from cameras are transmitted to the adjacent routing equipment via wired or wireless transmission, and then to the cloud server via the Internet. Cloud servers possess powerful VM resources such as CPU, memory, and network bandwidth in order to provide all kinds of cloud services such as automatic diagnosis and alarm, geographical information system (GIS) services, location-based services, and medical decision making (MDM). Different users such as hospitals, clinics, researchers, and even patients ubiquitously acquire multiple cloud services by a variety of interfaces such as personal computers, TVs, and mobile phones. This enables the sharing of monitored data to authorized social networks or medical communities to search for personalized trends and group patterns, offering insights into disease evolution, the rehabilitation process, and the effects of drug therapy.

While some attempts have been made to integrate WBANs and MCC to improve pervasive healthcare services, the existing work has had limited success in developing a clinically effective system; therefore, the full potential of this integrated technology remains unutilized. In the following section, we identify several key issues we believe must be addressed in order to enable large-scale pervasive healthcare services and applications.

For the proposed architecture, we further stress the following three important aspects: the inclusion of communication standards for WBANs, the use of hybrid clouds in the wMCC platform, and the authorized social networks for analyzing the trends.

- *Communication standards for WBANs*: One of the critical issues in WBANs is low power consumption, which gives rise to some constraints in the communication standards and protocols. A number of protocols and standards are available for communication between nodes in WBANs, such as Bluetooth over IEEE 802.15.1, Zigbee over IEEE 802.15.4, UWB over IEEE 802.15.6, Insteon, Z-Wave, ANT, RuBee, and radio frequency identification (RFID) [5].
- *Hybrid clouds*: In general, a hybrid cloud computing architecture can accelerate the migration from existing IT resources in hospitals to cloud computing, make full use of WBAN resources, and reduce costs. Important medical data and applications such as GIS deployment can be deployed on a local private cloud to guarantee security, while operations related to system development, upgrade, and testing can be carried out on a public cloud. Moreover, when there are not enough resources on the local private cloud at the peak load time, some work can be switched to the public cloud.
- *Social networks*: The wMCC platform will increasingly incorporate the analysis of social networks into pervasive healthcare analytics. The research contents of WBANs introduced into social networks include not only epidemiological studies but also analysis modeling of patient communication and education, disease prevention, mental health diagnosis and treatment, and the study of healthcare organizations and systems.

Cloud-Enabled WBAN Functionalities

As shown in Fig. 2, the medical condition of a patient can be monitored as determined by the corresponding healthcare system, and subsequently updated in the cloud by means of a smart phone, a WiFi connection, or something similar, according to the patient's location (e.g., home, hospital, or outdoor environment). Any abnormalities that do not require immediate treatment may be logged into the cloud and registered by the patient's ID for future reference. Because of MCC support and the improved communication bandwidth, doctors or other caregivers can communicate with patients directly by mobile devices in the form of medical video streaming. If needed, the patient can then be asked to visit the healthcare facility.

The user's profile and medical history data are maintained by the management center of the local private cloud. According to a user's service priority and/or doctor's availability, the doctor may access the user's information as needed. At the same time, automated notifications can be issued to his/her relatives based on this data via various telecommunication means. Besides these basic services, the cloud services also provide GIS deployment, medical data storage, MDM, virtual resource optimization management, and so on. With cloud support, the mobile devices of medical staff will easily exhibit richer mobile video streaming from remote cameras.

From a cloud computing research perspective, we specifically consider the following aspects: massive medical data storage, optimization and management of virtual resources, semantic interactions, and search of medical information. The key technologies in semantic analysis include the establishment of medical knowledge bases, ontology technology, semantic reasoning, capturing the real intention of patient messages, semantic data mining technology, and hidden information discovery by means of parallel semantic reasoning. MapReduce technology and distributed file system represented by the Hadoop Distributed File System (HDFS) are used in a parallel reasoning method based on cloud computing [6].

The logic flowchart of a pervasive healthcare system with MCC capability is given in Fig. 3. We focus on supporting function designs for patients in different locations and using different MCC services:

- *Home*: For the patient at home, we can obtain real-time location information by various wireless location methods such as time difference of arrival (TDOA) and time of arrival (TOA), and further determine patient activity by data fusion technology. To provide better services, we should install cameras connected to diverse high-speed communications, such as ultra wideband (UWB) and 60 GHz millimeter wave, to store medical video streaming in the cloud and provide richer multimedia contents for users.
- *Outdoor environment*: In general, a smart phone is used to gather and deliver the patient's physiological data information to the cloud for outdoor patients. When an accident happens, immediate family, a doctor, or a nurse are immediately informed, and they attempt rescue according to the GPS location. Also, if a patient falls seriously ill, they can conveniently request help.
- *Hospital*: Using GIS for hospitals with a local private cloud, doctors or caregivers can quickly obtain the location information and physiological data of the patient by various smart terminals such as smart phones or personal digital assistants (PDAs).

Research Directions for QoS Improvement

We propose four research directions for QoS improvement in wMCC platforms, including the development of routing protocols to support efficient data transmission to the clouds, cloud resource allocation, semantic interactions, and data security and privacy mechanisms.

Reliable and Energy-Efficient Routing Protocols for WBANs

Reliable routing protocols for WBANs must support multihop communication and provide low end-to-end delay, low packet drop rate, and low energy consumption. Because patients' conditions change continuously and may cause massive mobility issues, new routing protocols may offer numerous methods to solve these issues. After investigating proactive, reactive, and hybrid routing protocols for WBANs, we focus on temperature, cluster-based, and cross-layer routing solutions.

Temperature routing focuses on the effects of tissue heating on the human body and their consequences during multihop communication. One of the approaches to reduce tissue heating is to minimize the transmission power and traffic rate. Another approach is to always avoid high-temperature nodes when forwarding data packets. The Thermal-Aware Routing Algorithm (TARA) adopts this approach, but has a high packet drop rate and low reliability. An alternative solution is to select the lowest-temperature route (not necessarily the next hop) to forward the data packets, and provide low packet loss and high reliability.

For sparse WBANs, clustering is considered as done in Low Energy Adaptive Clustering Hierarchy (LEACH) architecture. Although conventional LEACH aggregates data from

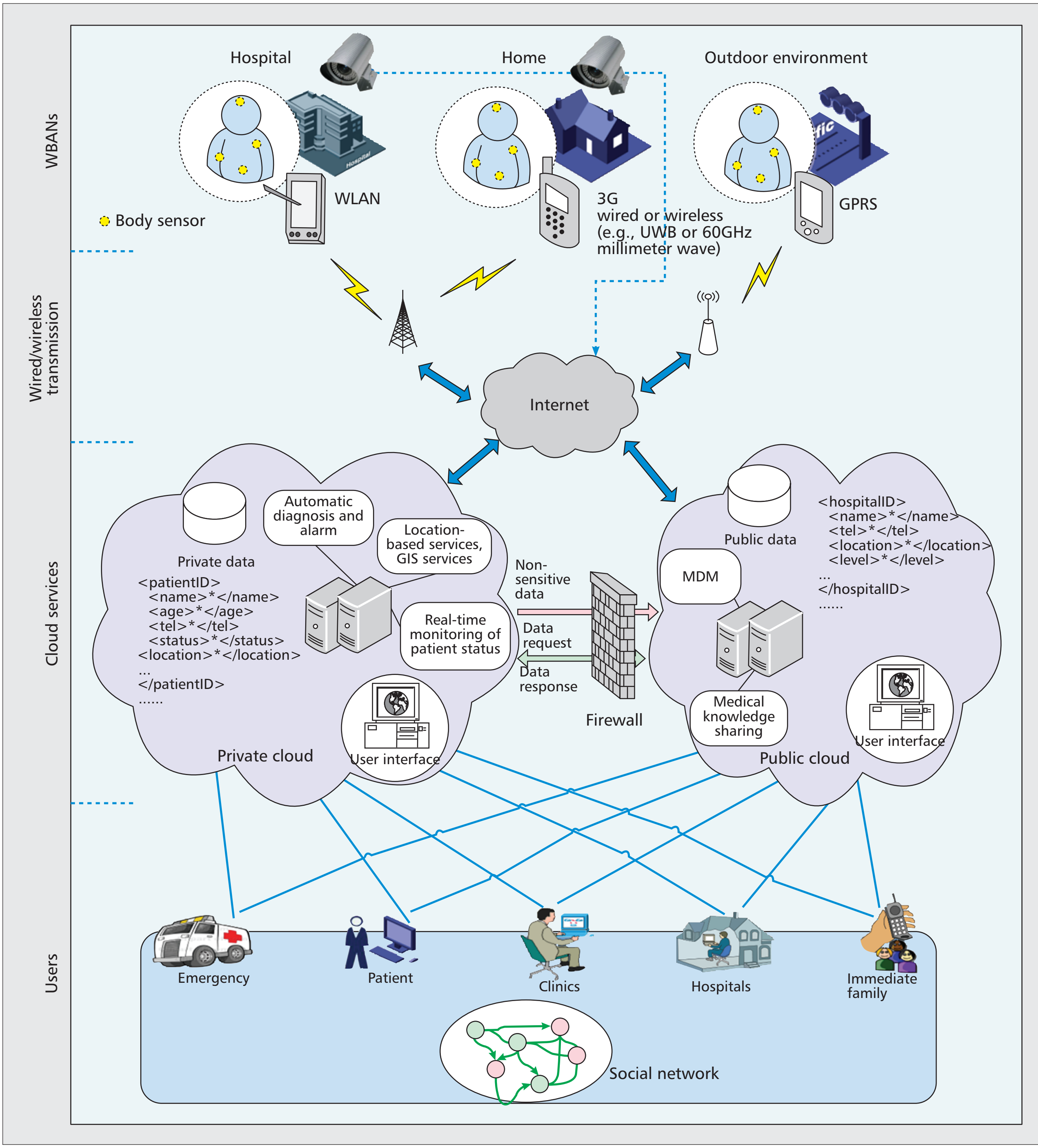

Figure 2. *A framework for a pervasive healthcare system with MCC capability.*

cluster heads, it is extremely unreliable for WBANs. Cross-layer solutions are proposed to solve this problem. Much of the research on cross-layer routing solutions considers IEEE 802.15.4 at the medium access control (MAC) and physical layers [7]. However, IEEE 802.15.4 is not suitable for WBANs for many reasons, including its limited data rate and high energy consumption. The future cross-layer routing protocol may partially consider the IEEE 802.15.6 MAC protocol. Because the IEEE 802.15.6 MAC protocol is solely designed for WBANs, adding an efficient routing protocol at the network layer will increase network performance by connecting the nodes that are in the line of sight. This may ultimately decrease the packet drop rate and average energy consumption. Because these protocols can decrease the packet drop rate and end-to-end delay, they must be able to ensure efficient data transmission to the wMCC platform.

Cloud Resource Allocation Mechanisms

Developing scalable, energy-efficient, and cost-effective VM resource allocation mechanisms is a hot research topic. The basic concern of VM allocation is that a physical machine must have sufficient capacity to host VMs [8]. Generally, two

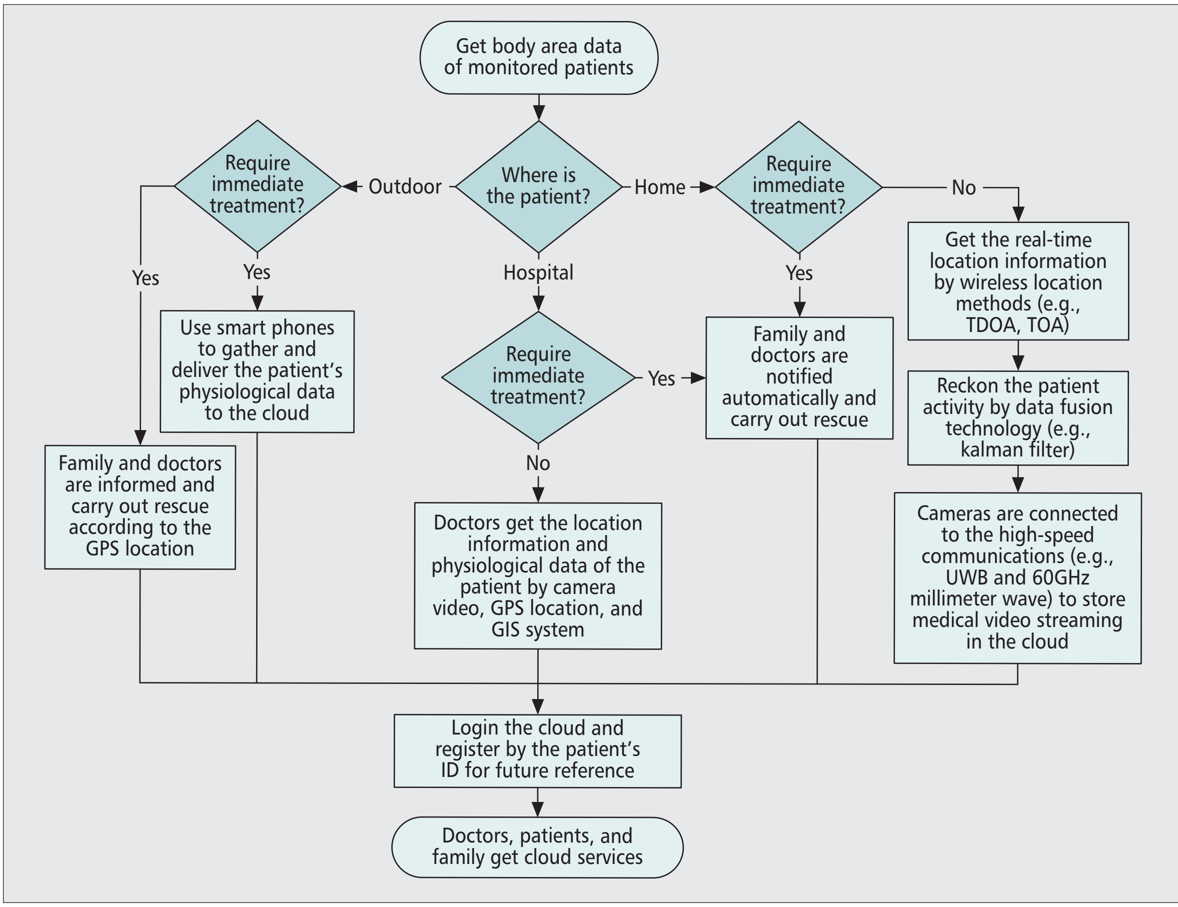

Figure 3. *Logic flowchart of a pervasive healthcare system with MCC capability.*

methods are used to solve the VM resource allocation problem. The first method is to design a linear programming (LP) model that optimizes VM allocation using cost objectives and constraints on the resource utilization condition, CPU utilization, energy consumption, and delay of services. The second approach is to use different heuristics by generating candidate allocation schemes and selecting the best among them.

Semantic Interactions

In extreme heterogeneous cloud-enabled WBANs, all kinds of resources, such as bandwidth, computing, storage, software, and data resources, are integrated to provide information and application service to users. Semantic models can provide a set of generic standard protocols for heterogeneous and distributed computing [9]. It is necessary to build the semantic modeling analysis for pervasive healthcare service in cloud-enabled WBANs in order to extract the desired medical data from mass data, realize the real intelligence, and improve the functional portability, expansibility, and QoS.

It is difficult to move data from a schema-less data store to a schema-driven data store, such as a relational database, because of the uncertain platform data model. It would be a significant advantage to set up the semantic modeling of data to provide a platform independent data representation in the pervasive healthcare cloud space. Semantic models are useful for pervasive healthcare cloud service from the aspects of functional definition, data model, service description enhancement, and so on. The information with the semantic is easy to understand and process for the computer in the pervasive healthcare service. The ontology technology is used to implement information semantic interaction in cloud-enabled WBANs.

The semantic annotations can be used to generate machine comprehensible semantics for web resources in a cloud-enabled pervasive healthcare system. Figure 4 shows that a web service level agreement (WSLA) representation is created from an HTML webpage.

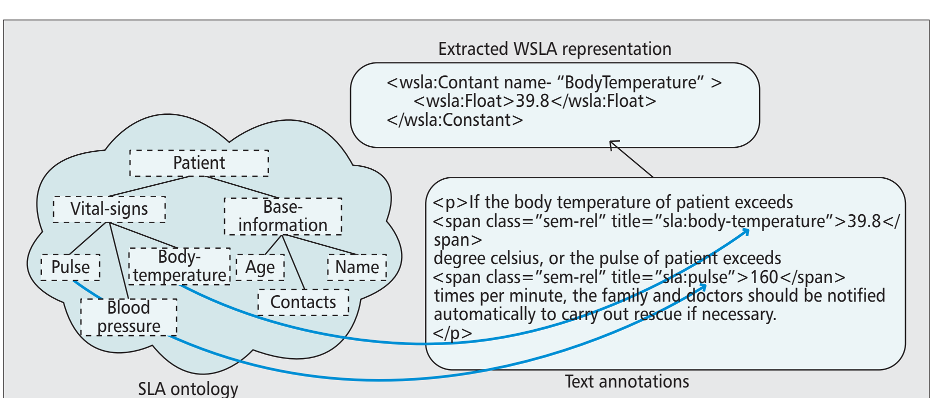

Figure 4. *Extracting the WSLA representation from an HTML webpage.*

Data Security in the wMCC Platform

The security of patient-related data is an indispensable component of the wMCC platform. In [10], Li *et al.* looked into two important data security issues for WBANs: secure and dependable distributed data storage, and fine-grained distributed data access control for sensitive and private patient medical data. In this article, since the MCC is introduced into WBANs, some new issues on data security are emerging.

In designing a secure wMCC platform, a number of design factors including encryption, scalability, access control, data partitioning, user diversity, and mobile access should be considered. The current research on the security of a wMCC platform includes key management and encrypted storage. A comparison of the key management approaches is given in Table 1. The shortcomings of traditional key management are giving way to advancements in completely secure cloud storage ideas. The goal is to encrypt medical data stored in the cloud so that the provider can access it at any time. Figure 5 illustrates a typical proxy re-encryption scenario: a medical data owner uploads encrypted content to the medical cloud data store using a shared public key; another user requests it, and a trusted authority invokes a re-encryption process either within the medical cloud or inside the authority itself; the content is then downloaded directly from the medical cloud or via the authority, and read by the recipient using his or her private key. If the recipient's access rights are revoked, content will not be re-encrypted to a form that can be read by that user.

Conclusions

The seamless integration of WBANs and MCC provides tremendous opportunities for pervasive healthcare systems. In this article, we provide a brief review and outlook of this promising field, and discuss a cloud-enabled WBAN architecture for pervasive healthcare systems. In particular, we study the functionality and reliability of MCC services. We also suggest some future research directions to improve performance and QoS of cloud-enabled WBANs. We believe cloud-enabled WBANs will attract enormous attention and research effort in the near future.

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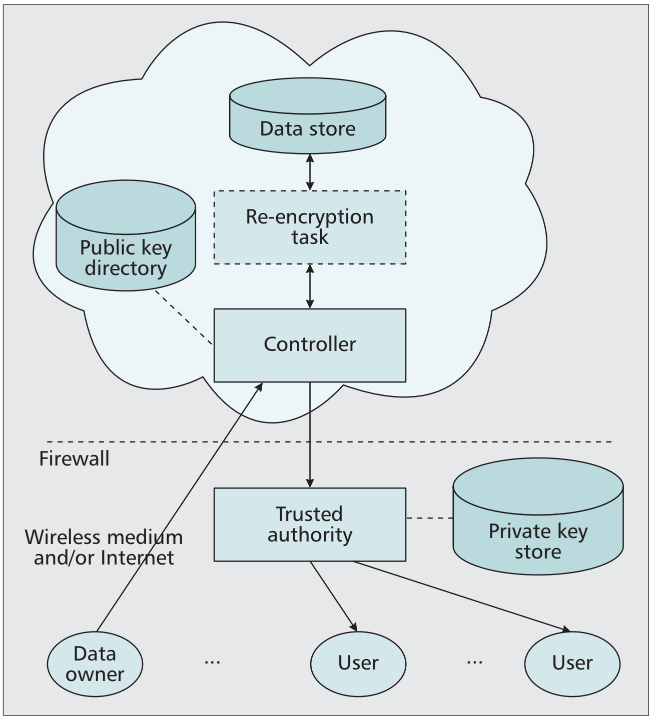

Figure 5. *Scenario illustrating the process of proxy medical data re-encryption.*

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Responsibility for storage of keys	Advantages	Disadvantages
Centralized in the cloud provider	Utilizes the scalable computational and network resources of the cloud. Relies upon the direct user-to-cloud link.	Requires trust in the cloud provider to not decode encrypted user data stored on its servers.
Centralized in a trusted authority that is outside of the cloud domain	Does not require trust in the cloud provider. May control access to cloud data as an intermediary node.	Requires maintenance of a scalable authority server by the client, or trust in a third-party guardian as a paid service.
Fully decentralized among users	Requires no additional network elements. Key sharing may utilize cheap local links such as Wi-Fi or Bluetooth.	Obtaining keys may require arbitration by an authority which entails additional traffic. Revocation is inefficient.

Table 1. *Comparison of key management approaches to mobile cloud security.*

Biographies

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