Ubiquitous WSN for Healthcare: Recent Advances and Future Prospects

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***Abstract*—Wireless sensor networks (WSNs) have witnessed rapid advancement in medical applications from real-time telemonitoring and computer-assisted rehabilitation to emergency response systems. In this paper, we present the state-of-the-art research from the ubiquity perspective, and discuss the insights as well as vision of future directions in WSN-based healthcare systems. First, we propose a novel tiered architecture that can be generally applied to WSN-based healthcare systems. Then, we analyze the IEEE 802 series standards in the access layer on their capabilities in setting up WSNs for healthcare. We also explore some of the up-to-date work in the application layer, mostly on the smartphone platforms. Furthermore, in order to develop and integrate effective ubiquitous sensing for healthcare (USH), we highlight four important design goals (i.e., proactiveness, transparency, awareness, and trustworthiness) that should be taken into account in future systems.**

***Index Terms*—Healthcare applications, smartphone, system design goals, tiered architecture, ubiquitous sensing, wireless sensor network (WSN).**

I. Introduction

Advances in microelectromechanical systems and wireless sensor networks (WSNs) have opened up great opportunities for modern healthcare. The future will see more and more integration between current specialized medical resources and wireless sensor technologies to match the expectation that healthcare should not be fragmented and episodic. Given the broad range of possible medical applications and needs, it is impracticable to apply the same sensor and wearable monitoring platform everywhere [1]. Therefore, it is important to realize the pros and cons of various solutions, and accordingly select the most promising technology for a given scenario.

Traditionally, healthcare systems highly concentrate on hospitals and clinics. The new venue of care moves to the patient's home, where clinician can combine modern information technologies with old-fashioned human caring [2]. Particularly, WSNs have become indispensable in the realization of smart homes [3]. The embedded wireless sensors interact with the inhabitants to form an intelligent environmental network. Some users even desire the capability to provide continuous medical monitoring and emergency communication outside the home.

In practice, a main concern is to select appropriate technical standards and protocols from three categories: 1) medical systems; 2) wireless communications; and 3) wireless specific devices. In this paper, we will focus on the second category, while briefly mentioning the first and last categories. For wireless communications, there are many well established and fast growing standards within the IEEE communications society such as IEEE 802.11, 802.15, 802.16, 802.20, and 802.22 series. However, several key issues are still open and deserve further investigation from the community. For instance, which IEEE communication standards are appropriate enablers for certain health service? What are the suitable candidate technologies for the clinical applications at hand? What are the ultimate goals of future ubiquitous healthcare and how do we prepare for it?

In this paper, we propose an interesting tiered architecture for WSN-based healthcare systems. We then summarize the distinct sensor network technologies for healthcare services and extend the vision to explore the design goals of future WSN-based healthcare systems. In addition to technology developments, other aspects related to human willingness, medical practice, regulations, and practical implementation issues are key correlation forces. These factors are combined to extract the four important design goals of ubiquitous sensing for healthcare (USH), which include proactiveness, transparency, awareness, and trustworthiness.

II. System Architecture

Designing a system architecture is usually the first step toward a solution. Several papers have explicitly illustrated their system models designed to meet the practical needs [5]–[7]. For

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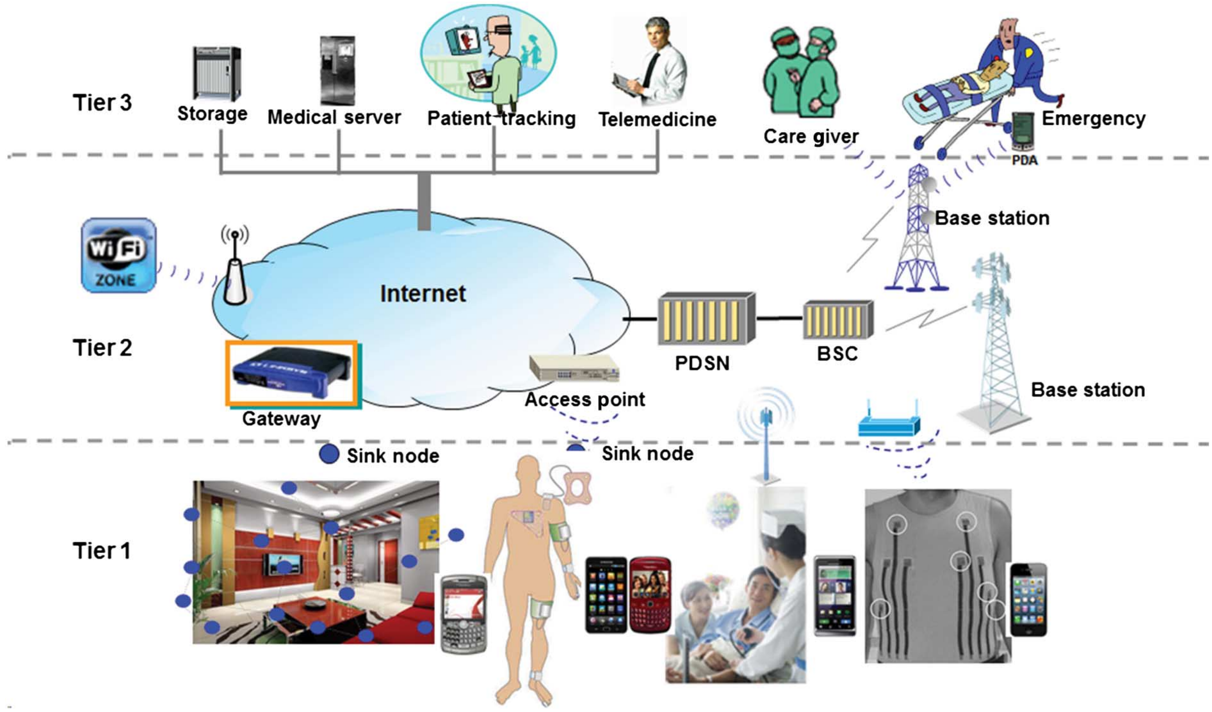

Fig. 1. System architecture of WSN-based healthcare applications.

instance, Mitra *et al.* presented several lessons learned from developing an experimental platform for ubiquitous healthcare called the KNOWME [7]. The KNOWME platform adopts a three-tier architecture, including the body sensor network (BSN) layer, the mobile phone, and a back-end server. In [5], Liang *et al.* further envisioned a typical remote health monitoring system with an architecture of three domains: 1) body area domain; 2) communication and networking domain; and 3) service domain. Similarly, a conceptual representation of WSN-based physiological signal monitoring system was illustrated in [6]. Health-related information is collected via body-worn sensors and transmitted to the caregiver through an information relay such as an Internet gateway or a cell phone. Making use of the information, caregivers can intervene when necessary. Moreover, an online database server can be set up to save acquired data and users information for further analysis.

These design frameworks are specific to user requirements. Therefore, they are not applicable to different application domains. We integrate and extend their functions to form a more general-purpose system architecture (Fig. 1). At the bottom, tier 1 encompasses a large number of wireless medical sensor nodes that are integrated to form diverse WSNs. Using appropriate wireless communication technology, the sensed data will be collected and relayed to remote healthcare practitioners via wired or wireless communication infrastructure (tier 2). Usually the Internet, WiMAX, or 3G mobile is the main channel through which many components get connected to form a harmonious backbone network, where the WSNs can be linked to the enterprise level for data storage or remote access. At the top layer (tier 3), based on synergy of information from multiple medical sensors, the healthcare service providers are able to examine the user's health state in order to offer feedback through a user-friendly interface.

By extracting the major features that diverse healthcare systems have in common, we further present a block diagram of ubiquitous WSNs for healthcare in Fig. 2. The three-tier architecture offers an abstraction that consists of high-level components and functions, as opposed to implementation details. WSN in tier 1 is one of the wireless radio access networks, playing the same role as a LAN does in traditional wired networks. Convergence of various back end systems will be the key activity that layer 2 will perform. The next-generation core network should seamlessly blend heterogeneous networks, across fixed, mobile, wireless, or satellite infrastructure creating a single multiservice network for the top layer. Ubiquity of WSNs is taken into consideration as this feature highlights future application trends. Fig. 2 also presents the representative international standard organizations that have a strong tie to this field.

With this three-layer system architecture, it is feasible to offer more reliable data delivery with less energy consumption in the underlying sensor networks. Tier 2 consisting of more powerful networking capabilities will get involved in the communication between the caregiver and the sensor networks (end user), mitigating the impact of the limited capacities of the sensor nodes. In addition, real-time medical response will be achieved by the guarantee of less hop count and higher bandwidth in this middle layer. Since tier 2 will be responsible for the major part of data delivery, sensor nodes are less frequently involved in communication and data processing, thereby increasing their lifetime. With this framework in mind, in practice, the most difficult issue then lies in the adoption of most appropriate network technologies, standards, and protocols to form a smooth system of medical care.

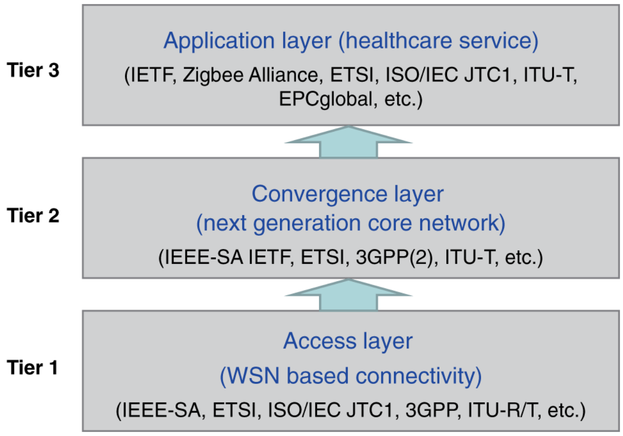

Fig. 2. Block diagram of the architecture model for WSN-based healthcare systems.

In Sections III and IV, we mainly discuss the candidate communication protocols in the access layer, and some novel research topics raised more recently in the application layer.

III. Communication Standards for WSN-Based Healthcare Applications

For wireless communication, most integrated circuit suppliers made their products conforming to international standards. Different technologies and standards of wireless networking have been developed and are actively constructed within the IEEE community. For WSN-based healthcare, however, only some of these standards are appropriate.

Since IEEE 802.11-2012 is a standard for WLAN, it is intended to provide continuous network connection and high throughput rather than mobility, coverage, or energy efficiency of the network. When switching from wireless *ad hoc* networks to more resource constrained WSNs, IEEE 802.11 is not suitable for healthcare data transmission due to its several design orientations [6]. The IEEE 802.20 standard focuses on high velocity mobile broadband systems. It used to be directed as a competitor to 3G wireless cellular technologies instead of as a primary supporting technology for WSN. In March 2011, 802.20 was put to hibernation due to lack of activity.

An alternative standard is IEEE 802.22-2011, the world's first standard built on cognitive radio (CR) technology, which defines the air interface utilizing fallow segments of the incumbent TV broadcast bands. In a CR network, although it is possible for unlicensed users to use licensed spectrum bands on a noninterference basis to incumbent subscribers, such coexistence for WSN applications remains to be a very difficult problem [9].

With advantages in transmission speed, security, mobility, and QoS, IEEE 802.16-2009 (WiMAX) is a good choice for telemedicine service providers in both mobile and fixed environments [10]. High-quality medical images such as radiology and ultrasound images can be transmitted with significantly reduced delay through the high bandwidth. Therefore, some monitoring and diagnostic processes can be performed simultaneously with the presence of a large network capability. Strong QoS further increases the efficiency and reliability of data transmission. For instance, in real-time polling services, time-sensitive, variable bit rate traffic such as diagnostic images can be transmitted from ambulance to a doctor for prehospital diagnosis while patients are still on the way to the hospital.

The 802.16 MAC, unlike the 802.11 MAC, does not rely on distributed channel allocation mechanism and does not support direct peer-to-peer (*ad hoc*) transmission. It is collision free. The benefit of this is that as the number of users that share the channel increases, the channel throughput stays relatively stable because none of the bandwidth is wasted for collisions. Therefore, IEEE 802.16 fits well with healthcare applications that are designed to be as unobtrusive as possible with high QoS requirement. As a result, the integration of low-rate wireless private area networks and a wireless mesh backbone could be a complete wireless solution for delivering real-time medical services.

The most important standards covering link technologies between data collectors and wireless sensors for healthcare application are based on IEEE 802.15. The first group member is IEEE 802.15.1-2005 (Bluetooth). Classic Bluetooth is normally not regarded as a long-term health-related access technology because of its high duty cycle and relatively high transmission power [8]. Since Bluetooth low-energy (BT-LE) technology is an unavoidable candidate among low-power access technologies, it is necessary to consider it in the big picture. A distinctive feature of BT-LE is an implementation of two equally important alternatives: 1) single-mode and 2) dual-mode. Single-mode device has compact radio communication unit suitable for incorporating into the wireless medical monitors. Power consumption of these medical monitors is very low, allowing them to run for even years on standard coin cell battery. Single-mode devices cannot talk directly to classic, regular Bluetooth devices. Dual-mode devices, on the other hand, are radio communication devices targeted for personal computers (PCs) or handsets. The most interesting additional functionality of a PC or a cell phone equipped with dual-mode BT-LE module is that it is able to communicate with single-mode devices directly. Accordingly, medical information can be forwarded from a wireless sensor (monitor) to a PC or a cell phone and then to a remote caregiver.

Although ZigBee-based WSNs are most broadly recognized and ideal for use in acute care hospitals and beyond, a disadvantage is that its low bandwidth of 250 kbps increases the time it takes to send the same amount of data by up to four times compared to BT-LE. The ubiquity of Bluetooth in the cell phones and the consumer desire to use this facility as the healthcare hub will motivate people to use BT-LE devices in the smart medical treatment, making it a strong competitor to ZigBee in this domain.

BSN is a type of WSN aimed to be deployed on human body to gather physiological parameters for health purposes [11]. The unique characteristics compared to majority of general wireless personal area networks include shorter communication range, more limited computation capability and data rate, more sensitive data, higher safety regulation requirements for specific absorption rate, etc. Recognizing the rapid technological developments and great market potential in this sector, IEEE also

TABLE I
COMPARISON OF IEEE 802 SERIES STANDARDS FOR WSN-BASED HEALTHCARE APPLICATIONS

Standard	802.11n	BT-LE (802.15.1)	ZigBee (802.15.4)	802.15.6	802.16e	802.22
Freq. band (Hz)	2.4G; 5G	2.4G	868M; 915M; 2.4G	13.5M; 400M; 900M	2.3G; 2.5G; 3.3G; 3.4-3.8G	54-862M
Data rate (bps)	Up to 600M	Up to 1M	869M: 20k; 915M: 40k; 2.4G: 250k	Up to 480k	DL up to 46M	Up to 260k
Modulation	QPSK; QAM	GFSK	DSSS with BPSK/OQPSK	DBPSK; DQPSK	QPSK; QAM	QPSK; QAM
Coverage range	LAN ~200 m	PAN ~10 m on body	PAN ~100 m	BAN ~10 m	MAN min mobile to BS 36m	RAN
Security	Up to 128-bit AES	Up to 128-bit AES with counter mode CBC MAC	Up to 128-bit AES with CBC MAC	Three security level from MK to PTK to GTK	DES-CBC AES-CCM AES-CTR AES-CBC	AES-GCM
Fitness into the architecture	Basically access layer	Access layer	Access layer	Access layer	Convergence layer	Not clear
Scope of health applications	Community health services without much mobility	Long period, mobile health devices (access network)	Long period, mobile health devices (access network)	Body sensor networks (access network)	Wide area, high mobility (backbone network)	Not clear

developed its typical enabling technology lately, IEEE 802.15.6-2012. A star topology is typically adopted in BSN, but it cannot always meet some desired requirements like reliability. Therefore, a star-mesh hybrid topology extends the traditional scheme by creating mesh networking among centrally organized coordinators for multiple star networks.

Table I summarizes the typical performance values of IEEE 802 wireless standards and their fitness option for health-related applications. In fact, as healthcare business picks up momentum, there is a battle brewing over wireless standards in the BSN arena. Till now, there is no clear-cut winner.

IV. APPLICATION LAYER ADVANCES FOR WSN-BASED HEALTHCARE

The practice of medical treatment can be summarized as a three-stage process: 1) data acquisition; 2) symptom recognition/interpretation; and 3) decision-making on prescription. As a result, the introduction of wireless connections to exchange sensor data can provide a high flexibility for both medical staff and patient. The physicians make a treatment based on the patient's electronic clinical reports and medical history by consulting the pharmaceutical handbook, evidence-based database, and other resources.

In the past, research and development community paid considerable attention to designing WSN-oriented prototypes for accurately obtaining user's vital signs and timely detection of anomalies [1]. They normally play the function of remote monitoring or telemedicine. The sensed data are captured and sent to a remote site for further evaluation. Many early interesting projects were well presented and discussed in literature, such as LifeGuard [12], CodeBlue [13], and ALARMNET [14]. The interested readers may refer to the original papers for further details.

A major goal of recognizing human activities with wireless sensors is to assist the individual in maintaining a healthy lifestyle and effectively improving the quality of life. These studies can be roughly divided into noncritical and critical applications, most of which are built on mobile devices like smartphones.

In noncritical cases, smartphone embedded with diverse sensors is used to facilitate everyday life in all possible aspects. For instance, recently in [15], Kwon *et al.* explore the potential that heart rate can be measured remotely by the video of facial muscle action recorded using smartphone camera. They detect facial region on the image of each video frame, and yield the raw trace signal by which the cardiac pulse signal of heart rate can be further extracted. Therefore, the iPhone application, FaceBEAT, can measure user's heart rate at a reliable level without the time and location limit. To measure and keep track of sleep duration and patterns, Chen *et al.* design a best effort sleep (BES) model which can infer sleep quality [16]. BES was evaluated by volunteers using smartphones in a completely unobtrusive way. Results from their 1-week 8-person study show that the BES model can accurately estimate sleep duration and can cope with the natural variation in users' sleep routines and environments.

By reviewing the work published within the past two years, we further witness the paradigm upgrade from only monitoring traditional physiological parameters (e.g., ECG, electroencephalography, electrooculography, electromyography, electrodermal activity, pulse wave velocity, and blood pressure) to dynamically monitoring human activities and inferring relevant psychological indications.

For example, BeWell and its variant [17] are proposed to track a diverse range of user daily behaviors, and provide intelligent feedback to identify early signs of decline. Multiple wellness dimensions are displayed as Android phone wallpapers with three animated animals: 1) turtle; 2) clown fish; and 3) school of fish representing sleep, physical, and social activeness. Field trials show that users react positively to their wellbeing feedback experience and are able to identify appropriate corrective actions to take. SapoFit [18] is another smartphone-based mobile health application that promotes a healthier life style. It allows users to control their basal metabolic rate, body mass index, sports activity, and follow food plans based on their needed calories. All personal data are recorded on a local smartphone database for easy access. This profile information will customize the alert system to motivate users to follow the respective diet program and physical activities.

In critical applications such as detecting emergency events like falls, such systems are required to have a low rate of false alarm. To deal with this issue, different systems use different strategies to reduce the false alarm rate. For instance, Doukas *et al.* introduce the context awareness concept into the utilization of three separate information channels (audio, visual, and motion data) for patient status interpretation [19]. The false positives that may be generated by audio or motion features can be minimized by using proper rules among information from all three channels. User-based evaluation together with classification results demonstrated the system's accuracy and acceptability in assisted persons. However, a large percentage of falls occur at nighttime, when a person is unlikely to be wearing such an ambulatory monitoring device. By utilizing unobtrusive pressure mat and passive infrared sensors, Zhang *et al.* investigate the feasibility of performing nighttime fall detection through scripted scenarios [20]. The system attempted to identify falls at nighttime where the subject is unable to recover without help. It is more effective to identify risk factors associated with fall and apply specific fall prevention strategies to reduce those risks.

So far, most of the research has focused on somatic diseases and only a few have targeted mental illness, such as schizophrenia, bipolar disorder, depression, and alcoholism. With the help of smartphone technologies and innovative processes proposed by recent research approaches, we can envision a new generation of services in the treatment of mental health diseases. Such kind of persuasive monitoring systems would be able to continuously monitor data on activities and mood, providing timely feedback to users in order to help them adjust their behaviors. The European project MONARCA in the Seventh Framework Program plays an exemplary role in this regard [21]. It aims at validating and developing mobile technologies for multiparametric, long-term monitoring of physiological and behavioral information relevant to bipolar disorder. In [22], Mayora *et al.* highlight a series of challenges identified and lessons learnt during the design, development, and evaluation of the MONARCA system. The main findings focus not only on the technological and clinical aspects but also on other nonfunctional requirements that are key in the development of such complicated personal health systems and services. To investigate which biosignals will provide relevant psychological indicators and to which extension body motion noise impairs this identification, Kusserow *et al.* utilize wearable sensors in natural settings under free-living conditions [23]. The analysis of accumulated short-term stress arousal could contribute to understanding long-term stress arousal, e.g., work overload and burnout. In particular, they observed that multimodel measurements can resolve ambiguities in biosignal patterns caused by parallel stress arousal and physical activity transitions.

Continuing miniaturization and integration of sensors, radio devices, and processors already provide engineers and scientists insights into the smartphone-based biological systems ranging from remote user monitoring to much broader applications in personal well-being improvement. In Section V, we will illustrate the design directions in healthcare management that take these devices into more consideration.

V. Future Directions: USH

Nowadays a more powerful, more prevalent device with perceived user acceptance is smartphone [24]. Mobile healthcare also perceives a shift from wearing body sensors to carrying multifunctional wireless devices such as smartphones. While a comprehensive review is beyond the scope of this paper, some representative examples are highlighted in Section IV [15]–[22]. Here, we summarize the main superiority and feasibility of smartphone-based healthcare applications.

1) The pervasive use of smartphones and the ubiquity of WiFi connections enable medical informatics to overcome the time and location barriers. This method is especially useful in those instances in which a rapid response is critical or when conditions are changing dynamically.
2) A rich set of embedded sensors (e.g., camera, accelerometer, vibrating gyroscope, magnetometer, goniometer, actometer, pedometer, and pressure sensor) of the smartphones are collectively enabling revolution in nearly all aspects of healthcare.
3) Commercial wearable devices are commonly intrusive, and place a burden on user's daily routines, while smartphones are usually unobtrusive and do not need to follow a cumbersome usage protocol—reducing potential usability issues.
4) Smartphone sensing requires no additional hardware; therefore, applications can be nearly free. This has led to an adoption of more cost-effective strategies than conventional methods of wearable BSN.
5) Smartphones may provide an effective solution to some challenges that would be extremely difficult to overcome under certain circumstances. For example, with smartphones in the hands of thousands, we may predict and track the outbreaks of disease across populations more effectively.

However, these new capabilities present different challenges for technical issues such as mobility control [25], information security [26], [28], and new applications [27]. With respect to information security, it is surprising that only a few well-researched evidences exist in this specific field, while we identify security as one of the greatest concerns now and in the future. For private access and secure data transmission within a BSN, Drira *et al.* propose a hybrid authentication and key agreement scheme [28]. They present two protocols to authenticate and establish pairwise and group keys between all tiers and to provide a public key and private keys for smartphones. Security analysis and performance analysis show that their scheme is resilient against known attacks and calculation load is reduced.

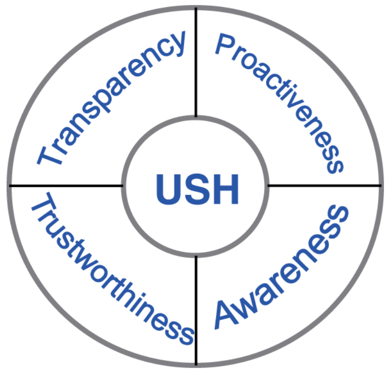

Fig. 3. Design goals of future USH systems.

Although the previous research with respect to telemonitoring has made some outstanding contributions, the approaches proposed thus far have not delved in the realm of ubiquitous healthcare. We call it ubiquitous sensing for healthcare (USH). Innovations in traditional healthcare systems, including human-centric technical design, user active self-care, physician support, safe, and concurrent data management, should be associated with USH solutions. Therefore, in a USH service, we can expect the four goals of ubiquity as *proactiveness, transparency, awareness, and trustworthiness* (Fig. 3).

A. Proactiveness

Recall the current health delivery systems supported by WSNs, they are mostly reactive. When an unhealthy status of a person is detected by the medical sensors, related data are transmitted to the doctor where diagnosis is established in order to prevent further exacerbation of the illness. The doctor's instructions are carried out by the patient, who then waits for the body's reaction. However, prevention is always better than cure. A USH system should be available in the right place and at the right time, which implies proactiveness [29]. A USH consumer (not only patient) will send out appropriate physiological and behavioral data from embedded, intelligent, and networked devices in a sentient manner, and expect instantaneous receipt of medical information and relevant expertise. This implies an updated methodology of *moving from managing illness to maintaining wellness*. Imagine an everlasting service session under any connection with any device, or seamlessness, it will highly alleviate the present healthcare problems caused by being reactive in nature.

B. Transparency

The components of healthcare systems should not intrude on the user's consciousness but hide the underlying technologies from him, which implies transparency. Naturally, placing more sensors across the body will generate more comprehensive data. It is very likely, however, that both usability and compliance will suffer. Hence it is not the device but an environment. Instead of carrying a device with you wherever you go, a device is available wherever you are in need. The user can thus concentrate on the task at hand. It rightly outperforms the aforementioned research fields of building wearable health monitoring facilities that utilizes BSN.

C. Awareness

A user's context can be quite rich, consisting of attributes such as personal history, physical location, emotional state, physiological state, daily behavioral patterns, and so on. A key challenge is to acquire the information required to function with regard to the rich and time-varying context parameters. Unless carefully designed, a proactive system can be annoying and thus defeat the objective of invisibility. Self-tuning in this effort can be an important tool. Pervasive devices should extend the human senses by providing adaptive awareness of the surrounding environment, through which we set up mutual realization between the user-context and the service-feedback. The ultimate goal is that the system will recognize the user wherever he or she logs on, on any network and with any equipment. The applications will also be adapted in the best possible way given these surrounding conditions. It is a comprehensive intelligent environment rather than a collection of services supplied by individual devices.

D. Trustworthiness

As mentioned before, USH also brings simultaneously significant safety challenges in the deployment of healthcare services. A companying goal of USH is to address security issues in a strategic and interdisciplinary effort aimed at trustworthiness. Unfortunately, wireless has long presented operators of networks with much more security vulnerabilities compared to traditional wired networks, and the majority privacy protection solutions proposed for WSN are not designed for healthcare in mind. In ordinary WSN, for instance, unintentional interference from nearby nodes will normally cause misconception of data. However, if a decision is made on the basis of the corrupted data in a healthcare scenario, it could be a matter of life and death.

The USH is not synonymous with pervasive computing, yet it relies on all of those approaches including the Internet, embedded devices, mobile communication technology, the Internet of Things, etc. The fruition of the four design objectives is to ensure healthcare supply chain integrity, *offering the right service, in the right condition, at the right time, in the right place, for the right user, and at the right price*.

In addition to specific information communication technologies, *understanding human values* is a crucial factor for technical professionals in developing any successful USH application. Always design healthcare systems with care, bearing in mind both end users and other stakeholders. It is already ubiquitous healthcare at the very start, reducing resistance to new technologies by healthcare and social-care professionals.

VI. Conclusion

Sensing and computing have never been so intermixed in people's everyday lives. While WSNs bear the potential to provide users with high-quality medical care, the complexity of such a system raises many fundamental questions of technology, cognitive, and cost acceptance. Therefore, exploiting awareness of a user's context, recognition of a user's activity, and a user's health background to create a truly customized experience for an individual is a significant challenge. This paper provides a comprehensive survey of recent advancement in WSN-based healthcare, exploiting the potential of USH service. A conceptual framework of USH system is developed from a usage scenario. After analyzing both the representative enabling technologies and development trends mostly with respect to the platforms of smartphones, we propose an updated design concept of USH. The merits of USH will aid in realizing rapid changes of a nation's healthcare infrastructure and healthcare delivering systems. Trial and error are inevitable and acceptable, and more courage is encouraged to take on the challenges on this promising paradigm.

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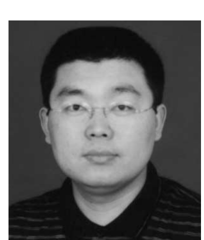

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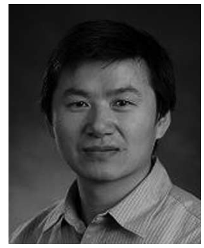

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