IEEE Access
The journal for rapid open access publishing

Received April 4, 2015, accepted May 8, 2015, date of publication June 1, 2015, date of current version June 4, 2015.

Digital Object Identifier 10.1109/ACCESS.2015.2437951

The Internet of Things for Health Care: A Comprehensive Survey

S. M. RIAZUL ISLAM[1], (Member, IEEE), DAEHAN KWAK[2], MD. HUMAUN KABIR[1], MAHMUD HOSSAIN[3], AND KYUNG-SUP KWAK[1], (Member, IEEE)

[1]UWB Wireless Communications Research Center, Inha University, Incheon 402-751, Korea
[2]Networked Systems and Security Laboratory, Rutgers University, Newark, NJ 07102, USA
[3]Secure and Trustworthy Computing Laboratory, University of Alabama at Birmingham, AL 35233, USA

Corresponding author: K. S. Kwak (kskwak@inha.ac.kr)

This work was supported by the Ministry of Science, ICT and Future Planning, Korea, through the Information Technology Research Center Support Program under Grant IITP-2015-H8501-15-1019 supervised by the Institute for Information and communications Technology Promotion.

ABSTRACT The Internet of Things (IoT) makes smart objects the ultimate building blocks in the development of cyber-physical smart pervasive frameworks. The IoT has a variety of application domains, including health care. The IoT revolution is redesigning modern health care with promising technological, economic, and social prospects. This paper surveys advances in IoT-based health care technologies and reviews the state-of-the-art network architectures/platforms, applications, and industrial trends in IoT-based health care solutions. In addition, this paper analyzes distinct IoT security and privacy features, including security requirements, threat models, and attack taxonomies from the health care perspective. Further, this paper proposes an intelligent collaborative security model to minimize security risk; discusses how different innovations such as big data, ambient intelligence, and wearables can be leveraged in a health care context; addresses various IoT and eHealth policies and regulations across the world to determine how they can facilitate economies and societies in terms of sustainable development; and provides some avenues for future research on IoT-based health care based on a set of open issues and challenges.

INDEX TERMS Internet of things, health care, services, applications, networks, architectures, platforms, security, technologies, industries, policies, challenges.

I. INTRODUCTION

The Internet of Things (IoT) is a concept reflecting a connected set of anyone, anything, anytime, anyplace, any service, and any network. The IoT is a megatrend in next-generation technologies that can impact the whole business spectrum and can be thought of as the interconnection of uniquely identifiable smart objects and devices within today's internet infrastructure with extended benefits. Benefits typically include the advanced connectivity of these devices, systems, and services that goes beyond machine-to-machine (M2M) scenarios [1]. Therefore, introducing automation is conceivable in nearly every field. The IoT provides appropriate solutions for a wide range of applications such as smart cities, traffic congestion, waste management, structural health, security, emergency services, logistics, retails, industrial control, and health care. The interested reader is referred to [1]–[5] for a deeper understanding of the IoT.

Medical care and health care represent one of the most attractive application areas for the IoT [6]. The IoT has the potential to give rise to many medical applications such as remote health monitoring, fitness programs, chronic diseases, and elderly care. Compliance with treatment and medication at home and by healthcare providers is another important potential application. Therefore, various medical devices, sensors, and diagnostic and imaging devices can be viewed as smart devices or objects constituting a core part of the IoT. IoT-based healthcare services are expected to reduce costs, increase the quality of life, and enrich the user's experience. From the perspective of healthcare providers, the IoT has the potential to reduce device downtime through remote provision. In addition, the IoT can correctly identify optimum times for replenishing supplies for various devices for their smooth and continuous operation. Further, the IoT provides for the efficient scheduling of limited resources by ensuring their best use and service of more patients. Fig. 1 illustrates recent healthcare trends [7]. Ease of cost-effective interactions through seamless and secure connectivity across individual patients, clinics, and healthcare organizations is an important trend. Up-to-date healthcare

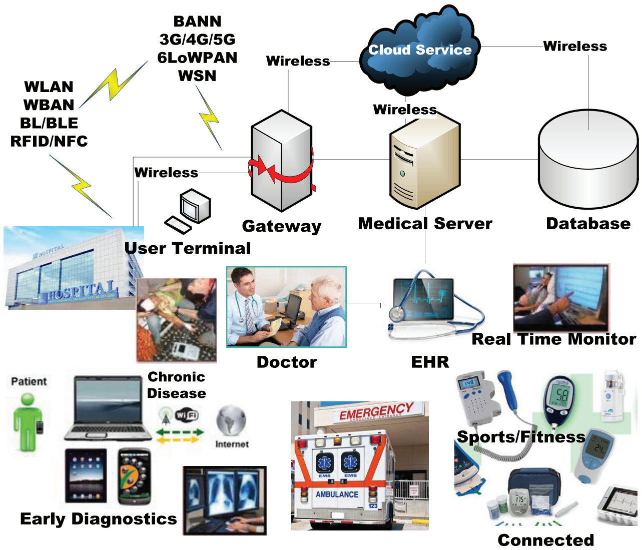

FIGURE 1. Healthcare trends.

networks driven by wireless technologies are expected to support chronic diseases, early diagnosis, real-time monitoring, and medical emergencies. Gateways, medical servers, and health databases play vital roles in creating health records and delivering on-demand health services to authorized stakeholders.

In the last few years, this field has attracted wide attention from researchers to address the potential of the IoT in the healthcare field by considering various practical challenges. As a consequence, there are now numerous applications, services, and prototypes in the field. Research trends in IoT-based health care include network architectures and platforms, new services and applications, interoperability, and security, among others. In addition, policies and guidelines have been developed for deploying the IoT technology in the medical field in many countries and organizations across the world. However, the IoT remains in its infancy in the healthcare field. At this stage, a thorough understanding of current research on the IoT in the healthcare context is expected to be useful for various stakeholders interested in further research. This paper examines the trends in IoT-based healthcare research and uncovers various issues that must be addressed to transform healthcare technologies through the IoT innovation. In this regard, this paper contributes by

- Classifying existing IoT-based healthcare network studies into three trends and presenting a summary of each.
- Providing an extensive survey of IoT-based healthcare services and applications.
- Highlighting various industrial efforts to embrace IoT-compatible healthcare products and prototypes.
- Providing extensive insights into security and privacy issues surrounding IoT healthcare solutions and proposing a security model.
- Discussing core technologies that can reshape healthcare technologies based on the IoT.
- Highlighting various policies and strategies that can support researchers and policymakers in integrating the IoT innovation into healthcare technologies in practice.
- Providing challenges and open issues that must be addressed to make IoT-based healthcare technologies robust.

It should be noted that R&D activities in the field of healthcare services based on the wireless sensor network (WSN) [8], [9] can be considered as initial IoT-based healthcare research efforts. However, the ongoing trend is to shift away from registered standards and adopt IP-based sensor networks using the emerging IPv6-based low-power wireless personal area network (6LoWPAN). If WSNs become a core part of the Internet, then a careful analysis is necessary. To better understand the evolution of WSNs toward the IoT and thus their fundamental differences, the reader is referred to [10]–[12].

II. IoT HEALTHCARE NETWORKS

The IoT healthcare network or the IoT network for health care (hereafter "the IoThNet") is one of the vital elements of the IoT in health care. It supports access to the IoT backbone, facilitates the transmission and reception of medical data, and enables the use of healthcare-tailored communications. As shown in Fig. 2, this section discusses the IoThNet topology, architecture, and platform. However, it should be mentioned that the proposed architectures in [13] and [14] can be considered as a good starting point for developing insights into the IoT network.

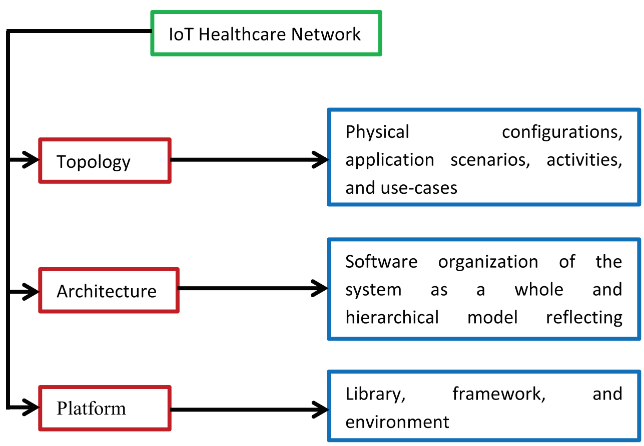

FIGURE 2. IoT healthcare network (IoThNet) issues.

A. THE IoThNet TOPOLOGY

The IoThNet topology refers to the arrangement of different elements of an IoT healthcare network and indicates representative scenarios of seamless healthcare environments. Fig. 3 describes how a heterogeneous computing grid collects enormous amounts of vital signs and sensor data such as blood pressure (BP), body temperature, electrocardiograms (ECG), and oxygen saturation and forms a

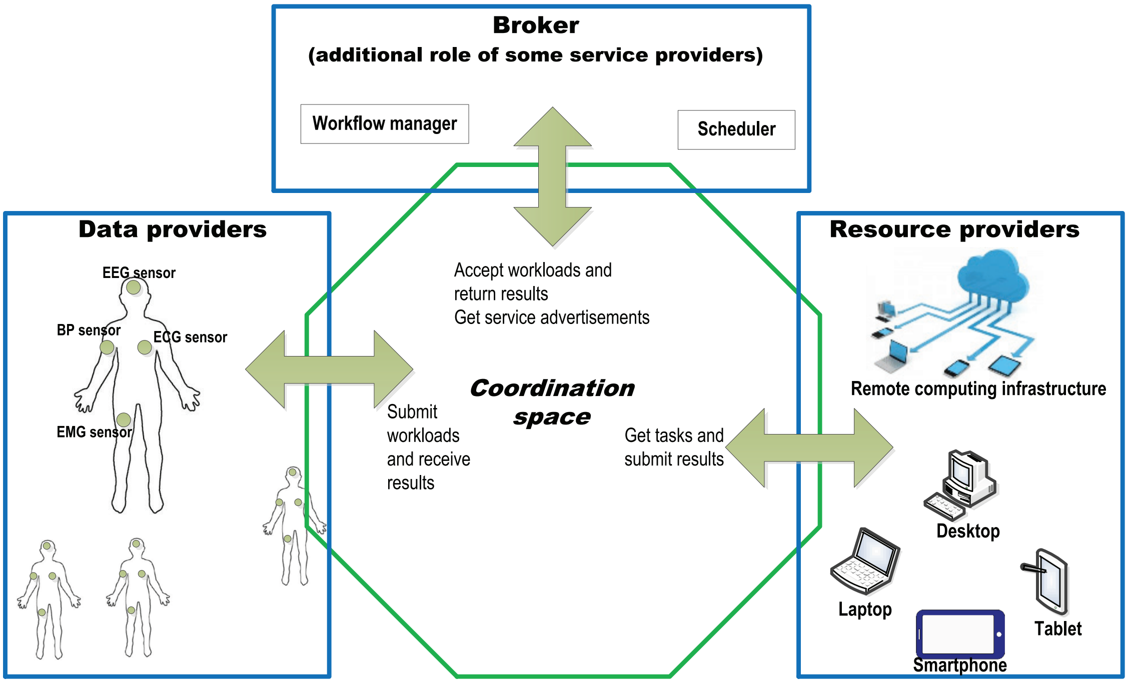

FIGURE 3. A conceptual diagram of IoT-based ubiquitous healthcare solutions.

typical IoThNet topology. It transforms the heterogeneous computing and storage capability of static and mobile electronic devices such as laptops, smartphones, and medical terminals into hybrid computing grids [15].

Fig. 4 visualizes a scenario in which a patient's health profile and vitals are captured using portable medical devices and sensors attached to his or her body. Captured data are then analyzed and stored, and stored data from various sensors and machines become useful for aggregation. Based on analyses and aggregation, caregivers can monitor patients from any location and respond accordingly. In addition, the topology includes a required network structure for supporting the streaming of medical videos. For example, the topology in Fig. 4 supports the streaming of ultrasound videos through an interconnected network with worldwide interoperability for microwave access (WiMAX), an internet protocol (IP) network, and a global system for a mobile (GSM) network as well as usual gateways and access service networks. Similar conceptual structures are found in [16]–[19].

Fig. 5 presents an IoThNet topology showing the role of a gateway. Here intelligent pharmaceutical packaging (iMedPack) is nothing but an IoT device that manages the problem of medicine misuse, thereby ensuring pharmaceutical compliance. The intelligent medicine box (iMedBox) is considered a healthcare gateway with an array of various required sensors and interfaces of multiple wireless standards. Various wearable sensors and IoT devices are wirelessly connected to healthcare gateways connecting the patient's environment to the health-IoT cloud, a heterogeneous network (HetNet) that enables clinical diagnosis and other analyses. The gateway itself can investigate, store,

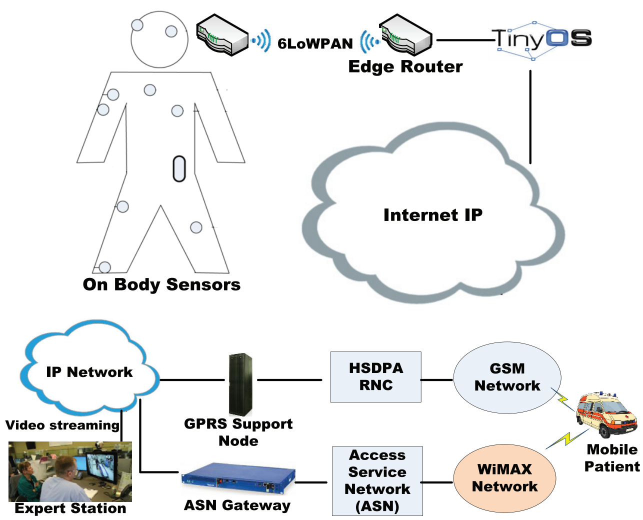

FIGURE 4. Remote monitoring in wearables and personalized health care.

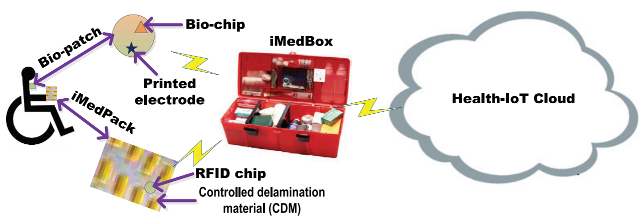

FIGURE 5. An IoThNet topology with an intelligent healthcare gateway.

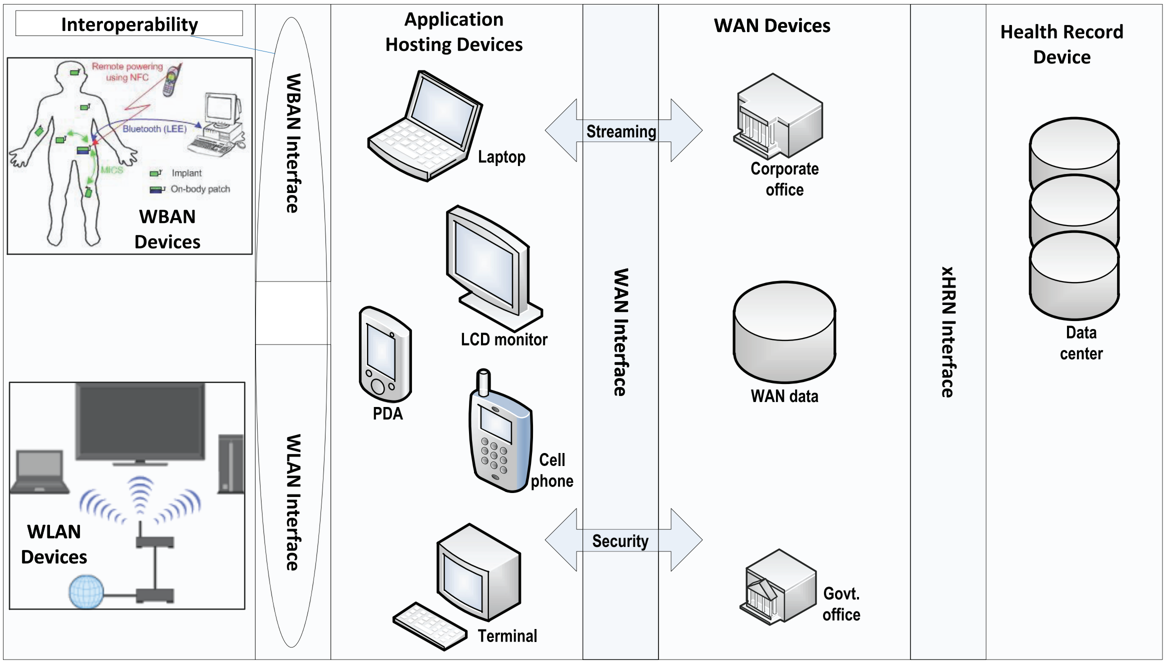

FIGURE 6. Continua Health Alliance's framework-based simplified reference architecture.

and display all collected data [20]. A similar IoThNet topology is found in [21], which integrates clinical devices with the IoT healthcare enterprise infrastructure.

Identifying associated activities and roles in medical services is a fundamental factor in designing the IoThNet topology. Pre-, in-, and post-treatment processing involves healthcare services mainly from the perspective of healthcare service providers. Such healthcare activities have been demonstrated in the context of emergency medical services [22], and an IoThNet topology including cloud computing for pervasive health care has been proposed [23]. This can be viewed as a conventional complete-mesh networking system with the omnipresence of internet connectivity. Then the topology must include a medical rule system in the case of a semantic medical monitoring system [24].

B. THE IoThNet ARCHITECTURE

The IoThNet architecture refers to an outline for the specification of the IoThNet's physical elements, their functional organization, and its working principles and techniques. To start, the basic reference architecture in Fig. 6 is presented for the telehealth and ambient assisted living systems recommended by Continua Health Alliance. The key issues have been identified for this architecture [25]: the interoperability of the IoT gateway and the wireless local area network (WLAN)/wireless personal area network (WPAN), multimedia streaming, and secure communications between IoT gateways and caregivers.

Many studies [18], [21], [23], [26]–[33] have justified that the IPv6-based 6LoWPAN is the basis of the IoThNet.

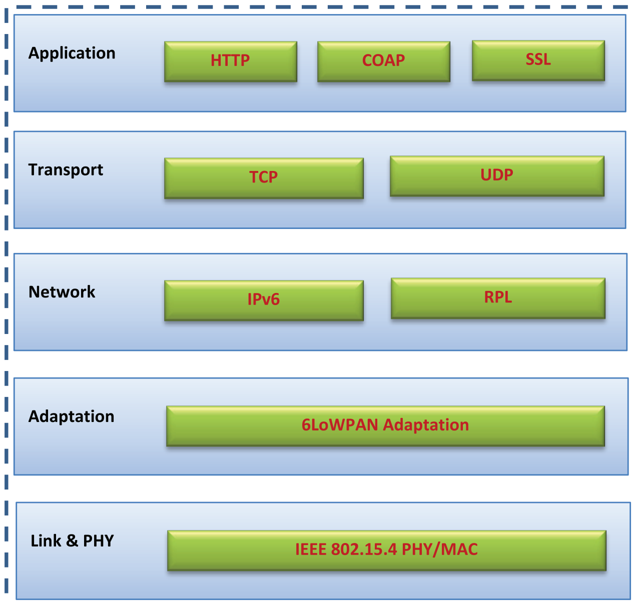

FIGURE 7. The protocol stack of 6LoWPAN.

As designed in [34], Fig. 7 shows the layer structure of the 6LoWLAN. According to the IoThNet concept, sensors and wearables use IPv6 and 6LoWPAN systems for data transmission over the 802.15.4 protocol. Data are then replied back by sensor nodes with the help of the user datagram protocol (UDP). However, the 6LoWPAN is limited in that it does not support mobile IPv6 (MIPv6), a subset of the IPv6 protocol with mobility. To introduce mobility provision to the 6LoWPAN, a protocol for exchanging messages between mobile patient nodes, base networks, and visited networks is proposed in [26].

To address mobility, four alternative procedures are considered in [29], including soliciting routers, waiting for a new directed acyclic graph (DAG) information object (DIO), attaching to other available parent nodes, and sending DAG information solicitation (DIS) messages. Among these, soliciting routers and sending DIS messages represent the fastest methods because they are initiated by the mobile node itself. A typical gateway protocol stack for community medical services is described in [35]. This stack explicitly describes how periodic traffic, abnormal traffic, and query-driven traffic can be managed within the HetNet. A complex eHealth service delivery method consisting of three phases has been proposed in [36], including composition, signalization, and data transmission. Signalization protocols serve mainly as the basis of complex service composition, quality-of-service (QoS) negotiation, and resource allocation procedures in the IoThNet. Fig. 8 shows the state encountered in the QoS negotiation procedure, which is nothing but the creation of a connection to expected QoS values.

Medical devices have been considered for vehicular networks, and captured health data have been examined through IPv6 application servers [18]. Here the lightweight auto-configuration protocol shown in Fig. 9 has introduced for vehicle-to-infrastructure (V2I) communications in the IoThNet. This protocol uses the IPv6 route as a default route in the routing table. This provides a set of IPv6 addresses for health devices in a vehicle. The extent to which big data can

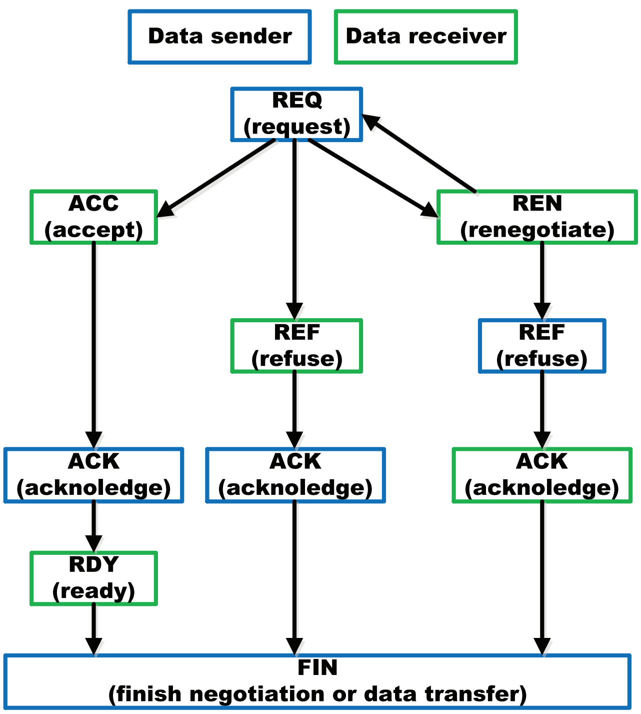

FIGURE 8. The negotiation process (blue by the sender and green by the receiver).

reshape the data structure in healthcare services is described in [37], and the question of how multiple communications standards can be coordinated to give rise to the IothNet is discussed in [38]. The data distribution architecture is examined in the case of cloud computing integration in [22]. The next subsection discusses this structure for the IoThNet platform because this involves both the architecture and platform.

C. THE IoThNet PLATFORM

The IoThNet platform refers to both the network platform model and the computing platform. As shown in Fig. 10, a service platform framework focusing on residents' health information is presented in [39]. This framework shows a systematic hierarchical model of how caregivers or agents can access various databases from the application layer with the help of a support layer. A similar concept of data center platforms as the middleware between smart objects and the business layer can be found in [40].

The importance of standardizing interfaces across stakeholders of the IoThNet toward the design of an open platform is emphasized in [41]. As shown in Fig. 11, three categories of interface standardization to establish a cooperative ecosystem have been presented, including hardware and software interfaces, health data formats (electronic health record; EHR), and security schemes. This can eventually ensure associated interoperability. A big picture of an automating design methodology (ADM) platform for the IoThNet, particularly for rehabilitation purposes, is presented in [42]. As shown in Fig. 12, this design framework includes the human–machine interface, multidisciplinary optimization, and application management.

The feasibility of using VIRTUS, an event-driven middleware package, to support IoT healthcare applications is analyzed in [43], and reliable and scalable communications over the IoThNet have been found to be feasible through VIRTUS based on the XMPP, a protocol for instant messaging, even in the case of poor connectivity. A method to enable the IoT gateway to handle multiple users with multiple sensors is proposed in [33]. This method provides an algorithmic approach to how the gateway reads raw health data received from an edge router and parses captured data in some predetermined format in the database. A three-layer cloud platform for accessing ubiquitous cloud data through the IoThNet is designed in [22]. The tenant database layer stores multi-tenant databases. The resource layer is responsible for controlling data access, and the business layer performs required coordination for data sharing and interoperation. It should be noted that distributed health data are organized using a resource control mechanism.

Some studies [25], [31], [44], [45] have addressed IoThNet platform issues. Although these studies have not provided a comprehensive and generalized analysis of such models, some design issues are noteworthy in specific cases. A semantic platform architecture is introduced in [46]. This architecture offers semantic interoperability across heterogeneous systems and devices and provides user

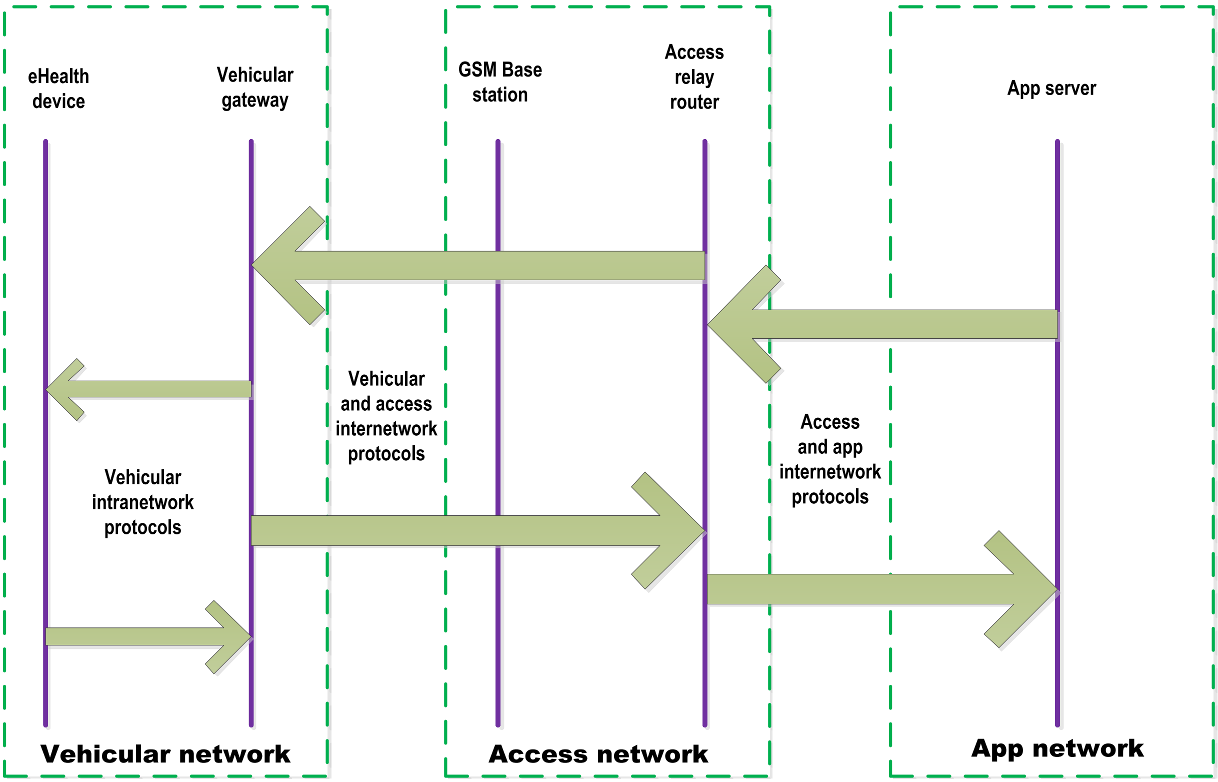

FIGURE 9. The auto-configuration protocol in V2I scenario.

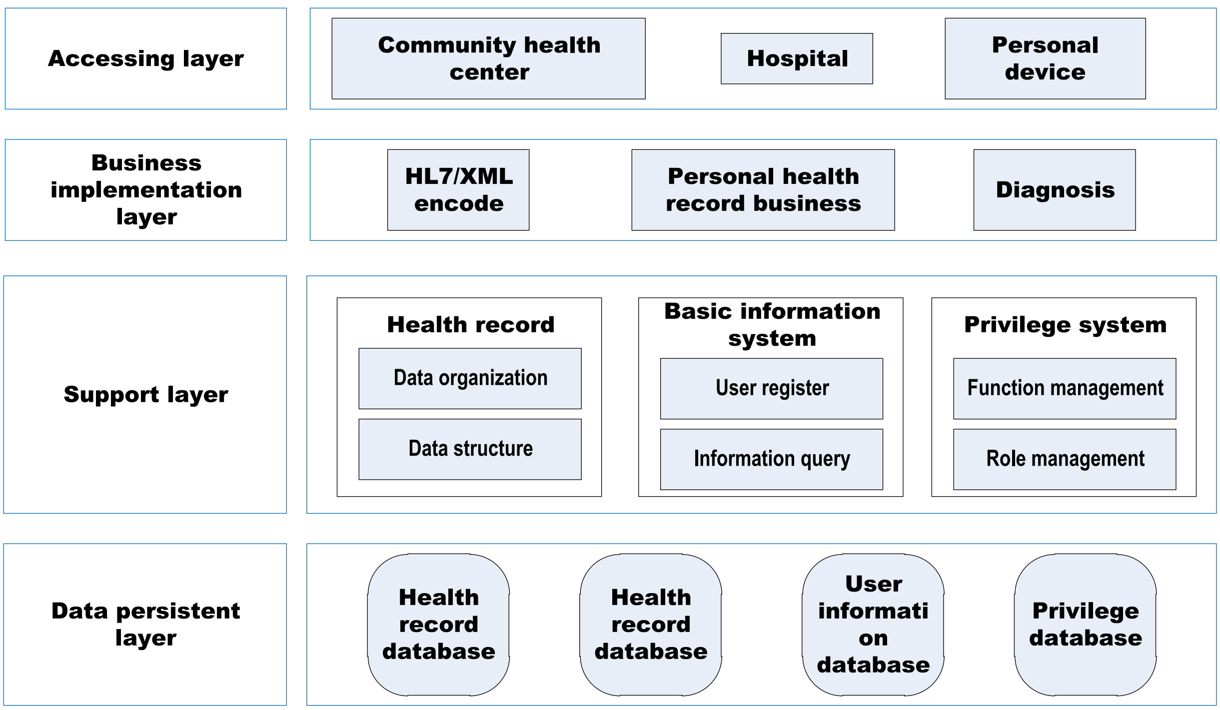

FIGURE 10. A functional framework of a health information service model.

environments and domotic devices with some semantic capability. Its semantic layer can support four types of ontologies.

III. IoT HEALTHCARE SERVICES AND APPLICATIONS

IoT-based healthcare systems can be applied to a diverse array of fields, including care for pediatric and elderly patients,

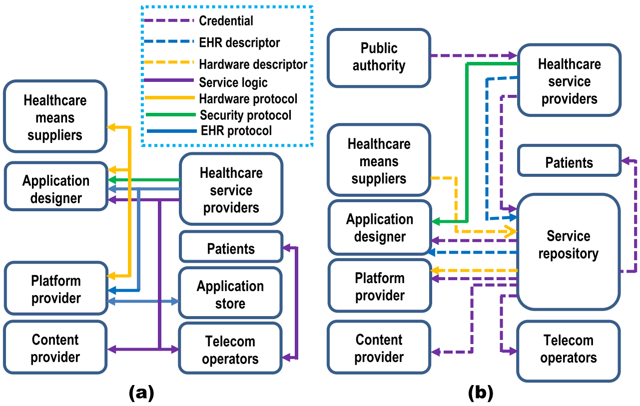

FIGURE 11. Platform interfaces (a) without standardization (b) with standardization.

the supervision of chronic diseases, and the management of private health and fitness, among others. For a better understanding of this extensive topic, this paper broadly categorizes the discussion in two aspects: services and applications. Applications are further divided into two groups: single- and clustered-condition applications. A single-condition application refers to a specific disease or infirmity, whereas a clustered-condition application deals with a number of diseases or conditions together as a whole. Fig. 13 illustrates this categorization. Note that this classification structure is framed based on today's available healthcare solutions using the IoT. This list is inherently dynamic in nature and can be easily enhanced by adding additional services with distinct features and numerous applications covering both single- and clustered-condition solutions. This section introduces each of the services and applications shown in the figure.

A. IoT HEALTHCARE SERVICES

The IoT is anticipated to enable a variety of healthcare services in which each service provides a set of healthcare solutions. In the context of healthcare, there is no standard definition of IoT services. However, there may be some cases in which a service cannot be objectively differentiated from a particular solution or application. This paper proposes that a service is by some means generic in nature and has the potential to be a building block for a set of solutions or applications. In addition, it should be noted that general services and protocols required for IoT frameworks may require slight modifications for their proper functioning in healthcare scenarios. These include notification services, resource-sharing services, internet services, cross-connectivity protocols for heterogeneous devices, and link protocols for major connectivity. The easy, fast, secure, and low-power discovery of devices and services can be added to this list. However, a discussion on such generalized IoT services is beyond the scope of this survey. The interested reader is referred to the literature for a more comprehensive understanding of this topic. The following subsections include various types of IoT healthcare services.

1) AMBIENT ASSISTED LIVING (AAL)

In general, neither a smart home nor a typical IoT-based medical service is inevitably supposed to offer specialized

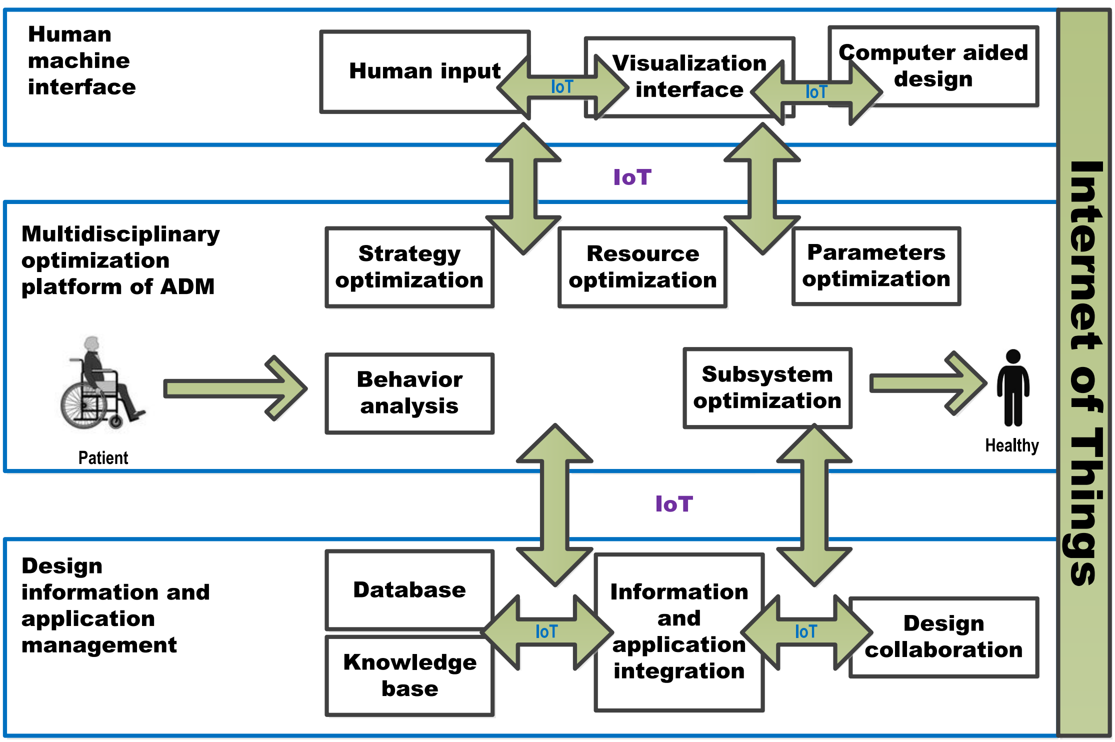

FIGURE 12. An automating design methodology framework.

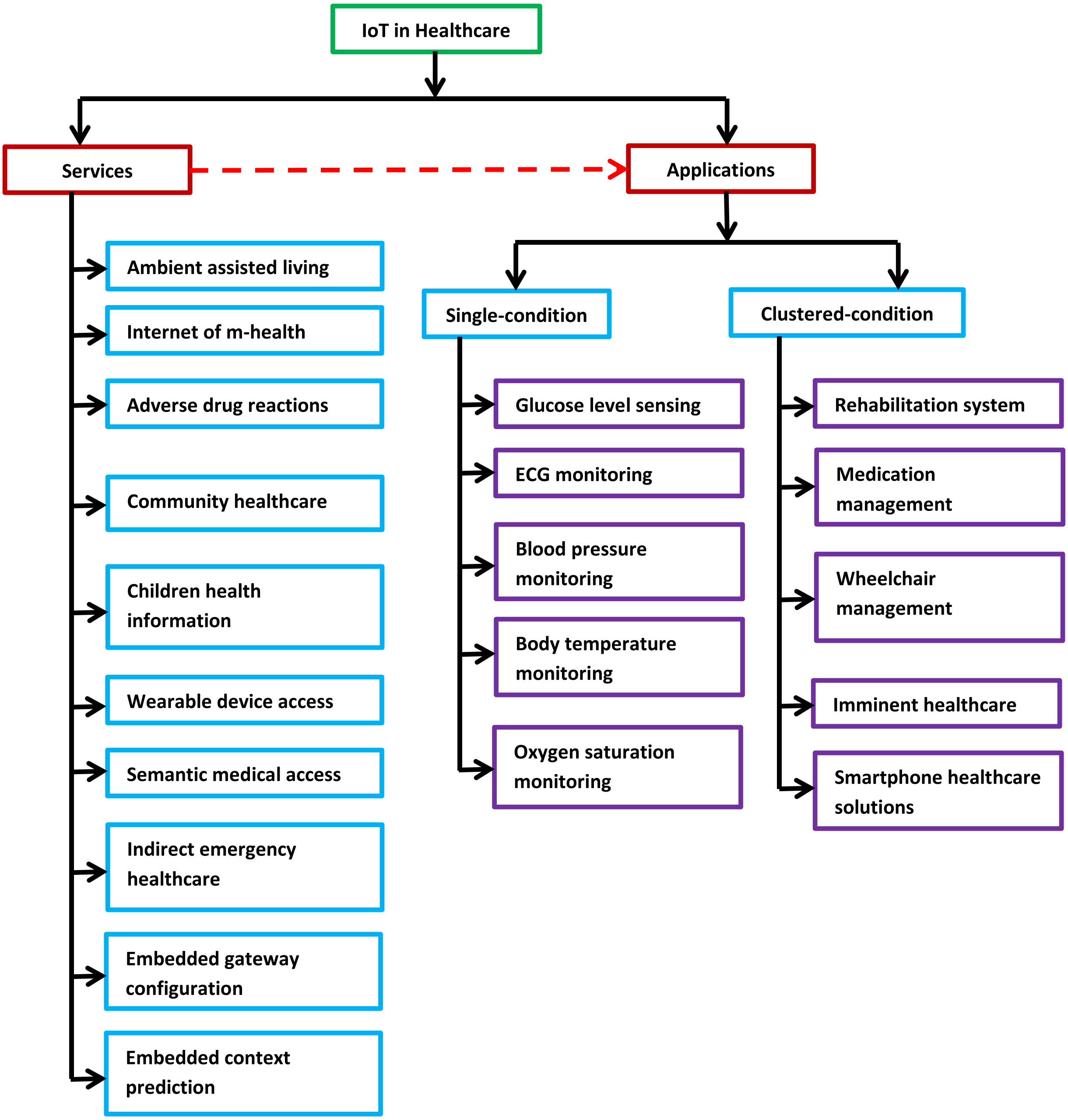

FIGURE 13. IoT healthcare services and applications.

services to elderly individuals. That is, a separate IoT service is obligatory. An IoT platform powered by artificial intelligence that can address the health care of aging and incapacitated individuals is called ambient assisted living (AAL). The purpose of AAL is to extend the independent life of elderly individuals in their place of living in a convenient and safe manner. Solutions provided by AAL services can make elderly individuals confident by ensuring greater autonomy and giving them human-servant-like assistance in case of any problem. Several studies have discussed AAL based on the IoT. A modular architecture for automation, security, control, and communication is proposed for IoT-based AAL in [26]. This architecture basically serves as a framework for providing healthcare services to elderly and incapacitate individuals. As the underlying technology for implementing this architecture, 6LoWPAN is used for active communications, and radio frequency identification (RFID) and near-field communications (NFC) are used for passive communications. This architecture has been extended by incorporating algorithms based on medical knowledge to detect problems facing elderly individuals. The question of how the central AAL paradigm over the IoT can be realized is discussed in [47], and it has been argued that a combination of keep-in-touch (KIT) smart objects and closed-loop healthcare services can facilitate AAL. Then this resultant infrastructure can employ the IoT to enable communication between stakeholders such as elderly individuals, caregivers, physicians, and family members. These efforts have motivated researchers to develop protocols for making KIT smart objects and closed-loop healthcare services function through the IoT. An open, secure, and flexible platform based on the IoT and cloud computing is proposed in [25]. This platform addresses various limitations associated with interoperability, security, the streaming quality of service (QoS), and data storage, and its feasibility has been verified by installing an IoT-based health gateway on a desktop computer as reference implementation. Previous studies have highlighted the need for AAL and corresponding technological support and presented a tentative road map for state-of-the-art AAL technologies [19]. Further, an IoT-based secure service for AAL-based medication control is examined in [48].

2) THE INTERNET OF m-HEALTH THINGS (m-IoT)

As shown in [49], m-health is nothing but mobile computing, medical sensors, and communications technologies for healthcare services. In theory, m-IoT familiarizes a novel healthcare connectivity model that connects the 6LoWPAN with evolving 4G networks for future internet-based m-health services. Although m-IoT characteristically represents the IoT for healthcare services, it is worth mentioning that there exist some specific features intrinsic to the global mobility of participating entities. This leads to the conceptualization of m-IoT services. The use of m-IoT services has been examined based on the potential of m-IoT for the noninvasive sensing of the glucose level, and the m-IoT architecture, implementation issues, and challenges are addressed in [28]. Context-aware issues and m-IoT ecosystems are two distinct challenges in m-IoT services [19]. A system for message-exchange-based mobility is introduced, but its low network power consumption is not verified in [26].

3) ADVERSE DRUG REACTION (ADR)

An adverse drug reaction (ADR) is an injury from taking a medication [50]. This may happen after a single dose of a drug or its prolonged administration or as a consequence of a combination of two or more drugs. Because the ADR is inherently generic, that is, not specific to the medication for a particular disease, there is a need to separately design certain common technical issues and their solutions (called ADR services). An IoT-based ADR is proposed in [51]. Here the patient's terminal identifies the drug by means of barcode/NFC-enabled devices. With the help of a pharmaceutical intelligent information system, this information is then coordinated to sense whether the drug is compatible with its allergy profile and electronic health record. The iMedPack has been developed as part of the iMedBox to address the ADR [20] by making use of RFID and controlled delamination material (CDM) technologies.

4) COMMUNITY HEALTHCARE (CH)

Community healthcare monitoring comes with the concept of establishing a network covering an area around a local community. This may be an IoT-based network around a municipal hospital, a residential area, or a rural community. The concatenation of several such networks can be realized as a cooperative network structure. In this regard, a specialized service called community health care (CH) is inevitable for meeting collective technical requirements as a package. A cooperative IoT platform for rural healthcare monitoring has been proposed and found to be energy-efficient [52]. Here a distinct authentication and authorization mechanism should be incorporated because it is a cooperative network. A community medical network is proposed in [35]. This network integrates multiple wireless body area networks (WBANs) to materialize CH. The structure of a community medical network can be viewed as a "virtual hospital." A resident health information service platform based on a a functional framework of a four-layer structure has been considered, and a method for sharing data between medical facilities and the service platform for obtaining health records and accessing remote medical advice is presented in [39].

5) CHILDREN HEALTH INFORMATION (CHI)

Raising awareness around children's health and cultivating the general public as well as children themselves on needs of children with emotional, behavioral, or mental health problems and their family members are crucial [53]. This has motivated researchers to develop a specialized IoT service called children health information (CHI) to address this need in an effective manner. In this regard, an interactive totem placed in a pediatric ward offering CHI services aimed at educating, amusing, and empowering hospitalized children is proposed in [54], and an IoT-based m-health service that can encourage children to acquire good nutritional habits with the help of their teachers and parents is presented in [44].

6) WEARABLE DEVICE ACCESS (WDA)

Various nonintrusive sensors have been developed for a diverse range of medical applications [55], particular for WSN-based healthcare services. Such sensors are prospective enough to deliver the same services through the IoT. On the other hand, wearable devices can come with a set of desirable features appropriate for the IoT architecture. Therefore, the integration of aforementioned sensors into wearable products is apparent. However, the heterogeneous nature of wearable products and medical sensors uncovers numerous challenges for researchers and developers working toward the said integration. In this context, a dedicated service called wearable device access (WDA) is required. The integration of wearable devices into applications based on WSNs for IoT scenarios is presented in [56]. This method introduces a prototype system that can be used in a wide variety of healthcare applications through various mobile computing devices such as smartphones and smart watches. An activity recognition method based on mobile devices for the remote monitoring of patients is proposed in [57], an IoT-based remote activity monitoring system using wearable devices is demonstrated in [43], and the question of how Bluetooth low energy (BLE) can enable a WBAN for wearable devices is addressed in [30].

7) SEMANTIC MEDICAL ACCESS (SMA)

The use of semantics and ontologies to share large amounts of medical information and knowledge has been widely considered [58]. The wide potential of medical semantics and ontologies has received close attention from designers of IoT-based healthcare applications. Placing medical semantics and ontologies on the top of the IoT calls for a separate service called semantic medical access (SMA). A semantic medical monitoring system based on IoT sensors is proposed in [24]. IoT healthcare applications employ medical rule engines to analyze massive amounts of sensor data stored in the cloud. A ubiquitous data-accessing method that can collect, integrate, and interoperate IoT data for emergency medical services is proposed [22], and a similar method is presented in [46]. Several studies have discussed semantic medical issues in the context of the IoT environment [31], [45], [57].

8) INDIRECT EMERGENCY HEALTHCARE (IEH)

There are many emergency situations where healthcare issues are heavily involved, including adverse weather conditions, transport (aviation, ship, train, and vehicle) accidents, earthen sites collapse, and fire, among others. In this context, a dedicated service called indirect emergency health care (IEH) can be offer a bundle of solutions such as information availability, alter notification, post-accident action, and record keeping. To the authors' knowledge, no major study has addressed these issues in emergency health care based on IoT networks. In this regard, there is a need to address the question of how appropriate healthcare systems can be envisioned. Here the interested reader is referred to [59] and [60].

9) EMBEDDED GATEWAY CONFIGURATION (EGC)

The embedded gateway configuration (EGC) service is an architectural service that connects network nodes (to which patients are directly connected), the Internet (to which required servers and clients are directly connected), and other medical equipment. From a service perspective, although a gateway may emerge with different characteristics, this requires some common integration features depending on the specific purpose of the deployed gateway. It is in this regard that the notion of the EGC service becomes relevant. As part of a ubiquitous healthcare system, a good example of an EGC service is found in [33]. Here the service allows for automated and intelligent monitoring. A personal mobile gateway is employed for a medical sensor network based on the IoT in [61], and the question of how an IoT gateway may be implemented using mobile computing devices is discussed in [25].

10) EMBEDDED CONTEXT PREDICTION (ECP)

To build context-aware healthcare applications over IoT networks, third-party developers require generic frameworks with suitable mechanisms, which can be called the embedded context prediction (ECP) service. Such a framework is developed in [62] in the context of ubiquitous health care. A number of research challenges in context-aware ubiquitous healthcare systems have been uncovered [63]. More or less similar research challenges need to be addressed for context-aware healthcare applications over IoT networks, and a context predictor is applied to IoT-enabled remote health monitoring in [64].

B. IoT HEALTHCARE APPLICATIONS

In addition to IoT services, IoT applications deserve closer attention. It can be noted that services are used to develop applications, whereas applications are directly used by users and patients. Therefore, services are developer-centric, whereas applications, user-centric. In addition to applications covered in this section, various gadgets, wearables, and other healthcare devices currently available in the market are discussed. These products can be viewed as IoT innovations that can lead to various healthcare solutions. The next subsections address various IoT-based healthcare applications, including both single- and clustered-condition applications.

1) GLUCOSE LEVEL SENSING

Diabetes is a group of metabolic diseases in which there are high blood glucose (sugar) levels over a prolonged period. Blood glucose monitoring reveals individual patterns of blood glucose changes and helps in the planning of meals, activities, and medication times. An m-IoT configuration method for noninvasive glucose sensing on a real-time basis is proposed in [28]. In this method, sensors from patients are linked through IPv6 connectivity to relevant healthcare providers. The utility model in [65] unveils a transmission device for the transmission of collected somatic data on blood glucose based on IoT networks. This device includes a blood glucose collector, a mobile phone or a computer, and a background processor. A similar innovation is found in [66]. In addition, a generic IoT-based medical acquisition detector that can be used to monitor the glucose level is proposed in [67].

2) ELECTROCARDIOGRAM MONITORING

The monitoring of the electrocardiogram (ECG), that is, the electrical activity of the heart recorded by electrocardiography, includes the measurement of the simple heart rate and the determination of the basic rhythm as well as the diagnosis of multifaceted arrhythmias, myocardial ischemia, and prolonged QT intervals [68]. The application of the IoT to ECG monitoring has the potential to give maximum information and can be used to its fullest extent [69]. A number of studies [20], [31], [33], [35], [40], [56], [70] have explicitly discussed IoT-based ECG monitoring. The innovation in [71] introduces an IoT-based ECG monitoring system composed of a portable wireless acquisition transmitter and a wireless receiving processor. The system integrates a search automation method to detect abnormal data such that cardiac function can be identified on a real-time basis. There exists a comprehensive detection algorithm of ECG signals at the application layer of the IoT network for ECG monitoring [72].

3) BLOOD PRESSURE MONITORING

The question of how the combination of a KIT blood pressure (BP) meter and an NFC-enabled KIT mobile phone becomes part of BP monitoring based on the IoT is addressed in [47]. A motivating scenario in which BP must be regularly controlled remotely is presented by showing the communications structure between a health post and the health center in [73]. The question of how the Withings BP device operates depends on the connection to an Apple mobile computing device is addressed in [74]. A device for BP data collection and transmission over an IoT network is proposed in [75]. This device is composed of a BP apparatus body with a communication module. A location-intelligent terminal for carry-on BP monitoring based on the IoT is proposed in [76].

4) Body Temperature Monitoring

Body temperature monitoring is an essential part of healthcare services because body temperature is a decisive vital sign in the maintenance of homeostasis [77]. In [28], the m-IoT concept is verified using a body temperature sensor that is embedded in the TelosB mote, and a typical sample of attained body temperature variations showing the successful operation of the developed m-IoT system is presented. A temperature measurement system based on a home gateway over the IoT is proposed in [78]. The home gateway transmits the user's body temperature with the help of infrared detection. Another IoT-based temperature monitoring system is proposed in [79]. The main system components responsible for temperature recording and transmission are the RFID module and the module for monitoring body temperature.

5) OXYGEN SATURATION MONITORING

Pulse oximetry is suitable for the noninvasive nonstop monitoring of blood oxygen saturation. The integration of the IoT with pulse oximetry is useful for technology-driven medical healthcare applications. A survey of CoAP-based healthcare services discusses the potential of IoT-based pulse oximetry [80]. The function of the wearable pulse oximeter Wrist OX2 by Nonin is illustrated in [31]. This device comes with connectivity based on a Bluetooth health device profile, and the sensor connects directly to the Monere platform. An IoT-optimized low-power/low-cost pulse oximeter for remote patient monitoring is proposed in [81]. This device can be used to continuously monitor the patient's health over an IoT network. An integrated pulse oximeter system for telemedicine applications is described in [82]. A wearable pulse oximeter for health monitoring using the WSN can be adapted to the IoT network [83].

6) REHABILITATION SYSTEM

Because physical medicine and rehabilitation can enhance and restore the functional ability and quality of life of those with some physical impairment or disability, they represent a vital branch of medicine. The IoT has the potential to enhance rehabilitation systems in terms of mitigating problems linked to aging populations and the shortage of health experts. An ontology-based automating design method for IoT-based smart rehabilitation systems is proposed in [42]. This design successfully demonstrates that the IoT can be an effective platform for connecting all necessary resources to offer real-time information interactions. IoT-based technologies can form a worthwhile infrastructure to support effective remote consultation in comprehensive rehabilitation [84]. There are many IoT-based rehabilitation systems such as an integrated application system for prisons [85], the rehabilitation training of hemiplegic patients [86], a smart city medical rehabilitation system [87], and a language-training system for childhood autism [88].

7) MEDICATION MANAGEMENT

The noncompliance problem in medication poses a serious threat to public health and causes huge financial waste across the world. To address this issue, the IoT offers some promising solutions. An intelligent packaging method for medicine boxes for IoT-based medication management is proposed in [89]. This method entails a prototype system of the I2Pack and the iMedBox and verifies the system by field trials. This packaging method comes with controlled sealing based on delamination materials controlled by wireless communications. The eHealth service architecture based on RFID tags for a medication control system over the IoT network is presented in [90]. Here the prototype implementation is demonstrated, and this ubiquitous medication control system is designed specifically for providing AAL solutions.

8) WHEELCHAIR MANAGEMENT

Many researchers have worked to develop smart wheelchairs with full automation for disabled people. The IoT has the potential to accelerate the pace of work. A healthcare system for wheelchair users based on the IoT technology is proposed in [40]. The design comes with WBANs integrated with various sensors whose functions are tailored to IoT requirements. A medical support system considering peer-to-peer (P2P) and the IoT technology is implemented in [91]. This system provides for chair vibration control and can detect the status of the wheelchair user. Another noteworthy example of IoT-based wheelchair development is the connected wheelchair designed by Intel's IoT department [92]. This development eventually shows that standard "things" can evolve into connected machines driven by data. This device can monitor vitals of the individual sitting in the chair and collect data on the user's surroundings, allowing for the rating of a location's accessibility.

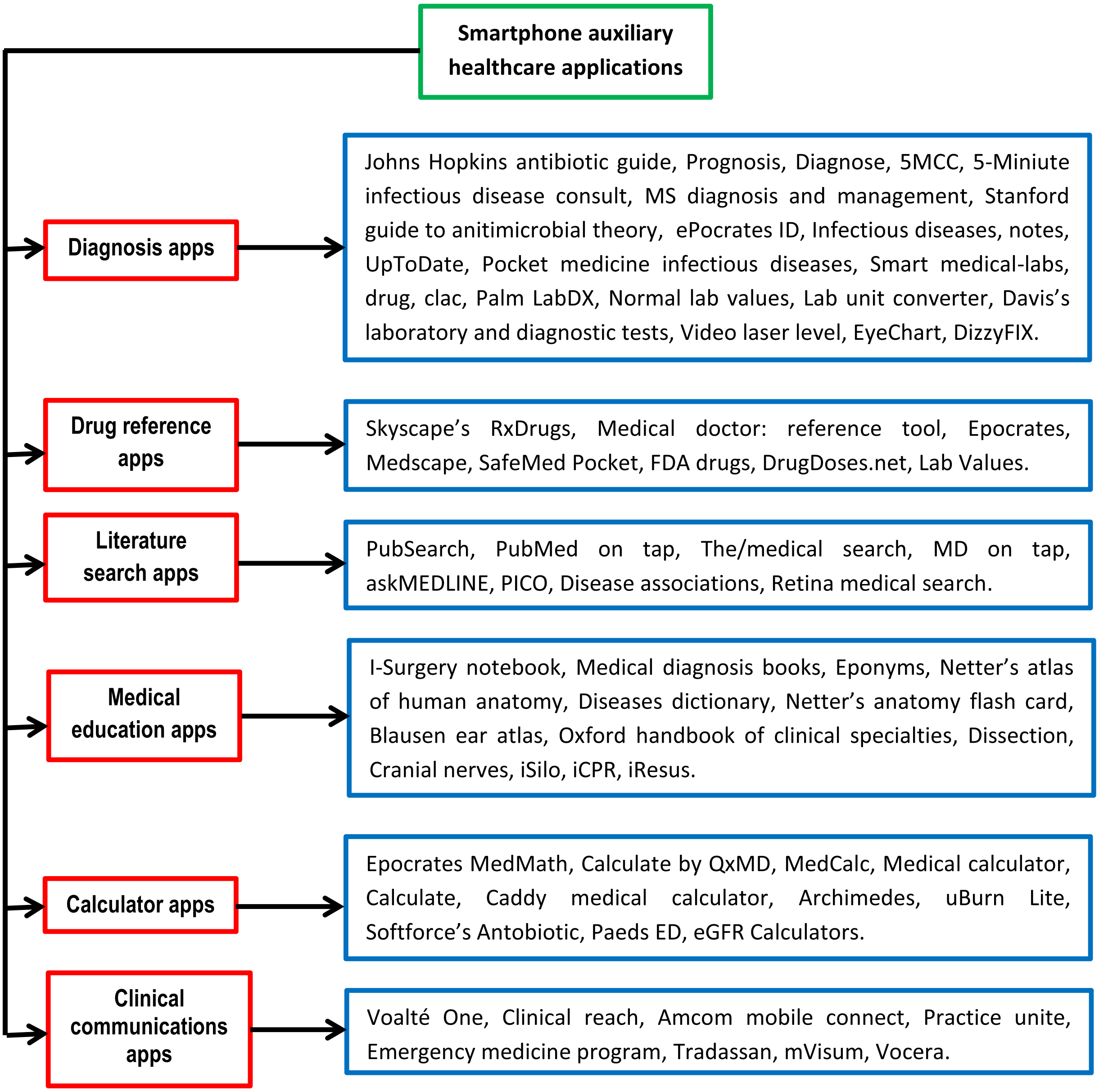

FIGURE 14. Auxiliary healthcare apps for smartphones.

9) IMMINENT HEALTHCARE SOLUTIONS

Many other portable medical devices are available though there is no explicit demonstration of the integration of those devices into IoT networks. That is, it is only a matter of time before these devices become embedded with IoT functions. Increasing numbers of medical healthcare applications, devices, and cases have kept pace with the growing demand for IoT-based services across the world. Some healthcare areas whose integration with the IoT appears imminent include hemoglobin detection, peak expiratory flow, abnormal cellular growth, cancer treatment, eye disorder, skin infection, and remote surgery [52], [93], [94]. Most devices today are portable diagnostic devices with conventional connectivity.

10) HEALTHCARE SOLUTIONS USING SMARTPHONES

Recent years have witnessed the emergence of electronic devices with a smartphone-controlled sensor, which highlights the rise of smartphones as a driver of the IoT. Various hardwire and software products have been designed to make smartphones a versatile healthcare device. An extensive review of healthcare apps for smartphones is systematically provided in [95], including a discussion on apps for patients and general healthcare apps as well as on medical education, training, information search apps, and others (collectively referred to as auxiliary apps). In addition, there are many recent apps serving similar purposes [96]–[101]. Based on these references, Fig. 14 presents a classification diagram of auxiliary apps. Note that this figure includes no general healthcare apps and apps for patients, which are addressed later in this section. Diagnostic apps are used to access diagnostic and treatment information. Drug reference apps typically provide names of drugs, their indications, dosages, costs, and identifying features. Literature search apps facilitate searches for biomedical literature databases to find appropriate medical information. Medical education apps typically deal with tutorials, training, various surgical demonstrations, color illustrations of different images, and medical books. Calculator apps come with various medical formulas as well as equations and calculate respective parameters of interest (e.g., the body surface burn percentage). Clinical communication apps simplify communication between clinicians within a hospital. A number of image analysis algorithms for smartphones that facilitate noncontact measurements useful for healthcare applications are introduced in [102]. A good (but not complete) survey of smartphone apps providing healthcare solutions is presented [70]. Smartphones can effectively perform the following healthcare diagnosis and/or monitoring: the detection of asthma, chronic obstructive pulmonary disease, cystic fibrosis, coughing, allergic rhinitis, nose-related symptoms of the respiratory tract, the heart rate, BP, blood oxygen saturation, and melanoma and the analysis of wounds in advanced diabetes patients [81]–[83], [103]–[107]. In addition to its ubiquitous deployment capability and availability for users, there is a great advantage of using smartphone healthcare apps in terms of providing low-cost solutions. However, many challenges remain, including computational complexity, power consumption, and noisy environments around smartphones, which should be easy to solve. In addition, there are many health and fitness accessories suitable for smartphones that can help individuals achieve their best shape. For example, Fitbit Flex, a fitness tracking wristband, keeps track of steps taken, the distance travelled, and calories burned. A separate section of this paper provides a more detailed discussion on existing commercial healthcare products that can be viewed as a foundation of IoT healthcare devices.

Table 1 lists various healthcare applications and discusses their required sensors, operations, and IoT associations, but it does not focus on any smartphone healthcare apps. For this, Table 2 includes various smartphone-based healthcare apps with a short description of each. Although there are many apps by developers across the world, this paper discusses some selected apps based on their type, popularity, and intuitive analysis. Most of the apps listed here can be used easily. The interested reader is encouraged to find up-to-date apps similar to those listed here.

IV. IoT HEALTHCARE INDUSTRY TRENDS AND STATUS

The emerging IoT in the healthcare field has experienced a burst of activity and creativity, exciting entrepreneurs and venture capital firms. The space appears as an active group of new start-ups and large firms that are willing to be part of what may be a giant market as well as enabling products and technologies. This section provides an extensive list of these products and technologies for a better understanding of the IoT status.

Edisse has a prototype wearable sensor for real-time tracking, fall detection, and alerts. It basically combines the GPS, mobile data, short messaging services (SMSs), and an accelerometer to detect unusual movements such as a fall and then reports them to a third party such as adult children or other caregivers [108]. Withings has developed a number of healthcare devices [109], including a set of internet/app-enabled scales, a BP device/app, and a baby monitor. A Chinese firm has developed miPlatform, an integrated all-in-one medical imaging and information management platform supporting cloud-based image storage and computation, web-based 3D image post-processing and visualization, and integrated telemedicine competence [110]. Neusoft has provided broad IT solutions for China's medical industry and personal healthcare network services [111], and it also offers their services for hospitals, public health facilities, and health management. Neusoft has focused on IoT-based healthcare services. LiftMaster has developed products that make home access easier and put its owner in control of how he or she comes and goes [112]. It ensures full control and connectivity by staying connected to smartphones anywhere, anytime. The potential of LiftMaster in the IoT field can be easily seen for home applications for elderly individuals. Garmin's Vivosmart is a fitness band/smartwatch that can issue smart notifications to let the user decide on taking action or continuing on her or her active way [113]. Jawbone's UP3 is many state-of-the-art sensors offering the user a full picture of his or her health status and includes activity tracking, sleep tracking, smart coaching, and heart health sensing [114]. As shown in Fig. 15, Angel is designed to measure the user's pulse, temperature, activity, and blood oxygen level [115]. This wrist band sends to the user's smartphone this vital information. A group of researchers in Korea has introduced a sufficiently compact and subtle wearable BP sensor that can be used to deliver nonstop monitoring for a long period without disturbing the daily activity of the user [116]. An iHealth Lab team has developed a set of IoT healthcare devices including a wireless BP wrist monitor, a BP dock, a wireless body analysis scale, iHealth Lite, iHealth Edge, a wireless pulse oximeter, iHealth Align, and a wireless smart glucose-monitoring system [117]. Basis has developed a health tracker that can help the user improve his or her fitness, sleep, and stress [118]. The device comes with heart rate tracking and body intelligence quotient (IQ) intelligence. Phyode has introduced a health wristband that measures the user's heart rate variability, infers the agility of the autonomic nervous system, and displays the user's mental state [119]. Rejuven's Rejiva monitors the user's total health by measuring his or her ECG, heart rate variability, respiratory rate, sleep position, restfulness, breathing index, and energy level [120]. The device can also investigate the state of the autonomic nervous system.

TABLE 1. IoT applications in health care.

Infirmity/condition	Sensors used; operations; IoT roles/connections
Diabetes	A non-invasive opto-physiological sensor; the sensor's output is connected to the TelosB mote that converts an analog signal to a digital one; IPV6 and 6LoWPAN protocol architectures enabling wireless sensor devices for all IP-based wireless nodes.
Wound analysis for advanced diabetes patients	A smartphone camera; image decompression and segmentation; the app runs on the software platform in the smartphone's system-on-chip (SoC) to drive the IoT.
Heart rate monitoring	Capacitive electrodes fabricated on a printed circuit board; digitized right on top of the electrode and transmitted in a digital chain connected to a wireless transmitter; BLE and Wi-Fi connect smart devices through an appropriate gateway.
BP monitoring	A wearable BP sensor; oscillometric and automatic inflation and measurement; WBAN connects smart devices through an appropriate gateway.
Body temperature monitoring	A wearable body temperature sensor; skin-based temperature measurement; WBAN connects smart devices through an appropriate gateway.
Rehabilitation system	A wide range of wearable and smart home sensors; cooperation, coordination, event detection, tracking, reporting, and feedback to the system itself; Interactive heterogeneous wireless networks enable sensor devices to have various access points.
Medication management	Delamination materials and a suit of wireless biomedical sensors (touch, humidity, and CO_2); the diagnosis and prognosis of vitals recorded by wearable sensors; the global positioning system (GPS), database access, web access, RFIDs, wireless links, and multimedia transmission.
Wheelchair management	WBAN sensors (e.g., accelerometers, and ECG, and pressure); nodes process signals, realize abnormality, communicate with sink nodes wirelessly, and perceive surroundings; smart devices and data center layers with heterogeneous connectivity.
Oxygen saturation monitoring	A pulse oximeter wrist by Nonin; intelligent pulse-by-pulse filtering; ubiquitous integrated clinical environments.
Eye disorder, skin infection	Smartphone cameras; visual inspection and/or pattern matching with a standard library of images; the cloud-aided app runs on the software platform in the smartphone's SoC to drive the IoT.
Asthma, chronic obstructive pulmonary disease, cystic fibrosis	A built-in microphone audio system in the smartphone; calculates the air flow rate and produces flow-time, volume-time, and flow-volume graphs; the app runs on the software platform in the smartphone's SoC to drive the IoT.
Cough detection	A built-in microphone audio system in the smartphone; an analysis of recorded spectrograms and the classification of rainforest machine learning; the app runs on the software platform in the smartphone's SoC to drive the IoT.
Allergic rhinitis and nose-related symptoms	A built-in microphone audio system in the smartphone; speech recognition and vector machine classification; the app runs on the software platform in the smartphone's SoC to drive the IoT.
Melanoma detection	A smartphone camera; the matching of suspicious image patterns with a library of images of cancerous skin; the app runs on the software platform in the smartphone's SoC to drive the IoT.
Remote surgery	Surgical robot systems and augmented reality sensors; robot arms, a master controller, and a feedback sensory system giving feedback to the user to ensure telepresence; real-time data connectivity and information management systems.

TABLE 2. Smartphone apps for general health care.

Apps	Descriptions
Health Assistant	Keeps track of a wide range of health parameters such as body water and fat, weight, BP, body temperature, lipids, the glucose level, and various physical activities.
Healthy Children	Can search for pediatricians by location and request their advise for quick answers.
Google Fit	Tracks the user's walking, running, and cycling activities.
Calorie Counter	Keeps track of food consumed by the user as well as his or her weight and measurements, among others.
Water Your Body	Reminds the user to drink water every day and tracks his or her water-drinking habits.
Noom Walk	Serves as a pedometer to count the user's steps at all times.
Pedometer	Records the number of steps the user takes and displays related information such as the number of calories burned per a unit of time.
Period Calendar	Keeps track of the best periods, cycles, and ovulation dates and helps the user achieve or prevent pregnancy.
Period Tracker	Keeps track of periods and forecasts fertility.
Instant Heart Rate	Measures the heart rate by using the smartphone's built-in camera to sense changes of the color of the fingertip, which is directly related to the pulse.
Cardiax Mobile ECG	Serves as a companion app for Cardiax Windows's full-scale, 12-channel personal computer (PC) ECG system.
ECG Self-Monitoring	Serves as an automatic ECG device by registering ECG data based on the built-in "ECG self-check" software.
ElektorCardioscope	Displays ECG data through a wireless terminal.
Runtastic Heart Rate	Measures the heart rate on a real-time basis.
Heart Rate Monitor	Checks the heart rate on a real-time basis.
Cardiomobile	Monitors cardiac rehabilitation remotely on a real-time basis.
Blood Pressure (BP) Watch	Collects, tracks, analyzes, and shares BP data.
Finger Blood Pressure Prank	Measures BP based on the finger print.
OnTrack Diabetes	Tracks blood glucose and medication to help manage diabetes.
Finger Print Thermometer	Determines body temperature from the finger print.
Body Temperature	Keeps track of body temperature and identifies its severity.
Medisafe Meds & Pill Reminder	Reminds the user of medication times.
Dosecast edication Reminder	Reminds the user of medication times, tracks the inventory, and maintains a log for drug management.
Rehabilitation Game	Serves as interactive game facilitating the auditory rehabilitation of patients with hearing loss.
iOximeter	Calculates the pulse rate and SpO_2.
Eye Care Plus	Tests and monitors vision.
SkinVision	Keeps track of the user's skin health and enables the early discovery of any skin disorder.
Asthma Tracker and Log	Keeps track of the patient's asthma.

TABLE 2. (Continued) Smartphone apps for general health care.

my CF (cystic fibrosis)	Keeps track of the user's cystic fibrosis status.
PulmonaryRehabilitation	Serves as a pulmonary rehabilitation suite for self-management.
eCAALYX	Monitors several chronic conditions.
Test Your Hearing	Tests various aspects of hearing.
uHear	Allows for the self-assessment of hearing.
Real Noise 3	Helps to stay focused in a noisy environment.
Stop Tinnitus	Helps to relieve tinnitus.
Relax Melodies	Aids sleep and relieves insomnia.
Sleep Aid	Manages sleep apnea.
Fall Detector	Monitors human activity and issues alerts on falling.
Fade	Detects a fall.
iFall	Detects a fall and responds accordingly.
Calm	Helps the user mediate, relax, and sleep.
Mayo Clinic Meditation	Helps the user in exercise and meditation
Daily Yoga	Guards the user's health by helping him or her practice yoga.

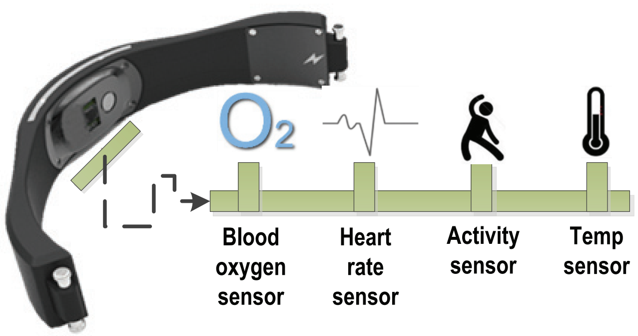

FIGURE 15. Positions of different sensors in angel.

Fuelband can measure the user's daily life activity and can track the whole-body movement [121]. The Sync smartband serves as a family activity tracker by counting the user's steps, calories, and rapid-eye-movement (REM) sleep and notifying family members in a synchronized manner [122]. Similar innovations have been proposed by ibitz [123]. Reemo is a useful device that controls the user's IoT environment by using gestures [124]. Amiigo, Haloband, Samsung Gear Fit, Omate True Smart, Orb, Memi, Fitbit Force, Melon, Olive, Runtastic Orbit, and Shine are wristbands designed mainly as health trackers [125]–[135]. RunScribe, Reebook Checklight, Micoach, and Micoach Smart Ball are wearables designed specifically for runners and athletes. These devices can help athletes run smarter, longer, and safer [136]–[138]. OMsignal is designing bio-sensing apparel and is trying to bring about a paradigm shift in the user's approach to his or her health [139]. Vessyl is a connected cup that automatically identifies and tracks what the user is drinking on a real-time basis [140]. Owlet comes with an anklet-bootie that enables caregivers to track the newborn's health. The device can track the newborn's heart rate, oxygen level, temperature, and sleep quality. Sproutling has introduced a smart baby monitor with similar purposes [141], [142]. Pulseon and AliveCor have designed connected devices for monitoring the heart rate [143], [144]. Skulpt is trying to develop a connected device for measuring the user's body composition and individual muscles [145]. NutriCrystal is a smart food scale that keeps track of nutritional intake [146]. Temp-Drop is a smart sensor that keeps track of fertility in a simple and safe manner [147]. The Proteus ingestible pill sensor, developed by Proteus Digital Health, is powered by contact with the user's stomach fluid and communicates a signal that determines the time and identify of the drug taken [148]. GlowCaps, developed by Vitality Inc., fits prescription bottles and delivers services that help the user maintain his or her prescription schedule [149]. Mimo's Mimo Monitor is a new type of infant monitor that offers parents and caregivers with real-time information on the baby's breathing, body temperature, body position, and various activity levels through the smartphone [150]. Preventice's BodyGuardian is for users with cardiac arrhythmias and can remotely read the user's biometrics. It can send data to physicians and allows the user to have his or her everyday life outside a clinical setting [151]. Fig. 16 shows a representative collection of today's IoT-based healthcare products.

In addition to the aforementioned trends in healthcare products and prototypes, it is worth noting core healthcare activities and visions of some key IoT players.

FIGURE 16. Selected IoT healthcare products and prototypes.

Table 3 provides a list of firms and their status on IoT-based healthcare solutions.

Firms such as Bsquare, Solair, Net4Thing, Orbcomm, Flexera, and PubNub have shown promise in developing IoT solutions for connected healthcare products.

V. IoT HEALTHCARE SECURITY

The IoT is growing rapidly. In the next several years, the medical sector is expected to witness the widespread adoption of the IoT and flourish through new eHealth IoT devices and applications. Healthcare devices and applications are expected to deal with vital private information such as personal healthcare data. In addition, such smart devices may be connected to global information networks for their access anytime, anywhere. Therefore, the IoT healthcare domain may be a target of attackers. To facilitate the full adoption of the IoT in the healthcare domain, it is critical to identify and analyze distinct features of IoT security and privacy, including security requirements, vulnerabilities, threat models, and countermeasures, from the healthcare perspective (Fig. 17).

A. SECURITY REQUIREMENTS

Security requirements for IoT-based healthcare solutions are similar to those in standard communications scenarios.

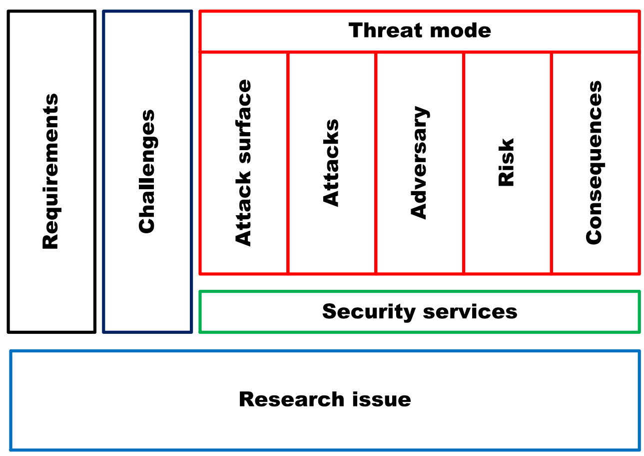

FIGURE 17. Security issues in IoT-based health care.

Therefore, to achieve secure services, there is a need to focus on the following security requirements.

1) CONFIDENTIALITY

Confidentiality ensures the inaccessibility of medical information for unauthorized users. In addition, confidential messages resist revealing their content to eavesdroppers.

TABLE 3. The IoT healthcare status and visions of some well-known technology firms.

Firm	Status and vision
CISCO	CISCO is ready to provide converged systems based on unrelated networks and can introduce effective algorithm for handling cumulative traffic loads originating from massively deployed IoT healthcare devices with advanced data analytics. In addition, it can offer clients a new class of intelligent applications to increase efficiency without losing security. CISCO has worked with leading healthcare organizations to develop a medical-grade network architecture [152].
Microsoft	Microsoft has focused on using an intelligent system to uncover the potential of IoT-based healthcare solutions. Intelligent systems provide the backbone of technologies that allow for the capture of health data from devices to ensure required connectivity. Microsoft has business intelligence tools capable of extracting important insights from collected data [153].
Google	Google has opened its code for an open-source physical web standard for the IoT [154], which can be considered an attempt to arrange an easier approach to communicate with connected medical devices.
Samsung	Samsung Electronics, together with the University of California, San Francisco, has established a digital health innovation lab to develop new smart health technologies. In addition, Samsung, together with IMEC (a leading bio-sensing research institute), has developed the Simband platform, an open reference design for sensor modules. Samsung's goal is a ubiquitous and seamless user experience for better health for everyone with no additional complexity [155].
Qualcomm	The 2net Platform of Qualcomm Life offers a set of wireless health solutions that can capture and deliver health device data to integrated portals and databases from almost all wireless medical devices of users. Such data can be stored in a system to integrate security and interoperability. Qualcomm is trying to develop intelligent, intuitive, and innovative IoT healthcare solutions [156].
Intel	Intel-powered devices can strengthen information security and improve interactions between doctors and patients. Intel emphasizes real-time synchronous communications systems and health data streaming, which can help reduce the cycle time and improve the first-time quality of many existing medical workflow environments. Intel's vision is to bring about IoT-based healthcare solutions anytime, anywhere [157].
IBM	IBM redefines value and success in health care through the notion of smarter health care. IMB has helped to develop a set of IoT devices through partnerships of other renowned firms across the world. It focuses on a series of healthcare solutions such as connected home health, data governance for health care, and health analytics for healthcare providers [158].
Apple	Apple has publicly claimed the IoT as an ultimate technology. The Apple watch can be considered a smart watch, a fitness tracker, or a heart monitor. The Memorial Hermann healthcare system relies completely on Apple's solutions to provide efficient and connected healthcare services focusing on secure access, physician gains, and better care [159].
Wind River Systems	Wind River has developed a cloud and business logic model for medical solutions based on the IoT. It designs specialized gateways, data centers, supervisory/data aggregation systems, and device control systems/sensors for this purpose. This model is expected to improve medical services facilitating life-enhancing aid for patients and providers [160].
Deutsche Telekom	Deutsche Telekom follows the concept of a secure healthcare internet system [161]. It serves as a bridge between associated stakeholders. Researchers on the team focus on developing technologies that can help healthcare services gradually become personal, local, and digital instead of being centrally organized.
GSMA	GSMA, an association of mobile operators and related firms, has launched connected living programs to bring the mobile industry and healthcare stakeholders together to deliver sustainable mHealth solutions over an intelligent and secure IoT network [162].

TABLE 3. (Continued) The IoT healthcare status and visions of some well-known technology firms.

ThingWorx	ThingWorx solutions are used by many firms to develop connected healthcare products. ThingWorx enables firms to efficiently enter a connected product space [163].
Numerex	Numerex is one of the top providers of IoT solutions and offers stakeholders required support for designing new mHealth products and converting wired legacy systems into wireless ones [164].
Machina Research	Machina Research has worked on developing a set of solutions for connected healthcare systems based on the IoT. Topics covered by its research team include AAL, remote clinical monitoring, clinical trials, connected medical environments, and telemedicine [165].
Aeris	Aeris is ready to deliver IoT solutions for remote patient monitoring, medical device manufacturers, and healthcare providers [166].
Eurotech	Eurotech designs connected medical and healthcare products that can serve as building blocks for large systems [167].

2) INTEGRITY
Integrity ensures that received medical data are not altered in transit by an adversary. In addition, the integrity of stored data and content should not be compromised.

3) AUTHENTICATION
Authentication enables an IoT health device to ensure the identity of the peer with which it is communicating.

4) AVAILABILITY
Availability ensures the survivability of IoT healthcare services (either local or global/cloud services) to authorized parties when needed even under denial-of-service attacks.

5) DATA FRESHNESS
Data freshness includes data freshness and key freshness. Because each IoT healthcare network provides some time-varying measurements, there is a need to ensure that each message is fresh. Data freshness basically implies that each data set is recent and ensures that no adversary replays old messages.

6) NON-REPUDIATION
Non-repudiation indicates that a node cannot deny sending a message sent earlier.

7) AUTHORIZATION
Authorization ensures that only authorized nodes are accessible for network services or resources.

8) RESILIENCY
If some interconnected health devices are compromised, then a security scheme should still protect the network/device/information from any attack.

9) FAULT TOLERANCE
A security scheme should continue to provide respective security services even in the presence of a fault (e.g., a software glitch, a device compromise, and a device failure).

10) SELF-HEALING
A medical device in an IoT healthcare network may fail or run out of energy. Then remaining or collaborating devices should enable a minimum level of security.

B. SECURITY CHALLENGES
Because IoT security requirements are not ensured by traditional security techniques, novel countermeasures are needed to address new challenges posed by the IoT. Challenges for secure IoT healthcare services include.

1) COMPUTATIONAL LIMITATIONS
IoT health devices are embedded with low-speed processors. The central processing unit (CPU) in such devices is not very powerful in terms of its speed. In addition, these devices are not designed to perform computationally expensive operations. That is, they simply act as a sensor or actuator. Therefore, finding a security solution that minimizes resource consumption and thus maximizes security performance is a challenging task.

2) MEMORY LIMITATIONS
Most IoT healthcare devices have low on-device memory. Such devices are activated using an embedded operating system (OS), system software, and an application binary. Therefore, their memory may not be sufficient to execute complicated security protocols.

3) ENERGY LIMITATIONS
A typical IoT healthcare network includes small health devices of limited battery power (e.g., body temperature and BP sensors). Such devices conserve energy by switching on the power-saving mode when no sensor reading needs to be reported. In addition, they operate at a low CPU speed if there is nothing important to be processed.

Therefore, the energy constraint property of IoT health devices makes finding an energy-aware security solution challenging.

4) MOBILITY

In general, healthcare devices are not static but mobile in nature. Such devices are connected to the Internet through IoT service providers. For example, a wearable body temperature sensor or a heart monitor may be connected to the Internet and notifies the concerned caregiver of the user's conditions. Such wearables are connected to the home network when the user is at home, whereas they are connected to the office network when he or she is at office. Different networks have different security configurations and settings. Therefore, developing a mobility-compliant security algorithm is a serious challenge.

5) SCALABILITY

The number of IoT devices has increased gradually, and therefore more devices are getting connected to the global information network. Therefore, designing a highly scalable security scheme without compromising security requirements becomes a challenging task.

6) COMMUNICATIONS MEDIA

In general, health devices are connected to both local and global networks through a wide range of wireless links such as Zigbee, Z-Wave, Bluetooth, Bluetooth Low Energy, WiFi, GSM, WiMax, and 3G/4G. Wireless channel characteristics of these networks make traditional wired security schemes less appropriate. Therefore, it is difficult to find a comprehensive security protocol that can treat both wired and wireless channel characteristics equally.

7) THE MULTIPLICITY OF DEVICES

Health devices within an IoT health network are diverse, ranging from full-fledged PCs to low-end RFID tags. Such devices vary according to their capability in terms of their computation, power, memory, and embedded software. Therefore, the challenge lies in designing a security scheme that can accommodate even the simplest of devices.

8) A DYNAMIC NETWORK TOPOLOGY

A health device may join an IoT health network anywhere, anytime. In addition, it can leave a network either gracefully (with proper exit notification) or disgracefully (abruptly). Temporal and spatial admission characteristics of medical devices make the network topology dynamic. Therefore, devising a security model for this type of dynamic network topology is a difficult challenge.

9) A MULTI-PROTOCOL NETWORK

A health device may communicate with other devices in the local network through a proprietary network protocol. In addition, the same IoT device may communicate with IoT service providers over the IP network. Therefore, security specialists find it difficult to devise a sound security solution for multi-protocol communications.

10) DYNAMIC SECURITY UPDATES

To mitigate potential vulnerabilities, there is a need to keep security protocols up-to-date. Therefore, updated security patches are needed for IoT health devices. However, designing a mechanism for the dynamic installation of security patches is a challenging task.

11) TAMPER-RESISTANT PACKAGES

Physical security is an important part of IoT health devices. An attacker may tamper with devices and then may later extract cryptographic secrets, modify programs, or replace those with malicious nodes. Tamper-resistant packaging is a way to defend against such attacks, but it is challenging to implement in practice.

C. A THREAT MODEL

Both IoT health devices and networks are vulnerable to security attacks because of the increased attack surface. The first scenario includes the expansion of native networks, cloud networks, and cloud services. The second scenario includes increased communication between IoT devices, networks, cloud services, and applications. The final one entails in-device hardware and software limitations.

Threats may originate from both within and outside the network. If an attack originates from a health device in a proximal network, then the attack is more severe. In addition, it is difficult to determine the malicious or compromising node within the proximal network. Further, the adversary may attack a health device and the network in a passive as well as active manner and can use similar types of IoT or power devices such as tablets and laptops to penetrate the network of interest.

D. AN ATTACK TAXONOMY

The IoT paradigm continues to evolve, and many additional IoT health devices and services are expected. Therefore, an attacker may devise different types of security threats to compromise both existing and future IoT medical devices and networks. Some threats are tangible, some are predictable, and many are hard to predict. This paper classifies existing and potential threats based on three key properties, namely information-, host-, and network-specific compromise.

1) ATTACKS BASED ON INFORMATION DISRUPTIONS

In-transit and stored health data can be manipulated or analyzed by an attacker to provide wrong information and remove information integrity. Such attacks include the following [168], [169]:

Interruption: An adversary launches denial-of-service (DoS) attacks to cause communications links to be lost or unavailable. This form of attack threatens network or healthcare service availability, network functionality, and device responsibility.

Interception: An adversary eavesdrops on medical information carried in messages to threaten data privacy and confidentiality.

Modification: An adversary gains unauthorized access to health data and tampers with them to create confusion and mislead innocent entities in the IoT health network.

Fabrication: An adversary forges messages by injecting false information to threaten message authenticity and confuse innocent participants.

Replay: An adversary replays existing messages to threaten message freshness. In addition, this increase confusion and misleads innocent entities.

2) ATTACKS BASED ON HOST PROPERTIES

Three types of attacks can be launched based on host properties [170].

User Compromise: An adversary comprises the user's health devices and networks by cheating or stealing. This type of attack reveals sensitive information such as passwords, cryptographic keys, and user data.

Hardware Compromise: An adversary tampers with physical devices and may extract on-device program codes, keys, and data. An attacker may reprogram compromised devices with malicious codes.

Software Compromise: An attacker takes advantage of software (e.g., operating systems, system software, and applications) vulnerabilities and glitches and forces IoT health devices to malfunction or dysfunction states (e.g., buffer overflow and resource exhaustion).

3) ATTACKS BASED ON NETWORK PROPERTIES

This type of attack comes in two forms: protocol- and layer-specific compromise.

Standard Protocol Compromise: An attacker deviates from standard protocols (application and networking protocols) and acts maliciously to threaten service availability, message privacy, integrity, and authenticity.

Network Protocol Stack Attack: As shown in Fig. 18, each layer of the protocol stack proposed by the IETF working group for the IoT network [171] has different types of vulnerabilities that an adversary may exploit to launch malicious activities. To improve the performance of IoT healthcare networks with respect to security, longevity, and connectivity under varying environmental conditions, security should be ensured at each layer of the protocol stack. The interested reader is referred to [172] and [173] for a better understanding of layer-wise issues.

E. A PROPOSED SECURITY MODEL

IoT medical paradigms are not yet robust but continue to develop. Therefore, it is difficult to identify and predict all possible vulnerabilities, threats, and attacks associated with the IoT medical domain. Nonetheless, when security specialists work to find tentative security solutions for apparent and predictable problems, such security schemes should have the capability to mitigate unseen or unpredictable issues that have yet to emerge. To achieve this security goal, security services should be designed with dynamic properties. That is, they should have the ability to reach decisions on unnoticed problems based on experience and knowledge.

Consider a scenario in which a security scheme includes services that can detect and evade two types of attacks on message integrity. However, now suppose that, with the expansion of health devices, networks, and applications, an attacker initiates a new type of attack that also threatens medical information integrity. In this case, existing security services are expected to be capable of at least identifying this new type of attack by using dynamic algorithms or those based on artificial intelligence. To address this issue, this paper proposes a security model for IoT-based healthcare services. This intelligent security model is collaborative in nature and uses the most recent knowledge base. Fig. 19 presents the collaboration scheme for the following three security services: Protection services are designed to reduce attacks. Detection services receive activity data from healthcare applications, devices, and networks and analyze captured

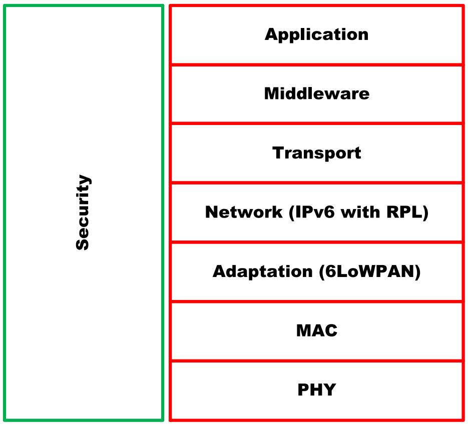

FIGURE 18. A layered networking model of secured IoT.

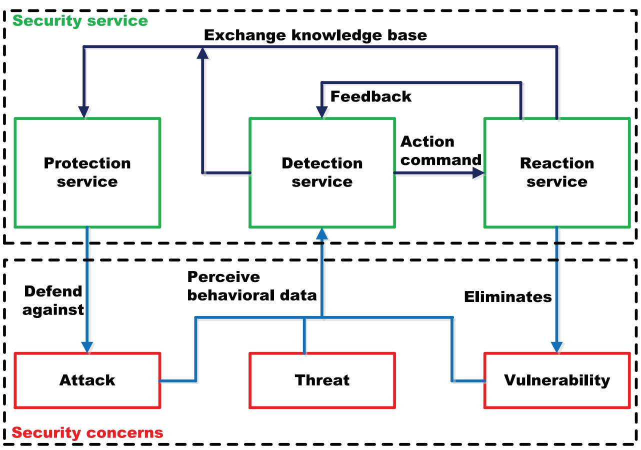

FIGURE 19. An intelligent collaborative security model.

health data, eventually detecting any anomaly. With the aid of defense mechanisms, reaction services help health entities survive all attacks.

These security services are designed using dynamic algorithms, and there is strong collaboration between these services to defend against present, possible, and unseen attacks. Upon intrusion detection, detection services issue action commands to reaction services and share their anomaly detection experience with protection services to minimize further attacks. In response to action commands from detection services, reaction services eliminate system malfunction risks and then share their action experience with both detection and protection services. In this way, inter-service collaboration is achieved.

VI. IoT HEALTHCARE TECHNOLOGIES

There are many enabling technologies for IoT-based healthcare solutions, and therefore it is difficult to prepare an explicit list. In this regard, the discussion focuses on several core technologies that have the potential to revolutionize IoT-based healthcare services.

A. CLOUD COMPUTING

The integration of cloud computing into IoT-based healthcare technologies should provide facilities with ubiquitous access to shared resources, offering services upon on request over the network and executing operations to meet various needs.

B. GRID COMPUTING

The insufficient computational capability of medical sensor nodes can be addressed by introducing grid computing to the ubiquitous healthcare network. Grid computing, more accurately cluster computing, can be viewed as the backbone of cloud computing.

C. BIG DATA

Big data can include huge amounts of essential health data generated from diverse medical sensors and provide tools for increasing the efficiency of relevant health diagnosis and monitoring methods and stages.

D. NETWORKS

Various networks ranging from networks for short-range communications (e.g., WPANs, WBANs, WLANs, 6LoWPANs, and WSNs) to long-range communications (e.g., any type of cellular network) are part of the physical infrastructure of the IoT-based healthcare network. In addition, the employment of ultra-wideband (UWB), BLE, NFC, and RFID technologies can help design low-power medical sensor devices as well communications protocols.

E. AMBIENT INTELLIGENCE

Because end users, clients, and customers in a healthcare network are humans (patients or health-conscious individuals), the application of ambient intelligence is crucial. Ambient intelligence allows for the continuous learning of human behavior and executes any required action triggered by a recognized event. The integration of autonomous control and human computer interaction (HCI) technologies into ambient intelligence can further enhance the capability of IoT-aided healthcare services.

F. AUGMENTED REALITY

Being part of the IoT, augmented reality plays a key role in healthcare engineering. Augmented reality is useful for surgery and remote monitoring, among others.

G. WEARBLES

Patient engagement and population health improvements can be facilitated by embracing wearable medical devices as landmarks. This has three major benefits: connected information, target-oriented healthcare communities, and gamification.

VII. IoT HEALTHCARE POLICIES

Evidence-based policies and technologies can be seen to become a driver of all cases of practical implementations. Similarly, policies and regulations play vital roles in transforming the healthcare sector in the next several decades. Although IoT-based healthcare services have yet to be addressed by existing policies, eHealth policies and strategies have been a key goal for many policy initiatives across the world. It can be argued that an organization that aims to develop both IoT and eHealth policies is likely to tailor its policies to IoT-based healthcare services. This section briefly discusses those countries and organizations working frame both IoT and eHealth policies and strategies.

A. INDIA

India introduced an eHealth policy between 2000 and 2002 to promote the use of information and communication technology (ICT) in the health sector and provide comprehensive guidelines and recommendations for the country's information technology (IT) infrastructure in the healthcare field (2003) and creation of a telemedicine task force (2005) [174]. Under the Digital India Program, the Indian government plans to transform India into a digitally empowered society and a knowledge-based economy and thus has implemented various initiatives. The Indian government has allocated Rs. 70.6 billion in the current budget to develop 100 smart cities in the country [175] and plans to create a $15 billion IoT industry in India by 2020 to increase the number of connected devices from around 200 million to over 2.7 billion [176]. These efforts are expected to boost the use of IoT in India's healthcare sector.

B. AUSTRALIA

In early 2008, the Australian health ministers' advisory council developed a strategic framework to guide national coordination and collaboration in eHealth based on a a series of national consultation initiatives including commonwealth, state, and territory governments, general practitioners, medical specialists, nursing and allied health, pathology, radiology, and pharmacy sectors, health information specialists, health service managers, researchers, scholars, and consumers [177]. In addition, the Australian government has worked to develop a strategic plan for the IoT.

C. JAPAN

Japan's Ministry of Internal Affairs and Communications (MIC) has developed the u-Japan Policy early in 2004 to accelerate the realization of network access ubiquity [178]. For cost savings and improved clinical outcomes through health IT, the Japanese government has been working on some recommendations for eHealth-friendly policies [179].

D. FRANCE

In 2008, the French government supported the creation of an object-naming service (ONS) root server for the country to enable the advancement of the IoT [180]. Registered with GS1 France, every product is supposed to be uniquely identified using global standards. The discovery of information on these products is enabled through domestic ONS nodes and portals. In this way, consumers become convinced that product data are accurate, authentic, and uniform across the country. Telemedicine services in France are widespread at the regional level and stimulate eHealth policy development. Electronic health records were formally introduced by legislation in 2004 [181]. The government has worked on advancing the IT infrastructure of hospitals, the use of eHealth, and solutions for challenges in semantic interoperability. The ''Hôpitaux 2012'' plan and the Law on Hospitals, Patients, Health, and Territory (la loi HPST) are worth mentioning in this regard [181].

E. SWEDEN

In July 2010, GS1 Sweden, a worldwide organization that works with distribution standards, and SE announced that they would jointly develop an ONS root server for the advancement of the IoT to enable networking for all physical objects through the Internet [180]. The Swedish ''National Strategy for eHealth'' policy provides a detailed set of action areas and statements [182].

F. GERMANY

Inn 2003, Germany enshrined its core eHealth activities in the legislation governing the healthcare sector [182]. Germany has an ambitious plan to play a leadership role in the engineering and manufacturing sector, including in the IoT domain [183]. According to High-Tech Strategy 2020 action plan, INDUSTRIE 4.0 is a strategic initiative in achieving this goal.

G. KOREA

South Korea is planning to expand its domestic market for the IoT from KRW 2.3 trillion in 2013 to KRW 30 trillion ($28.9 billion) by 2020 [183]. In May 2014, the government confirmed a plan for developing IoT services and products by establishing an open IoT ecosystem consisting of service, platform, network, device, and IT security sectors. Korea introduced policies to promote inclusiveness and equitable access to eHealth in 2008 [184]. Here the introduction of electronic medical records, ePrescription, and telemedicine is considered a key initiative driving the use of ICT in the healthcare sector [184].

H. CHINA

In July 2010, China's Ministry of Industry and Information Technology (MIIT) announced that it would promote the formulation of a unified national strategic plan for the IoT. The Chinese government decided that the MIIT would establish a clear position, development goals, timetables and a road map for introduce the IoT and facilitate R&D, commercialization, the creation of foundational technologies, and network connections and use. These measures are expected to stimulate the development of the IoT [180]. China's ''eHealth Eevelopment Strategy 2003-2010'' has attracted increasing investment interest.

I. THE U.S.

In February 2014, the Federal Trade Commission (FTC) commissioners discussed policy and regulatory implications of the IoT. The FTC has focused on two major areas of the IoT, namely the provision of notice and choice for non-consumer-facing network devices and the question of how devices that are part of the IoT can be ensured to have reasonable data security.

J. THE E.U.

Upon the European Commission's request, RAND Europe has worked to devise a European policy for the IoT. A research team has evaluated policy challenges to be addressed by policymakers from mid- and long-term perspectives and made some recommendations after assessing policy options for stimulating the development of the IoT in Europe [185]. In June 2010, the European Parliament proposed a resolution to help create the IoT. The E.U. parliament recommended the thorough assessment of any effects of this technology on health, privacy, and data protection. Under this resolution, a consumer enjoys the right to opt for a product that is not equipped or connected [180]. The European Council endorsed the eHealth Action Plan in 2004 [182], which is the first formal commitment expressed by all member states to cooperate in the area of eHealth. In April 2014, the European Commission launched a public consultation initiative for input from interested stakeholders on barriers and issues related to the use of mHealth in the E.U. [186].

K. THE WORLD HEALTH ORGANIZATION

In both developing and developed countries, mobile phones are used for a wide range of public health initiatives. In 2011, an initiative was taken to promote the use of mHealth for tobacco control in developing countries (WHO, 2011) [187]. However, most mHealth projects in developing countries

TABLE 4. National eHealth strategies across the world.

Country/region	eHealth strategy (year published)
Australia	National eHealth strategy (2008)
Australia	State eHealth strategy-Queensland (2006)
Denmark	National IT strategy 2003-2007 for the Danish healthcare service (2003)
The European Commission, DG for Information Society and Media, ICT for Health	European countries on their journey towards national eHealth infrastructures, evidence on progress and recommendations for cooperation actions (2011)
The European commission, DG for Information Society and Media, ICT for Health	eHealth priorities and strategies in European countries (2007)
The European Commission	Repository of eHealth strategies and priorities for EU member states (N/A)
Finland	eHealth roadmap – Finland (2007)
Kenya	National eHealth strategy (2011)
Mauritius	National eHealth Strategy: He@lth2015, seamless continuity of care (2010)
Saudi Arabia	National eHealth strategy (2011)
Scotland	National eHealth strategy (2011)
Sweden	National strategy for eHealth (2006)
Switzerland	Swiss eHealth strategy (2007)
The U.S.	Federal health IT strategic plan (2011)

have used text messages (SMS) mainly for increased awareness and communication campaigns and focused mainly on HIV, malaria, and MCH. It has been recommended that all target countries integrate the use of ICT in their national health information systems and infrastructure by 2015 [188]. Table 4 shows national eHealth strategies by country [189].

VIII. IoT HEALTHCARE CHALLENGES AND OPEN ISSUES

Many researchers have worked on designing and implementing various IoT-based healthcare services and on solving various technological and architectural problems associated with those services. In addition to research concerns in the literature, there are several other challenges and open issues that need to be carefully addressed. This section briefly presents both explored and unexplored issues surrounding IoT healthcare services.

A. STANDARDIZATION

In the healthcare context, there are many vendors that manufacture a diverse range of products and devices, and new vendors continue to join this promising technological race. However, they have not followed standard rules and regulations for compatible interfaces and protocols across devices. This raises interoperability issues. To address device diversity, immediate efforts are required. For example, a dedicated group can standardize IoT-based healthcare technologies. This standardization should consider a wide range of topics such as communications layers and protocol stacks, including physical (PHY) and media access control (MAC) layers, device interfaces, data aggregation interfaces, and gateway interfaces. The management of various value-added services such as electronic health records is another standardization issue. This management comes in various forms, including access management and healthcare professional registration. Various mHealth and eHealth organizations and IoT researchers can work together, and existing standardization bodies such as the Information Technology and Innovation Foundation (IETF), the Internet Protocol for Smart Objects (IPSO) alliance, and the European Telecommunications Standards Institute (ETSI) can form IoT technology working groups for the standardization of IoT-based healthcare services.

B. IoT HEALTHCARE PLATFORMS

Because the architecture of IoT-based healthcare hardware is more sophisticated than that of usual IoT devices and requires a real-time operating system with more stringent requirements, there is a need for a customized computing platform with run-time libraries. To build a suitable platform, a service-oriented approach (SOA) can be taken such that services can be exploited by using different application package interfaces (APIs). In addition to a specialized platform, libraries and appropriate frameworks should be built so that healthcare software developers and designers can make efficient use of given documents, codes, classes, message templates, and other useful data. Further, a particular class of disease-oriented libraries can be useful.

C. COST ANALYSIS

Researchers may perceive IoT-based healthcare services as a low-cost technology, but to the authors' knowledge, no comparative study has offered any evidence of this. In this regard, a cost analysis of a typical IoThNet may be useful.

D. THE APP DEVELOPMENT PROCESS

There are four basic steps in developing an app on the android platform: the setup, development, debugging and testing, and publishing. Similar approaches are generally taken on other platforms. In the process of healthcare app development, the participation of an authorized body or association of medical experts is typically required to ensure an app of acceptable quality. In addition, regular updates on healthcare apps based on the due consideration of recent advances in medical science are vital.

E. TECHNOLOGY TRANSITION

Healthcare organizations can modernize their existing devices and sensors across the healthcare field for smart resources by incorporating IoT approaches into the existing network configuration. Therefore, a seamless transition from the legacy system and setup to an IoT-based configuration is a major challenge. In other words, there is a need to ensure backward compatibility and flexibility in the integration of existing devices.

F. THE LOW-POWER PROTOCOL

There are many devices in IoT healthcare scenarios, and such devices tend to be heterogeneous in terms of their sleep, deep-sleep, receive, transmit, and composite states, among others. In addition, in terms of service availability, each communications layer faces an additional challenge in terms of power requirements. For example, finding an appropriate device discovery protocol that requires less power while ensuring service availability at the MAC layer is a difficult task.

G. NETWORK TYPE

In terms of the design approach, an IoT healthcare network can be of one of three fundamentally different types: data-, service-, and patient-centric architectures. In the data-centric scheme, the healthcare structure can generally be separated into objects based on captured health data. In a service-centric scheme, the healthcare structure is allocated by the assembly of characteristics that they must provide. In the patient-centric scheme, healthcare systems are divided according to the involvement of patients and their family members they consider for treatment. In this regard, answering the question of what network type is appropriate for IoT-based healthcare solutions becomes an open issue.

H. SCALABILITY

IoT healthcare networks, applications, services, and back-end databases should be scalable because related operations become more complex with the addition of diverse applications as a result of the exponential growth of demands from both individuals and health organizations.

I. CONTINUOUS MONITORING

There are many situations in which patients require long-term monitoring (e.g., a patient with a chronic disease). In this regard, the provision of constant monitoring and logging is vital.

J. NEW DISEASES AND DISORDERS

Smartphones are being considered as a frontier IoT healthcare device. Although there are many healthcare apps and new apps are being added to the list every day, the trend has been limited to a few categories of diseases. R&D activities for new types of diseases and disorders are essential, and the discovery of methods that can make the early detection of rare diseases mobile has long been an important task.

K. IDENTIFICATION

Healthcare organizations generally deal with multi-patient environments in which multiple caregivers discharge their duties. From this perspective, the proper identification of patients and caregivers is necessary.

L. THE BUSINESS MODEL

The IoT healthcare business strategy is not yet robust because it involves a set of elements with new requirements such as new operational processes and policies, new infrastructure systems, distributed target customers, and transformed organizational structures. In addition, doctors and nurses generally avoid learning and using new technologies. Therefore, there is an urgent need for a new business model.

M. THE QUALITY OF SERVICE (QoS)

Healthcare services are highly time sensitive and require QoS guarantees in terms of important parameters such as reliability, maintainability, and the service level. In this regard, the quantitative measurement of each such parameter within the IoThNet framework may be useful. In addition, system availability and robustness are central to offering QoS guarantees because any type of system disaster can put lives at danger in medical situations. Here the feasibility of plan B in the case of a system failure becomes an interesting issue.

N. DATA PROTECTION

The protection of captured health data from various sensors and devices from illicit access is crucial. Therefore, stringent policies and technical security measures should be introduced to share health data with authorized users, organizations, and applications. Here introducing an optimal algorithm for collaboration between protection, detection, and reaction services to prevent various attacks, threats, and vulnerabilities is an open challenge. Based on the discussion on IoT healthcare security in Section V, several research problems in this area are outlined as follows.

1) RESOURCE-EFFICIENT SECURITY

Because of resource (power, computation, and memory) constraints, IoT healthcare security schemes should be designed to maximize security performance while minimizing resource consumption.

2) PHYSICAL SECURITY

Because an attacker may tamper with and capture physical health devices and extract cryptographic secrets, the attacker may modify programs or replace captured devices with malicious ones. Therefore, devices should include tamper-resistant packaging.

3) SECURE ROUTING

Routing protocols for the IoT health network are particularly susceptible to device-capture attacks. Therefore, proper routing and forwarding methods are vital for real-time or semi-real-time communication in the desired network.

4) DATA TRANSPARENCY

IoT medical devices deal with personal heath data that may be used in IoT cloud services. Therefore, data-transparent services should be designed and developed such that the life cycle of personal data can be traced and data use can be controlled.

5) THE SECURITY OF HANDLING IoT BIG DATA

Biomedical sensors and devices generate huge amounts of health data, and there is a need to securely store captured data. Providing security measures for handling such data, including date transfer and maintenance, without compromising integrity, privacy, and confidentiality requires close attention and much effort.

O. MOBILITY

The IoT healthcare network must have the ability to support the mobility of patients such that they can be connected anywhere, anytime. This mobility feature is ultimately responsible for connecting dissimilar patient environments.

P. EDGE ANALYTICS

In the IoT health space, edge analytics such as analytics in edge devices plays an important role and can improve the feature of gateway devices. In this context, there is a need to examine healthcare data analytics to help system designers to optimize the data traffic and IoThNet architecture.

Q. ECOLOGICAL IMPACT

The full-scale deployment of IoT-based healthcare services requires many biomedical sensors embedded in semiconductor-rich devices. These sensors and devices also include rare earth metals and severely toxic chemicals. This has substantially unfavorable impacts on the environment, users, and human health, and for this reason, guidelines are needed for device manufacturing, the use of devices, and their proper disposal.

IX. CONCLUSIONS

Researchers across the world have started to explore various technological solutions to enhance healthcare provision in a manner that complements existing services by mobilizing the potential of the IoT. This paper surveys diverse aspects of IoT-based healthcare technologies and presents various healthcare network architectures and platforms that support access to the IoT backbone and facilitate medical data transmission and reception. Substantial R&D efforts have been made in IoT-driven healthcare services and applications. In addition, the paper provides detailed research activities concerning how the IoT can address pediatric and elderly care, chronic disease supervision, private health, and fitness management. For deeper insights into industry trends and enabling technologies, the paper offers a broad view on how recent and ongoing advances in sensors, devices, internet applications, and other technologies have motivated affordable healthcare gadgets and connected health services to limitlessly expand the potential of IoT-based healthcare services for further developments. To better understand IoT healthcare security, the paper considers various security requirements and challenges and unveils different research problems in this area to propose a model that can mitigate associated security risks. The discussion on several important issues such as standardization, network type, business models, the quality of service, and health data protection is expected to facilitate the provide a basis for further research on IoT-based healthcare services. This paper presents eHealth and IoT policies and regulations for the benefit of various stakeholders interested in assessing IoT-based healthcare technologies. In sum, the results of this survey are expected to be useful for researchers, engineers, health professionals, and policymakers working in the area of the IoT and healthcare technologies.

REFERENCES

[1] J. Höller, V. Tsiatsis, C. Mulligan, S. Karnouskos, S. Avesand, and D. Boyle, *From Machine-to-Machine to the Internet of Things: Introduction to a New Age of Intelligence*. Amsterdam, The Netherlands: Elsevier, 2014.

[2] G. Kortuem, F. Kawsar, D. Fitton, and V. Sundramoorthy, "Smart objects as building blocks for the Internet of Things," *IEEE Internet Comput.*, vol. 14, no. 1, pp. 44–51, Jan./Feb. 2010.

[3] K. Romer, B. Ostermaier, F. Mattern, M. Fahrmair, and W. Kellerer, "Real-time search for real-world entities: A survey," *Proc. IEEE*, vol. 98, no. 11, pp. 1887–1902, Nov. 2010.

[4] D. Guinard, V. Trifa, and E. Wilde, "A resource oriented architecture for the Web of Things," in *Proc. Internet Things (IOT)*, Nov./Dec. 2010, pp. 1–8.

[5] L. Tan and N. Wang, "Future Internet: The Internet of Things," in *Proc. 3rd Int. Conf. Adv. Comput. Theory Eng. (ICACTE)*, vol. 5. Aug. 2010, pp. V5-376–V5-380.

[6] Z. Pang, "Technologies and architectures of the Internet-of-Things (IoT) for health and well-being," M.S. thesis, Dept. Electron. Comput. Syst., KTH-Roy. Inst. Technol., Stockholm, Sweden, Jan. 2013.

[7] K. Vasanth and J. Sbert. Creating solutions for health through technology innovation. Texas Instruments. [Online]. Available: http://www.ti.com/lit/wp/sszy006/sszy006.pdf, accessed Dec. 7, 2014.

[8] J. Ko, C. Lu, M. B. Srivastava, J. A. Stankovic, A. Terzis, and M. Welsh, "Wireless sensor networks for healthcare," *Proc. IEEE*, vol. 98, no. 11, pp. 1947–1960, Nov. 2010.

[9] H. Alemdar and C. Ersoy, "Wireless sensor networks for healthcare: A survey," *Comput. Netw.*, vol. 54, no. 15, pp. 2688–2710, Oct. 2010.

[10] L. Mainetti, L. Patrono, and A. Vilei, "Evolution of wireless sensor networks towards the Internet of Things: A survey," in *Proc. 19th Int. Conf. Softw., Telecommun. Comput. Netw. (SoftCOM)*, Sep. 2011, pp. 1–6.
[11] D. Christin, A. Reinhardt, P. S. Mogre, and R. Steinmetz, "Wireless sensor networks and the Internet of Things: Selected challenges," in *Proc. 8th GI/ITG KuVS Fachgespräch 'Drahtlose Sensornetze'*, Aug. 2009, pp. 31–34.
[12] C. Alcaraz, P. Najera, J. Lopez, and R. Roman, "Wireless sensor networks and the Internet of Things: Do we need a complete integration?" in *Proc. 1st Int. Workshop Security Internet Things (SecIoT)*, Nov. 2010.
[13] Q. Zhu, R. Wang, Q. Chen, Y. Liu, and W. Qin, "IOT gateway: Bridging wireless sensor networks into Internet of Things," in *Proc. IEEE/IFIP 8th Int. Conf. Embedded Ubiquitous Comput. (EUC)*, Dec. 2010, pp. 347–352.
[14] I. Gronbaek, "Architecture for the Internet of Things (IoT): API and interconnect," in *Proc. Int. Conf. Sensor Technol. Appl.*, Aug. 2008, pp. 802–807.
[15] H. Viswanathan, E. K. Lee, and D. Pompili, "Mobile grid computing for data- and patient-centric ubiquitous healthcare," in *Proc. 1st IEEE Workshop Enabling Technol. Smartphone Internet Things (ETSIoT)*, Jun. 2012, pp. 36–41.
[16] W. Zhao, W. Chaowei, and Y. Nakahira, "Medical application on Internet of Things," in *Proc. IET Int. Conf. Commun. Technol. Appl. (ICCTA)*, Oct. 2011, pp. 660–665.
[17] N. Yang, X. Zhao, and H. Zhang, "A non-contact health monitoring model based on the Internet of Things," in *Proc. 8th Int. Conf. Natural Comput. (ICNC)*, May 2012, pp. 506–510.
[18] S. Imadali, A. Karanasiou, A. Petrescu, I. Sifniadis, V. Veque, and P. Angelidis, "eHealth service support in IPv6 vehicular networks," in *Proc. IEEE Int. Conf. Wireless Mobile Comput., Netw. Commun. (WiMob)*, Oct. 2012, pp. 579–585.
[19] R. S. H. Istepanian, "The potential of Internet of Things (IoT) for assisted living applications," in *Proc. IET Seminar Assist. Living*, Apr. 2011, pp. 1–40.
[20] G. Yang *et al.*, "A health-IoT platform based on the integration of intelligent packaging, unobtrusive bio-sensor, and intelligent medicine box," *IEEE Trans. Ind. Informat.*, vol. 10, no. 4, pp. 2180–2191, Nov. 2014.
[21] A. J. Jara, M. A. Zamora, and A. F. Skarmeta, "Knowledge acquisition and management architecture for mobile and personal health environments based on the Internet of Things," in *Proc. IEEE Int. Conf. Trust, Security Privacy Comput. Commun. (TrustCom)*, Jun. 2012, pp. 1811–1818.
[22] B. Xu, L. D. Xu, H. Cai, C. Xie, J. Hu, and F. Bu, "Ubiquitous data accessing method in IoT-based information system for emergency medical services," *IEEE Trans. Ind. Informat.*, vol. 10, no. 2, pp. 1578–1586, May 2014.
[23] C. Doukas and I. Maglogiannis, "Bringing IoT and cloud computing towards pervasive healthcare," in *Proc. Int. Conf. Innov. Mobile Internet Services Ubiquitous Comput. (IMIS)*, Jul. 2012, pp. 922–926.
[24] G. Zhang, C. Li, Y. Zhang, C. Xing, and J. Yang, "SemanMedical: A kind of semantic medical monitoring system model based on the IoT sensors," in *Proc. IEEE Int. Conf. eHealth Netw., Appl. Services (Healthcom)*, Oct. 2012, pp. 238–243.
[25] X. M. Zhang and N. Zhang, "An open, secure and flexible platform based on Internet of Things and cloud computing for ambient aiding living and telemedicine," in *Proc. Int. Conf. Comput. Manage. (CAMAN)*, May 2011, pp. 1–4.
[26] M. S. Shahamabadi, B. B. M. Ali, P. Varahram, and A. J. Jara, "A network mobility solution based on 6LoWPAN hospital wireless sensor network (NEMO-HWSN)," in *Proc. 7th Int. Conf. Innov. Mobile Internet Services Ubiquitous Comput. (IMIS)*, Jul. 2013, pp. 433–438.
[27] A. J. Jara, A. F. Alcolea, M. A. Zamora, A. F. J. Skarmeta, and M. Alsaedy, "Drugs interaction checker based on IoT," in *Proc. Internet Things (IOT)*, Nov./Dec. 2010, pp. 1–8.
[28] R. S. H. Istepanian, S. Hu, N. Y. Philip, and A. Sungoor, "The potential of Internet of m-health Things 'm-IoT' for non-invasive glucose level sensing," in *Proc. IEEE Annu. Int. Conf. Eng. Med. Biol. Soc. (EMBC)*, Aug./Sep. 2011, pp. 5264–5266.
[29] N. Bui, N. Bressan, and M. Zorzi, "Interconnection of body area networks to a communications infrastructure: An architectural study," in *Proc. 18th Eur. Wireless Conf. Eur. Wireless*, Apr. 2012, pp. 1–8.
[30] P. Lopez, D. Fernandez, A. J. Jara, and A. F. Skarmeta, "Survey of Internet of Things technologies for clinical environments," in *Proc. 27th Int. Conf. Adv. Inf. Netw. Appl. Workshops (WAINA)*, Mar. 2013, pp. 1349–1354.
[31] A. J. Jara, M. A. Zamora-Izquierdo, and A. F. Skarmeta, "Interconnection framework for mHealth and remote monitoring based on the Internet of Things," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 9, pp. 47–65, Sep. 2013.
[32] R. Tabish *et al.*, "A 3G/WiFi-enabled 6LoWPAN-based U-healthcare system for ubiquitous real-time monitoring and data logging," in *Proc. Middle East Conf. Biomed. Eng. (MECBME)*, Feb. 2014, pp. 277–280.
[33] M. F. A. Rasid *et al.*, "Embedded gateway services for Internet of Things applications in ubiquitous healthcare," in *Proc. 2nd Int. Conf. Inf. Commun. Technol. (ICoICT)*, May 2014, pp. 145–148.
[34] Z. Shelby and C. Bormann, *6LoWPAN: The Wireless Embedded Internet*, 1st ed. London, U.K.: Wiley, 2009.
[35] L. You, C. Liu, and S. Tong, "Community medical network (CMN): Architecture and implementation," in *Proc. Global Mobile Congr. (GMC)*, Oct. 2011, pp. 1–6.
[36] P. Swiatek and A. Rucinski, "IoT as a service system for eHealth," in *Proc. IEEE Int. Conf. eHealth Netw., Appl. Services (Healthcom)*, Oct. 2013, pp. 81–84.
[37] M. Diaz, G. Juan, O. Lucas, and A. Ryuga, "Big data on the Internet of Things: An example for the e-health," in *Proc. Int. Conf. Innov. Mobile Internet Services Ubiquitous Comput. (IMIS)*, Jul. 2012, pp. 898–900.
[38] X. Wang, J. T. Wang, X. Zhang, and J. Song, "A multiple communication standards compatible IoT system for medical usage," in *Proc. IEEE Faible Tension Faible Consommation (FTFC)*, Jun. 2013, pp. 1–4.
[39] W. Wang, J. Li, L. Wang, and W. Zhao, "The Internet of Things for resident health information service platform research," in *Proc. IET Int. Conf. Commun. Technol. Appl. (ICCTA)*, Oct. 2011, pp. 631–635.
[40] L. Yang, Y. Ge, W. Li, W. Rao, and W. Shen, "A home mobile healthcare system for wheelchair users," in *Proc. IEEE Int. Conf. Comput. Supported Cooperat. Work Design (CSCWD)*, May 2014, pp. 609–614.
[41] Z. Pang, Q. Chen, J. Tian, L. Zheng, and E. Dubrova, "Ecosystem analysis in the design of open platform-based in-home healthcare terminals towards the Internet-of-Things," in *Proc. Int. Conf. Adv. Commun. Technol. (ICACT)*, Jan. 2013, pp. 529–534.
[42] Y. J. Fan, Y. H. Yin, L. D. Xu, Y. Zeng, and F. Wu, "IoT-based smart rehabilitation system," *IEEE Trans. Ind. Informat.*, vol. 10, no. 2, pp. 1568–1577, May 2014.
[43] M. Bazzani, D. Conzon, A. Scalera, M. A. Spirito, and C. I. Trainito, "Enabling the IoT paradigm in e-health solutions through the VIRTUS middleware," in *Proc. IEEE 11th Int. Conf. Trust, Security Privacy Comput. Commun. (TrustCom)*, Jun. 2012, pp. 1954–1959.
[44] M. Vazquez-Briseno, C. Navarro-Cota, J. I. Nieto-Hipolito, E. Jimenez-Garcia, and J. D. Sanchez-Lopez, "A proposal for using the Internet of Things concept to increase children's health awareness," in *Proc. 22nd Int. Conf. Elect. Commun. Comput. (CONIELECOMP)*, Feb. 2012, pp. 168–172.
[45] X. Jia, H. Chen, and F. Qi, "Technical models and key technologies of e-health monitoring," in *Proc. IEEE Int. Conf. e-Health Netw., Appl. Services (Healthcom)*, Oct. 2012, pp. 23–26.
[46] V. Miori and D. Russo, "Anticipating health hazards through an ontology-based, IoT domotic environment," in *Proc. 6th Int. Conf. Innov. Mobile Internet Services Ubiquitous Comput. (IMIS)*, Jul. 2012, pp. 745–750.
[47] A. Dohr, R. Modre-Opsrian, M. Drobics, D. Hayn, and G. Schreier, "The Internet of Things for ambient assisted living," in *Proc. 7th Int. Conf. Inf. Technol., New Generat. (ITNG)*, Apr. 2010, pp. 804–809.
[48] F. Goncalves, J. Macedo, M. J. Nicolau, and A. Santos, "Security architecture for mobile e-health applications in medication control," in *Proc. 21st Int. Conf. Softw., Telecommun. Comput. Netw. (SoftCOM)*, Sep. 2013, pp. 1–8.
[49] R. S. H. Istepanian, E. Jovanov, and Y. T. Zhang, "Guest editorial introduction to the special section on m-health: Beyond seamless mobility and global wireless health-care connectivity," *IEEE Trans. Inf. Technol. Biomed.*, vol. 8, no. 4, pp. 405–414, Dec. 2004.
[50] ICH Expert Working Group, "Guidance for industry-E6 good clinical practice: Consolidated guidance," U.S. Dept. Health Human Services, Food Drug Admin., Silver Spring, MD, USA, Apr. 1996.

[51] A. J. Jara, F. J. Belchi, A. F. Alcolea, J. Santa, M. A. Zamora-Izquierdo, and A. F. Gomez-Skarmeta, "A pharmaceutical intelligent information system to detect allergies and adverse drugs reactions based on Internet of Things," in *Proc. IEEE Int. Conf. Pervasive Comput. Commun. Workshops (PERCOM Workshops)*, Mar./Apr. 2010, pp. 809–812.
[52] V. M. Rohokale, N. R. Prasad, and R. Prasad, "A cooperative Internet of Things (IoT) for rural healthcare monitoring and control," in *Proc. Int. Conf. Wireless Commun., Veh. Technol., Inf. Theory Aerosp. Electron. Syst. Technol. (Wireless VITAE)*, Feb./Mar. 2011, pp. 1–6.
[53] *Awareness Day 2014 Activities by Program Type*. [Online]. Available: http://www.samhsa.gov/sites/default/files/children-awareness-day-activities-by-program-2014.pdf, accessed Dec. 7, 2014.
[54] S. Vicini, S. Bellini, A. Rosi, and S. Sanna, "An Internet of Things enabled interactive totem for children in a living lab setting," in *Proc. ICE Int. Conf. Eng., Technol. Innov. (ICE)*, Jun. 2012, pp. 1–10.
[55] W.-Y. Chung, Y.-D. Lee, and S.-J. Jung, "A wireless sensor network compatible wearable u-healthcare monitoring system using integrated ECG, accelerometer and SpO_2," in *Proc. 30th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBS)*, Aug. 2008, pp. 1529–1532.
[56] P. Castillejo, J.-F. Martinez, J. Rodriguez-Molina, and A. Cuerva, "Integration of wearable devices in a wireless sensor network for an e-health application," *IEEE Wireless Commun.*, vol. 20, no. 4, pp. 38–49, Aug. 2013.
[57] G. Sebestyen, A. Hangan, S. Oniga, and Z. Gal, "eHealth solutions in the context of Internet of Things," in *Proc. IEEE Int. Conf. Autom., Quality Test., Robot.*, May 2014, pp. 1–6.
[58] A. Burgun, G. Botti, M. Fieschi, and P. Le Beux, "Sharing knowledge in medicine: Semantic and ontologic facets of medical concepts," in *Proc. IEEE Int. Conf. Syst., Man, Cybern. (SMC)*, vol. 6. 1999, pp. 300–305.
[59] J. Liu and L. Yang, "Application of Internet of Things in the community security management," in *Proc. 3rd Int. Conf. Comput. Intell., Commun. Syst. Netw. (CICSyN)*, Jul. 2011, pp. 314–318.
[60] Y. Xiao, X. Chen, L. Wang, W. Li, B. Liu, and D. Fang, "An immune theory based health monitoring and risk evaluation of earthen sites with Internet of Things," in *Proc. IEEE Int. Conf. Cyber, Phys. Soc. Comput. Green Comput. Commun. (GreenCom), IEEE Internet Things (iThings/CPSCom)*, Aug. 2013, pp. 378–382.
[61] I. Nikolaevskiy, D. Korzun, and A. Gurtov, "Security for medical sensor networks in mobile health systems," in *Proc. IEEE 15th Int. Symp. World Wireless, Mobile Multimedia Netw. (WoWMoM)*, Jun. 2014, pp. 1–6.
[62] G. Mantas, D. Lymberopoulos, and N. Komninos, "A new framework for ubiquitous context-aware healthcare applications," in *Proc. 10th IEEE Int. Conf. Inf. Technol. Appl. Biomed. (ITAB)*, Nov. 2010, pp. 1–4.
[63] H. Viswanathan, B. Chen, and D. Pompili, "Research challenges in computation, communication, and context awareness for ubiquitous healthcare," *IEEE Commun. Mag.*, vol. 50, no. 5, pp. 92–99, May 2012.
[64] M. P. R. Sai Kiran, P. Rajalakshmi, and A. Acharyya, "Context predictor based sparse sensing technique and smart transmission architecture for IoT enabled remote health monitoring applications," in *Proc. IEEE Int. Conf. Eng. Med. Biol. Soc. (EMBC)*, Aug. 2014, pp. 4151–4154.
[65] Z. J. Guan, "Somatic data blood glucose collection transmission device for Internet of Things," Chinese Patent 202 838 653 U, Mar. 27, 2013.
[66] L. Wei, Y. Heng, and W. Y. Lin, "Things based wireless data transmission of blood glucose measuring instruments," Chinese Patent 202 154 684 U, Mar. 7, 2012.
[67] Z. Lijun, "Multi-parameter medical acquisition detector based on Internet of Things," Chinese Patent 202 960 774 U, Jun. 5, 2013.
[68] B. J. Drew *et al.*, "Practice standards for electrocardiographic monitoring in hospital settings," *Circulation*, vol. 110, no. 17, pp. 2721–2746, Oct. 2004.
[69] P. K. Dash, "Electrocardiogram monitoring," *Indian J. Anaesthesia*, vol. 46, no. 4, pp. 251–260, Aug. 2002.
[70] E. Agu *et al.*, "The smartphone as a medical device: Assessing enablers, benefits and challenges," in *Proc. IEEE Int. Workshop Internet-Things Netw. Control (IoT-NC)*, Jun. 2013, pp. 48–52.
[71] M.-L. Liu, L. Tao, and Z. Yan, "Internet of Things-based electrocardiogram monitoring system," Chinese Patent 102 764 118 A, Nov. 7, 2012.
[72] Y. Xiaogang, L. Hongjiang, W. Jiaqing, and T. Wentao, "Realization of comprehensive detection algorithm of electrocardiogram signal at application layer electrocardiogram monitoring Internet of Thing," Chinese Patent 101 947 112 A, Jan. 19, 2011.
[73] J. Puustjarvi and L. Puustjarvi, "Automating remote monitoring and information therapy: An opportunity to practice telemedicine in developing countries," in *Proc. IST-Africa Conf.*, May 2011, pp. 1–9.
[74] L. M. R. Tarouco *et al.*, "Internet of Things in healthcare: Interoperatibility and security issues," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2012, pp. 6121–6125.
[75] Z. J. Guan, "Internet-of-Things human body data blood pressure collecting and transmitting device," Chinese Patent 202 821 362 U, Mar. 27, 2013.
[76] T. J. Xin, B. Min, and J. Jie, "Carry-on blood pressure/pulse rate/blood oxygen monitoring location intelligent terminal based on Internet of Things," Chinese Patent 202 875 315 U, Apr. 17, 2013.
[77] M. N. Ruiz, J. M. García, and B. M. Fernández, "Body temperature and its importance as a vital constant," *Revista Enfermeria*, vol. 32, no. 9, pp. 44–52, Sep. 2009.
[78] Z. Jian, W. Zhanli, and M. Zhuang, "Temperature measurement system and method based on home gateway," Chinese Patent 102 811 185 A, Dec. 5, 2012.
[79] Z. L. In, "Patient body temperature monitoring system and device based on Internet of Things," Chinese Patent 103 577 688 A, Feb. 12, 2014.
[80] H. A. Khattak, M. Ruta, and E. Di Sciascio, "CoAP-based healthcare sensor networks: A survey," in *Proc. 11th Int. Bhurban Conf. Appl. Sci. Technol. (IBCAST)*, Jan. 2014, pp. 499–503.
[81] E. C. Larson, M. Goel, G. Boriello, S. Heltshe, M. Rosenfeld, and S. N. Patel, "SpiroSmart: Using a microphone to measure lung function on a mobile phone," in *Proc. ACM Int. Conf. Ubiquitous Comput.*, Sep. 2012, pp. 280–289.
[82] E. C. Larson, M. Goel, M. Redfield, G. Boriello, M. Rosenfeld, and S. N. Patel, "Tracking lung function on any phone," in *Proc. ACM Symp. Comput. Develop.*, Jan. 2013, Art. ID 29.
[83] E. C. Larson, T. Lee, S. Liu, M. Rosenfeld, and S. N. Patel, "Accurate and privacy preserving cough sensing using a low-cost microphone," in *Proc. ACM Int. Conf. Ubiquitous Comput.*, Sep. 2011, pp. 375–384.
[84] B. Tan and O. Tian, "Short paper: Using BSN for tele-health application in upper limb rehabilitation," in *Proc. IEEE World Forum Internet Things (WF-IoT)*, Mar. 2014, pp. 169–170.
[85] D. Y. Lin, "Integrated Internet of Things application system for prison," Chinese Patent 102 867 236 A, Jan. 9, 2013.
[86] Z. Guangnan and L. Penghui, "IoT (Internet of Things) control system facing rehabilitation training of hemiplegic patients," Chinese Patent 202 587 045 U, Dec. 5, 2012.
[87] Y. Yue-Hong, F. Wu, F. Y. Jie, L. Jian, X. Chao, and Z. Yi, "Remote medical rehabilitation system in smart city," Chinese Patent 103 488 880 A, Jan. 1, 2014.
[88] S. Liang, Y. Zilong, S. Hai, and M. Trinidad, "Childhood autism language training system and Internet-of-Things-based centralized training center," Chinese Patent 102 184 661 A, Sep. 14, 2011.
[89] Z. Pang, J. Tian, and Q. Chen, "Intelligent packaging and intelligent medicine box for medication management towards the Internet-of-Things," in *Proc. 16th Int. Conf. Adv. Commun. Technol. (ICACT)*, Feb. 2014, pp. 352–360.
[90] I. Laranjo, J. Macedo, and A. Santos, "Internet of Things for medication control: E-health architecture and service implementation," *Int. J. Rel. Quality E-Healthcare*, vol. 2, no. 3, pp. 1–15, Jul. 2013.
[91] V. Kolici, E. Spaho, K. Matsuo, S. Caballe, L. Barolli, and F. Xhafa, "Implementation of a medical support system considering P2P and IoT technologies," in *Proc. 8th Int. Conf. Complex, Intell. Softw. Intensive Syst. (CISIS)*, Jul. 2014, pp. 101–106.
[92] *Dr. Hawking's Connected Wheelchair Project*. [Online]. Available: http://www.intel.co.kr/content/www/kr/ko/internet-of-things/videos/dr-hawkings-connected-wheelchair-video.html, accessed Dec. 8, 2014.
[93] E. Gayat *et al.*, "Performance evaluation of a noninvasive hemoglobin monitoring device," *Ann. Emergency Med.*, vol. 57, no. 4, pp. 330–333, Apr. 2011.
[94] M. Pesta, J. Fichtl, V. Kulda, O. Topolcan, and V. Treska, "Monitoring of circulating tumor cells in patients undergoing surgery for hepatic metastases from colorectal cancer," *Anticancer Res.*, vol. 33, no. 5, pp. 2239–2243, May 2013.
[95] A. S. M. Mosa, I. Yoo, and L. Sheets, "A systematic review of healthcare applications for smartphones," *BMC Med. Informat. Decision Making*, vol. 12, p. 67, Jul. 2012.
[96] [Online]. Available: http://www.medicaljoyworks.com
[97] [Online]. Available: http://www.prognosisapp.com
[98] [Online]. Available: http://www.imedicalapps.com/2014/01/diagnose-app-evidence-based-clinical-decision
[99] [Online]. Available: http://www.eagleget.com/apps/apk-file/4470
[100] [Online]. Available: https://www.apple.com/itunes/charts

[101] [Online]. Available: https://play.google.com/store/apps?hl=en
[102] P. J. F. White, B. W. Podaima, and M. R. Friesen, "Algorithms for smartphone and tablet image analysis for healthcare applications," *IEEE Access*, vol. 2, pp. 831–840, Aug. 2014.
[103] J. Lee, B. A. Reyes, D. D. McManus, O. Mathias, and K. H. Chon, "Atrial fibrillation detection using a smart phone," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Aug./Sep. 2012, pp. 1177–1180.
[104] J. Lee, B. A. Reyes, D. D. McManus, O. Mathias, and K. H. Chon, "Atrial fibrillation detection using an iPhone 4S," *IEEE Trans. Biomed. Eng.*, vol. 60, no. 1, pp. 203–206, Jan. 2013.
[105] N.-C. Chen, K.-C. Wang, and H.-H. Chu, "Listen-to-nose: A low-cost system to record nasal symptoms in daily life," in *Proc. ACM Int. Conf. Ubiquitous Comput.*, Sep. 2012, pp. 590–591.
[106] T. Wadhawan, S. Ning, R. Hu, K. Lancaster, X. Yuan, and G. Zouridakis, "Implementation of the 7-point checklist for melanoma detection on smart handheld devices," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Aug./Sep. 2011, pp. 3180–3183.
[107] L. Wang, P. C. Pedersen, D. Strong, B. Tulu, and E. Agu, "Wound image analysis system for diabetics," *Proc. SPIE*, vol. 8669, p. 866924, Mar. 2013.
[108] *Top Five Assistive Technologies*. [Online]. Available: https://www.edisse.com, accessed Jan. 25, 2015.
[109] *Advanced Tracking, Every Step of the Way*. [Online]. Available: http://www.withings.com/us, accessed Dec. 8, 2015.
[110] *The miPlatform Software: A Leading Comprehensive Medical Image and Information Management Platform*. [Online]. Available: http://www.hinacom.com/EN/ywly, accessed Dec. 8, 2014.
[111] *IT Solutions for Medical Industry and Personal Healthcare Network Service*. [Online]. Available: http://www.neusoft.com/solutions/1167, accessed Dec. 8, 2014.
[112] *Left Your Garage or Gate Open? No Problem*. [Online]. Available: https://www.liftmaster.com/For-Homes/MyQ-Connected-Home, accessed Dec. 8, 2014.
[113] *Smart Notifications Let You Decide: Take Action or Continue on Your Active Way*. [Online]. Available: http://sites.garmin.com/en-US/vivo/vivosmart, accessed Dec. 8, 2014.
[114] *UP3: The World'S Most Advanced Tracker*. [Online]. Available: https://jawbone.com, accessed Dec. 8, 2014.
[115] *The First Truly Open Sensor for Health and Fitness*. [Online]. Available: http://www.angelsensor.com, accessed Dec. 8, 2014.
[116] S. Noh *et al.*, "Ferroelectret film-based patch-type sensor for continuous blood pressure monitoring," *Electron. Lett.*, vol. 50, no. 3, pp. 143–144, Jan. 2014.
[117] *A Family of Products to Help You Stay Healthy*. [Online]. Available: http://www.ihealthlabs.com, accessed Jan. 10, 2015.
[118] *A Heart Rate Tracker You Can Count on*. [Online]. Available: http://www.mybasis.com, accessed Jan. 10, 2015.
[119] *W/Me Wearable Wellness Monitor and Coach*. [Online]. Available: http://appleinsider.com/articles/13/12/18/review-wme-wearable-wellness-monitor-and-coach, accessed Jan. 10, 2015.
[120] *Any Patient, Any Time, Anywhere*. [Online]. Available: http://rijuven.com, accessed Jan. 10, 2015.
[121] *Track Your Activity*. [Online]. Available: http://www.nike.com/us/en_us/c/nikeplus-fuelband, accessed Jan. 10, 2015.
[122] *Kids and Adult Wireless Pedometers*. [Online]. Available: http://ibitz.com, accessed Jan. 10, 2015.
[123] *Identity of Things: Beacons Could Lead the Way in IoT Automation*. [Online]. Available: http://www.actvcontent.com, accessed Jan. 10, 2015.
[124] *Reemo Watch*. [Online]. Available: http://www.getreemo.com, accessed Dec. 8, 2014.
[125] *Haloband: Control Your Smartphone With Simple Wrist Move*. [Online]. Available: http://www.haloband.me, accessed Dec. 8, 2014.
[126] *Multiple Motion Sensors*. [Online]. Available: https://amiigo.com, accessed Dec. 8, 2014.
[127] *Samsung Gear Fit: Features*. [Online]. Available: http://www.samsung.com/global/microsite/gear/gearfit_features.html, accessed Dec. 8, 2014.
[128] *Connecting the World Through Wearable Experiences*. [Online]. Available: http://www.omate.com, accessed Jan. 10, 2015.
[129] *Wear It Your Way*. [Online]. Available: https://www.fitbug.com/us/orb, accessed Jan. 10, 2015.
[130] *MEMI: How Does It Work*. [Online]. Available: http://www.hellomemi.com/index.html, accessed Jan. 10, 2015.
[131] *FORCE: Wireless Activity and Sleep Band*. [Online]. Available: http://www.fitbit.com/kr/force, accessed Dec. 8, 2014.
[132] *The Melon Headband: An Activity Monitor for Your Brain that Teaches You About Cognitive Performance*. [Online]. Available: http://www.usemelon.com, accessed Jan. 10, 2015.
[133] *Olive : A Wearable to Manage Stress*. [Online]. Available: https://www.indiegogo.com/projects/olive-a-wearable-to-manage-stress#/story, accessed Jan. 10, 2014.
[134] *Get Fitin a Flash*. [Online]. Available: http://misfit.com/#home, accessed Dec. 8, 2014.
[135] *Runtastic Orbit: How it Works*. [Online]. Available: https://www.runtastic.com/orbit, accessed Dec. 8, 2014.
[136] *The Most Advanced Running Wearable*. [Online]. Available: http://www.runscribe.com, accessed Jan. 12, 2015.
[137] *Reebok CHECKLIGHT Impact Sensor Cap Helps Keep Athletes Safe*. [Online]. Available: http://www.medgadget.com/2013/07/reebok-checklight-impact-sensor-cap-helps-keep-athletes-safe-video.html, accessed Jan. 12, 2015.
[138] *Smart Run: All-in-One Running Watch*. [Online]. Available: http://micoach.adidas.com/us/smartrun, accessed Dec. 10, 2014.
[139] *OMsignal Biometric Smartwear: Smart Shirt, Smart App, Smart Results*. [Online]. Available: http://www.omsignal.com, accessed Dec. 10, 2014.
[140] *Vessyl Automatically Knows and Trackseverything You Drink*. [Online]. Available: https://www.myvessyl.com, accessed Dec. 10, 2014.
[141] *The Smart Sock that Alerts You if Your Baby Stops Breathing*. [Online]. Available: https://www.owletcare.com, accessed Dec. 12, 2014.
[142] *Meet Sproutling: The Smarter Baby Monitor*. [Online]. Available: http://www.sproutling.com, accessed Dec. 10, 2014.
[143] *PulseOn Cloud: Jewel for Gym, Discreet for Street*. [Online]. Available: http://www.pulseon.com, accessed Jan. 12, 2015.
[144] *Alive ECG App: The Normal Detector*. [Online]. Available: http://www.alivecor.com/home, accessed Dec. 10, 2014.
[145] *Aim: The Ultimate Fitness Tracker*. [Online]. Available: http://www.skulpt.me, accessed Dec. 10, 2014.
[146] *Healthy Living Begins With What You Eat*. [Online]. Available: http://nutriplus.reflexwireless.com, accessed Dec. 10, 2014.
[147] *Introducing Tempdrop*. [Online]. Available: http://temp-drop.com/?variant=767520619, accessed Dec. 8, 2014.
[148] *Proteus Digital Health Feedback System*. [Online]. Available: https://www.informatics.manchester.ac.uk/SiteCollectionDocuments/Ecosystem-Meeting-March-2013/ProteusPresentationEcosystemMeetingMarch2013.pdf, accessed Dec. 8, 2014.
[149] *Reminders for What Matters Most*. [Online]. Available: http://www.vitality.net/glowcaps.html, accessed Dec. 5, 2014.
[150] *The Mimo Kimono: How it Works*. [Online]. Available: http://mimobaby.com, accessed Jan. 13, 2015.
[151] *BodyGuardian: Remote Monitoring System*. [Online]. Available: http://www.preventice.com/products/bodyguardian, accessed Jan. 2, 2015.
[152] *Cisco Services for Connected Health: Intelligent Network, Smart Medicine*. [Online]. Available: http://www.cisco.com/web/strategy/healthcare/connectedhealth/index.html, accessed Dec. 17, 2014.
[153] *Health Solutions From Microsoft*. [Online]. Available: http://www.microsoft.com/windowsembedded/en-us/healthcare.aspx, accessed Dec. 17, 2014.
[154] *Physical Web: Walk Up and Use Anything*. [Online]. Available: http://google.github.io/physical-web, accessed Dec. 17, 2014.
[155] *Intelligence for Smarter Health*. [Online]. Available: http://www.samsung.com/us/globalinnovation/innovation_areas, accessed Dec. 17, 2014.
[156] *Introducing the Award Winning 2net Platform*. [Online]. Available: http://www.qualcommlife.com/wireless-health, accessed Dec. 17, 2014.
[157] *Intel Across Healthcare*. [Online]. Available: http://www.intel.com/content/www/us/en/healthcare-it/intel-across-healthcare-dishman-video.html, accessed Dec. 17, 2014.
[158] *Smarter Healthcare: Redefining Value and Success in Healthcare*. [Online]. Available: http://www.ibm.com/smarterplanet/us/en/healthcare_solutions/nextsteps, accessed Dec. 17, 2014.
[159] *Memorial Hermann Healthcare System*. [Online]. Available: http://www.apple.com/iphone/business/profiles/memorial-hermann, accessed Dec. 17, 2014.
[160] *Wind Medical Resources*. [Online]. Available: http://iot.windriver.com/#!/Medical, accessed Dec. 17, 2014.

[161] *Driving Force for Connected Health*. [Online]. Available: https://www.telekom-healthcare.com/blob/33378/1b13d1a5eee7e3ce25d775f6cf083965/healthcare-solutions-imagebroschuere-2014-data.pdf, accessed Dec. 17, 2014.

[162] *mHealth: A New Vision for Healthcare*. [Online]. Available: http://www.gsma.com/connectedliving/mhealth, accessed Dec. 17, 2014.

[163] *ThingWorx: How it Works*. [Online]. Available: http://thingworx.com/markets, accessed Dec. 17, 2014.

[164] *M2M Connectivity Plays Important role for Patients Awaiting Heart Transplant Worldwide*. [Online]. Available: http://www.numerex.com/files/casestudy/20141216-ReliantHeart_CaseStudy.pdf, accessed Dec. 17, 2014.

[165] *Connected Health*. [Online]. Available: https://machinaresearch.com/what-we-do/advisory-service/connected-health, accessed Dec. 17, 2014.

[166] *Delivering Improved Health Outcomes and Reduced Cost of Medical Care With Remote Patient Monitoring*. [Online]. Available: http://www.aeris.com/for-enterprises/healthcare-remote-patient-monitoring, accessed Dec. 17, 2014.

[167] *Medical and Healthcare*. [Online]. Available: http://www.eurotech.com/en/industry+solutions/medical+healthcare, accessed Dec. 17, 2014.

[168] T. Zia and A. Zomaya, "Security issues in wireless sensor networks," in *Proc. IEEE Int. Conf. Syst. Netw. Commun.*, Oct. 2006, p. 40.

[169] Y. Wang, G. Attebury, and B. Ramamurthy, "A survey of security issues in wireless sensor networks," *IEEE Commun. Surveys Tuts.*, vol. 8, no. 2, pp. 2–23, Second Quarter 2006.

[170] Y. W. Law, "Key management and link-layer security of wireless sensor networks: Energy-efficient attack and defense," M.S. thesis, Inst. Program. Res. Algorithmic, Univ. Twente, Enschede, The Netherlands, 2005.

[171] *Internet Engineering Task Force (IETF)*. [Online]. Available: https://www.ietf.org/, accessed Jan. 6, 2015.

[172] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: A survey," *Comput. Netw.*, vol. 38, no. 4, pp. 393–422, 2002.

[173] R. A. Shaikh, S. Lee, Y. J. Song, and Y. Zhung, "Securing distributed wireless sensor networks: Issues and guidelines," in *Proc. IEEE Int. Conf. Sensor Netw., Ubiquitous, Trustworthy Comput.*, vol. 2. Jun. 2006, pp. 226–231.

[174] *Building Foundations For E-Health: India*. [Online]. Available: http://www.who.int/goe/data/country_report/ind.pdf, accessed Dec. 27, 2014.

[175] *IoT Policy Document*. [Online]. Available: http://deity.gov.in/sites/upload_files/dit/files/Draft-IoT-Policy%20(1).pdf, accessed Dec. 27, 2014.

[176] *Government Aims to Make $15 Billion Internet of Things Industry in India by 2020*. [Online]. Available: http://articles.economictimes.indiatimes.com/2014-1026/news/55446641_1_iot-100-smart-cities-draft-policy-document, accessed Dec. 27, 2014.

[177] *The National e-Health Strategy*. [Online]. Available: http://www.health.gov.au/internet/main/publishing.nsf/Content/National+Ehealth+Strategy, accessed Dec. 27, 2014.

[178] *The Internet of Things in Japan*. [Online]. Available: http://www.huawei.com/en/about-huawei/publications/winwin-magazine/hw-110837.htm, accessed Dec. 27, 2014.

[179] M. Akiyama and R. Nagai, "Information technology in health care: E-health for Japanese health services," A Report of the CSIS global health policy center, The Center for Strategic and International Studies and the Health and Global Policy Institute, Mar. 2012. [Online]. Available: http://csis.org/files/publication/120327_Akiyama_JapaneseHealthCare_web.pdf, accessed Dec. 27, 2014.

[180] *Advancing the 'Internet of Things'—Digital Economy Strategy Submission to Industry Canada*. [Online]. Available: https://www.ic.gc.ca/eic/site/028.nsf/eng/00307.html, accessed Dec. 27, 2014.

[181] J. Artmann and G. S. Empirica, "Dumortier'e-health strategies - country brief: France,"' ICT for Health Unit, DG Information Society and Media, European Commission, Oct. 2010. [Online]. Available: http://ehealthstrategies.eu/database/documents/france_countrybrief_ehstrategies.pdf, accessed Dec. 27, 2014.

[182] K. A. Stroetmann, J. Artmann, and V. N. Stroetmann, "e-health strategies-European countries on their journeytowards national e-health infrastructures," Information Society, European Commission, Jan. 2011. [Online]. Available: http://ehealth-strategies.eu/report/eHealth_Strategies_Final_Report_Web.pdf, accessed Dec. 27, 2014.

[183] *Internet of Things Needs Government Support*. [Online]. Available: http://www.informationweek.com/government/leadership/internet-of-things-needs-government-support/a/d-id/1316455, accessed Dec. 27, 2014.

[184] *Building Foundations for e-Health: Republic of Korea*. [Online]. Available: http://www.who.int/goe/data/country_report/kor.pdf, accessed Dec. 27, 2014.

[185] *Examining Europe's Policy Options to Foster Development of the Internet of Things*. [Online]. Available: http://www.prgs.edu/content/rand/randeurope/research/projects/internet-of-things, accessed Dec. 27, 2014.

[186] *Policy: Green Paper Consultation on m-Health*. [Online]. Available: https://ec.europa.eu/digital-agenda/en/mhealth, accessed Dec. 27, 2014.

[187] *Mobile Health (m-Health) for Tobacco Control*. [Online]. Available: http://www.who.int/tobacco/mhealth/en, accessed Dec. 27, 2014.

[188] *Directory of e-Health Policies*. [Online]. Available: http://www.who.int/goe/policies/en, accessed Dec. 27, 2014.

[189] *WHO-ITU National e-Health Strategy Toolkit*. [Online]. Available: http://www.itu.int/ITU-D/cyb/events/2012/eHealth/Nat_eH_Dev/Session%201/ITU-WHO%20National%20eHealth%20Strategy%20toolkit%20March%202012.pdf, accessed Dec. 27, 2014.

S. M. RIAZUL ISLAM (M'10) received the B.S. and M.S. degrees in applied physics and electronics from the University of Dhaka, Bangladesh, in 2003 and 2005, respectively, and the Ph.D. degree in information and communication engineering from Inha University, Korea, in 2012. He was a Lecturer with the Department of Electrical and Electronic Engineering, University of Dhaka, from 2005 to 2013. He served with the Department of Electrical and Electronic Engineering (formerly the Department of Applied Physics, Electronics and Communication Engineering), University of Dhaka, as an Assistant Professor, from 2013 to 2014. He served with the Solution Laboratory, Samsung Research and Development Institute Bangladesh, as a Chief Engineer, in 2014. He has been with the UWB Wireless Communications Research Center, Inha University, as a Research Professor, since 2014. His research interests include wireless communications, ultrawideband systems, relay networks, and 5G technology.

DAEHAN KWAK received the B.S. degree in information and computer engineering from Ajou University, Korea, in 2005, and the M.S. degree from the Korea Advanced Institute of Science and Technology, Korea, in 2008. He is currently pursuing the Ph.D. degree in computer science with Rutgers University, USA. He was with the Telematics and USN Research Division, Electronics and Telecommunications Research Institute, during his M.S. course, and the UWB Wireless Research Center, Inha University, Korea, as a Researcher. His current research interest includes mobile and pervasive computing, vehicular computing and networks, u-health networks/applications, and mobile applications.

MD. HUMAUN KABIR received the B.S. and M.S. degrees in physics from the University of Dhaka, Bangladesh, and the Ph.D. degree in information and communication engineering from Inha University, Korea, in 2014. He has been a Post-Doctoral Fellow with the UWB Wireless Communications Research Center, Inha University, since 2014. His research interests include molecular communication, nanonetworks, wireless body area networks, modulation techniques, and interference mitigation mitigation.

MAHMUD HOSSAIN received the B.S. degree in computer science and engineering from the Bangladesh University of Science and Technology, Bangladesh, in 2009. He is currently pursuing the Ph.D. degree with the Secure and Trustworthy Computing Laboratory, University of Alabama at Birmingham, USA. He served with the Solution Laboratory, Samsung Research and Development Institute Bangladesh, as a lead Engineer, from 2010 to 2014. His research interests include Internet of Things, mobile cloud computing, security, and embedded systems.

KYUNG-SUP KWAK (M'81) received the M.S. and Ph.D. degrees from the University of California at San Diego, in 1981 and 1988, respectively. From 1988 to 1989, he was with Hughes Network Systems, San Diego, CA. From 1989 to 1990, he was with the IBM Network Analysis Center, Research Triangle Park, NC. Since then, he has been with the School of Information and Communication Engineering, Inha University, Korea, as a Professor. He was the Dean of the Graduate School of Information Technology and Telecommunications with Inha University from 2001 to 2002. He has been the Director of the UWB Wireless Communications Research Center, Korea, since 2003. In 2006, he served as the President with the Korean Institute of Communication Sciences and the Korea Institute of Intelligent Transport Systems in 2009. His research interests include wireless communications, ultrawideband systems, sensor networks, wireless body area networks, and nanocommunications. He received a number of awards, including the Engineering College Achievement Award from Inha University, the LG Paper Award, the Motorola Paper Award, the Haedong Prize of Research, and various government awards from the Ministry of ICT, the President, and the Prime Minister of Korea, for his excellent research performances.