Internet of Things xxx (xxxx) xxx

Contents lists available at ScienceDirect

Internet of Things

journal homepage: www.elsevier.com/locate/iot

Research article

Harnessing the power of Internet of Things based connectivity to improve healthcare

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ARTICLE INFO

Article history:
Received 3 June 2019
Accepted 17 June 2019
Available online xxx

Keywords:
Architecture
Healthcare
Internet of Things (IoT)
Medical devices

ABSTRACT

Connectivity and interoperability are vital design characteristics of any Information and Communication Technology (ICT) infrastructure. Today, Internet of Things (IoT) technologies are being integrated with various types of medical systems in order to provide cost-effective, ubiquitous, on-time healthcare services to people who need them. Presently, the healthcare system has evolved into a complex ecosystem which consists of a wide range of devices, databases, communication technologies that work together to provide different healthcare services. In many healthcare information systems, these technologies and resources need to interact and collaborate with or without human intervention to enable the healthcare system to achieve its goal of providing efficient healthcare services. The Internet of Things technology has the potential to provide connectivity for a global network of billions of devices and it can therefore be harnessed to improve the quality and delivery of healthcare services. We explore and discuss how IoT-based connectivity can deliver improved healthcare solutions. We describe IoT-based healthcare solutions that have been implemented recently. Finally, we discuss future opportunities that can be explored for improved healthcare solutions based on the IoT concept.

1. Introduction

In the last few years, we have witnessed an explosive growth in the adoption and deployment of Internet of Things (IoT) technologies in many application domains (such as manufacturing, transportation, agriculture etc.). Given the increasing costs of healthcare in many countries, healthcare professionals have always been interested in solutions that can reduce healthcare costs and improve the efficiency of healthcare service delivery. To achieve these goals, the healthcare sector has been adopting various types of hardware, software, networking technologies in their Information Communication Technology (ICT) infrastructure. Recently, IoT has been attracting the attention of designers of healthcare systems who have been integrating various medical systems with IoT technologies to provide high quality affordable healthcare services to patients.

Today, connected healthcare systems play a pivotal role in connecting patients to healthcare providers, and doctors to various health data repositories, medical facilities and hospitals. This connectivity enables a comprehensive sharing of up-to-date relevant information among healthcare stakeholders (patients, hospitals, and healthcare professionals).

A major issue associated with the deployment of many technology-based solutions in the healthcare sector is the lack of connectivity among the stakeholders. Consider a typical healthcare scenario, where several stakeholders should be active,

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https://doi.org/10.1016/j.iot.2019.100074
2542-6605/

connected and collaborate with each other for the delivery of care to a patient. In a common scenario, these stakeholders include the patient, physician, medical laboratory, pharmacy, medical insurance scheme, and perhaps the patient's relatives. However, for most cases, these stakeholders are not optimally connected, and this results in several deficiencies which are propagated within the healthcare system [1]. The major benefits of a highly connected healthcare system include: increased clinical productivity through the provision of accurate and timely information, reduction in the spread of contagious diseases, minimizing duplicate laboratory activities which decreases the patient's bill, and improved clinical care protocol and the patient's safety by reducing human errors [1].

An IoT infrastructure can provide the connectivity required by the healthcare system infrastructure. IoT technologies can efficiently deliver the healthcare benefits mentioned earlier leading to a better healthcare system in general [2]. The IoT can be described as a massive global network of billions of connected devices [3]. It has a strong potential to transform and improve nearly every aspect of human life by providing better access to information, efficiency, and the automation of human tasks. These transformations and improvements will be achieved through the smart services implemented in several application domains such as travel, transportation, agriculture, business, healthcare, shopping, retail and energy. Some of these smart services include smart grid, smart transportation, smart healthcare, smart home, and smart business. However, with these potential transformations come complexities, which varies from industry to industry. Among all industries, the healthcare industry has been one of the fastest to adopt the IoT concept. Although the adoption is not widespread across every sector of the healthcare industry, it is gradually being accepted and incorporated into various ICT infrastructures that support different types of medical systems and devices [4]. Massive adoption of IoT technologies by the healthcare sector has been predicted over the next five years because of the rapid advancements and declining costs of enabling technologies (such as networks, hardware, software, and so on) that underpin the ICT infrastructure. The pervasiveness and ubiquity of IoT technologies in our daily lives demonstrate this growing trend.

Similar to other IoT smart services, the IoT Healthcare ecosystem is a heterogeneous mixture of low-powered devices with limited computing and communicating capabilities. The IoT healthcare ecosystem can enable seamless connectivity and communication among all healthcare stakeholders. Through the seamless connectivity, IoT devices can facilitate the acquisition, storing, tracking and monitoring of vital medical and health data, to provide better diagnosis and high-quality healthcare service to patients [5]. Integrating IoT features into the healthcare environment will reduce the high operational cost of hospital systems and the savings made can be used to further improve the quality and effectiveness of healthcare services that are focused on the elderly, patients with chronic health conditions, and those requiring constant supervision.

Moreover, the application of IoT in healthcare promises to not only improve the quality of patients' treatment and satisfaction, but also help healthcare providers to optimize their daily workflow operations. Workflow areas include service workflow, treatment workflow and surgical workflow. The deployment of an IoT ecosystem will facilitate the identification of bottlenecks in these workflow areas, thereby increasing workflow throughput, which would lead to an effective healthcare service. In addition, IoT technologies can be used to manage medical inventory, track patients and assets [6,7]. Another recently prominent application of IoT in healthcare is the concept of digital medication (pills), which is used in certain oncology and psychiatric treatment. Digital pills are tablets with ingestible sensors that track patients' medication dosage use [6].

At present, popular healthcare services that are currently being realized with the IoT concept include acquiring relevant medical data for patients' monitoring and assisting outpatients to adhere to treatment advice and the use of prescribed medications. Other healthcare services are assisted living, mobile health and home healthcare [6]. According to the authors of [4], the estimated spending on the IoT-based healthcare solutions will reach about $1 trillion by 2025. These solutions will empower the healthcare industry to focus on other health sectors which require highly specialized technologies to provide advanced personalized, accessible, and on-time healthcare services for everyone. As with other industries adopting IoT-based solutions, several challenges must be addressed in order to achieve the benefits of IoT-based solutions in healthcare. Such challenges include how to define appropriate IoT architectures that will deliver optimal, cost-effective services in each healthcare sector. Due to the different requirements and the diversity of the services in healthcare, it is difficult to define a universal IoT architecture for the healthcare industry. Each of the IoT-based healthcare service has its own complexity and often, specialized architectures must be designed and implemented to support each service area within the healthcare industry. Another complexity associated with IoT-based healthcare services is how to achieve a unified data platform which can aggregate the data from various sources (and likely to be in different formats). A unified data platform will enable a unified view of the data and thus facilitate an optimized healthcare system that provides tailored healthcare solutions based on the specific needs and requirements of healthcare stakeholders. The data aggregation issue is further exacerbated because of data ownership and data democratization policies. In addition, multiple data standards are used in healthcare for interactions between humans, devices, processes and applications. These include data format standards, message standards, document standards, process standards, which can be syntax based, semantics based, relationship based, purpose based, or classification based [2]. Such standards include the Fast Health Interoperability Resource (FHIR), Health Level 7 (HL7) and Health Insurance Portability and Accountability (HIPAA). Lastly, there are different country-based healthcare regulations and policies and it is necessary to comply with these regulations when developing and implementing an IoT-based healthcare solution [2]. However, in this work, we focus only on the architectures that have been recently proposed and designed for implementing IoT-based healthcare solutions.

Table 1
IoT-based healthcare devices, deployment areas and use cases.

Deployment area	Health service(s)	Device type	Use case	Complementary technologies
Home: External	Sensing air quality, adverse event alert (e.g. patients' fall), prescription medicine order and delivery, senior citizen assisted living	Home alarms, automated wheel chair, automated switches, voice-enabled devices, Carbon Monoxide (CO) sensor, motion monitor, temperature thermostat, smoke sensor	Pathfinder wheel chair [7], Amazon Alexa [8]	Artificial Intelligence (AI), Drones, Smart algorithms
Implants: Internal	Heart monitoring and treatment, Ultrasound, Magnetic Resonance Imaging (MRI), Hearing solutions	Monitoring sensors, diagnostics devices, cochlear implants, pacemakers, insulin pumps, artificial hips	Evera MRI-compatible implantable cardioverter defibrillator [9]	Nanotechnology, sensor technology
Mobile: Portable	Continuous measurement, tracking and monitoring of remote and out-patients' activity/vital sign data Health and fitness service	Mobile devices, fitness tracker, heart rate monitor, pulse oximeter	Fitbit [10]	Health apps on smartphones and tablets, Cellular technology
Medication: Internal and External	Medicine usage and adherence monitoring, Digital pill [6], Depression detection and monitoring	Automated pill dispenser, ingestible sensors, nanobots, skin patches, sensor embedded and connected inhaler, connected contact lenses, medication dosage sensor, depression monitoring watch	Gemalto (the Cinterion PHS8 smart card) [7], NantHealth's Vitality device [11], Apple watch [12]	Low-power device-to-device wireless networks, embedded sensor devices
Body: External	Temperature monitoring, auto-diagnosis of ailments (e.g., Chronic Obstructive Pulmonary Disease (COPD), Urinary Tract Infection (UTI in newborns))	Specialized temperature sensor, tracking watches, lenses, camera enable stethoscopes, step counter, enuresis [check this again if that what is it called] sensor	TempTraq [7], smart diapers [7], Vitaliti device [13], Teva's CareTRx [14]	Wearables, AI, Machine Learning
Surgery: Internal	Internal medical procedure	Imaging devices	Google glasses [15]	AI, sensors, 3D imaging

1.1. Research contributions of this work

We summarize the main research contributions of this work as follows:

- First, we present the devices and technologies that need to be incorporated into the IoT ecosystem for healthcare service delivery and some of the current use cases of these devices.
- Second, we discuss some of the driving technologies motivating the adoption of IoT in healthcare. We have presented each technology based on: IoT-based healthcare solutions they support, their enabling/complementary technologies and the challenges faced during deployment. Then, we present recently proposed IoT-based architectures for some healthcare services.
- Lastly, we discuss other important healthcare areas where the IoT concept can facilitate the delivery of improved healthcare services and the future opportunities that could be explored for more efficient healthcare service delivery by using IoT technologies and tools.

2. IoT-based healthcare devices and technologies

In this section, we classify the devices that are currently being utilized for healthcare services according to their deployment environment. We present some use case examples and their complementary technology. Then, we discuss some major technologies that are driving the deployment of IoT in healthcare.

Table 1 presents a classification of some devices and technologies that can be incorporated into the IoT ecosystem to enable some healthcare services. These applications and devices are not exhaustive, but we mention a few by classifying the devices and technologies based on the healthcare area where they are deployed. In addition, this section discusses a few of the technologies mentioned in Table 1.

In the home environment, healthcare services support the continuous treatment, monitoring of patients within the household, provide round the clock assistance and ensure that the surrounding environment does not hinder their treatment and monitoring. Implants are devices designed for some specialized healthcare services provided by internal medicine. These include services provided to monitor or treat internal body organs. Mobile healthcare services refer to services that should not be affected even if patients are on the move and thus require device and technologies that can support a patient's mobility. Medication refers to how the actual pills or drugs given to patients are supported or administered with the aid of technology. It can also be any specialized technology-based pill designed to treat certain ailments and diseases. Healthcare services that focus on the body are those that require vital physical medical data, which can be measured or acquired by placing appropriate medical devices on the external body parts of a patient. Surgical health services are those that require a view of the internal organ to operate on a patient to rectify any anomaly or perform a necessary medical procedure. An operation procedure can be regarded as invasive, non-invasive or minimally invasive. Services deployed externally are either on the external parts of the body while internal services are directed at internal body organs.

2.1. Mobile device

Mobile devices (e.g. smartphone) and tablets have become the most popular hand-held computing devices [15]. They are now ubiquitous and have penetrated every aspect of life. When combined with mobile software applications (apps) that have been developed for various user needs, mobile devices can ease human interaction and provides various types of services. In addition, some IoT devices communicate directly with mobile devices via wireless device-to-device communication [16,17] networks for the transmission of data, which can be accessed through the apps for information acquisition, making decisions or data storage for future access.

IoT-based healthcare solution supported by mobile wireless devices: In the IoT-based healthcare service area, smartphones are particularly useful. Currently, available medical services and applications making use of IoT are useful for measuring and capturing personal data such as blood pressure, heart rate, respiratory rate, and blood oxygen concentration [18]. Smartphones enable patients to personally capture and track their own vital medical records. Furthermore, mobile devices allow remote real-time streaming of patients' medical data to healthcare providers for continuous monitoring of patient's condition, which reduces in-person consultations. Measurements and acquisition of vital medical data are available on-demand for point-of-care, hospital-level diagnosis, treatment and prescription. Medical test results are available instantly for immediate diagnosis and appropriate treatment is recommended after the medical data has been analyzed and interpreted remotely either by a trained specialist or by specialized algorithms. Consequently, patients' admissions into healthcare facilities are minimized. Mobile device technology also facilitates the concept of mobile doctors through point-of-care, where patients can meet a doctor virtually in their home via a smartphone app. Other capabilities that are being developed on the mobile phone platform are non-invasive patient testing, facial gesture recognition software and voice analytics services to monitor and quantify continuous mood states for the diagnosis and treatment of underlying mental health disorders. The aggregation of mood parameters combined with other contextualized data can indicate a patients' emotional state and thus helps determine if an intervention is needed or if patients' recovery is progressing as expected.

The technologies that are enabling the use mobile devices in healthcare service delivery include: 5G cellular communication infrastructure for pervasive continuous connectivity and provision of high bandwidth, device-to-device communication networks, mobile software application, cloud and supercomputing. Others include: artificial intelligence, machine learning and big data analytics to learn and make reliable and accurate decision using patients' multi-layered medical data in way that no human could process in real-time.

Some of the challenges that need to be addressed in relation to the use of mobile device technology is healthcare are: Data synchronization and storage, data reliability, precise data interpretation, data security and privacy concerns, device battery life and device signal transmission interference.

2.2. Wearable device

Wearable devices are small, on-body devices, worn by people. They are always connected, hands-free, less distractive, and have multiple communication access interfaces [18–20]. Such devices include hand-worn terminals, body-mounted cameras or augmented reality headsets. The wearable technology is complemented by mobile device technology (smartphones) and mobile software applications (app). The user interface of a wearable is an app, which is accessible on a mobile device or desktop computer [21]. Thus, smartphones are required to carry out the task of processing and transmitting the information generated by a wearable device to the cloud or fog for storage [22]. Wearable devices can therefore be considered as an extension of mobile devices [15]. However, wearables are becoming smarter and more powerful and, in the future, they may not need the support of smartphones. Wearables enable their users to conveniently interact with services. For example, rather than typing or touching, voice control can be used to perform some activities such switching light on and off. The category of wearables with this capability is known as active wearables (e.g. smart watches and glasses). They provide information to users and serve as a source of input to control other devices within their proximity or which they may be remotely connected to. The other category of wearable devices is passive wearables which do not require any direct human interaction.

IoT-based healthcare solution supported by wearable devices: Medical wearable devices include heart rate monitors, fitness trackers, step counters, blood pressure measuring device. These devices automatically measure and capture patients' medical information such as blood pressure, glucose levels and heart rate. Therefore, it frees patients from having to remember to perform and record these measurements. Medical wearables allow patients to be involved in their own treatment regimen. Patients can view and monitor their medical vital signs first-hand and receive early warnings. Through analytics, healthcare providers can detect the pattern of progress of patients' treatment, especially for patients with chronic diseases or mental disorder. The clinicians can also be alerted about imminent adverse patients' internal or external events. For example, if an out-patient suffering from potential heart failure is not taking the required number of physical movement steps each day, it may be time to schedule such patients for a check-up. Also, if a pediatric diabetic patient blood glucose monitor continues to send alert about patient approaching high glucose levels, it might be time to schedule the parents for an educational session about dietary choices [23]. Data captured and analyzed from wearables, can improve the interaction between patient and healthcare provider and thus preventative care can be provided. For example, patients will be able view a chart of their sleep pattern, blood oxygen saturation, heart rate or glucose level, draw a conclusion regarding their unhealthy habits or problems and use the information to ask informed questions from their physician. Thus, patients are engaged and become more personally involved in their own health monitoring and treatment plan. Wearables are important for tracking how patients behave while healthcare providers are not available [23].

The enabling technologies include: system-on-chip (SoC), wearable computing, biosensors, ultra-low power device-to-device communication networks, energy harvesting, wireless charging, nanotechnology, material science, low-power integrated circuit, IPv6 over Low-Power Wireless Personal Area Networks (6LoWPAN) [24].

Some of the challenges include: data interoperability, device data consistency and accuracy, data privacy, lack of robust security protocols [18], battery life constraints, communication signal interference.

2.3. Body Area Network (BAN)

A Body Area Network is a healthcare tailored wireless communication network that facilitates the monitoring of the health status of a human body anywhere, anytime [25]. Sensors with wireless communication capability are implanted/attached to the internal and/or external portions of a patients' body. The sensor data collected is then transmitted over a low-power wireless network to the appropriate server through a gateway device. For the IoT-based healthcare applications, the Wireless Body Area Network (WBAN) is gaining popularity as the number and types of wearable devices continue to grow and become more affordable.

IoT-based healthcare solution supported by BAN: A network of sensors deployed on different parts of the body can be used to measure the body temperature distribution, or to detect patients' fall. Thus, real-time monitoring for Assisted Living [26] or for rehabilitation sessions is made possible. BAN makes rehabilitation achievable by providing data that shows either the improvement or decline of patients' condition. BAN also facilitates the process of early detection of abnormal health conditions and medical issues by issuing an emergency notification if an anomaly is detected. It also supports remote telemedicine. Data collected through a BAN can be used for future research to develop new healthcare products and provide effective education of healthcare industry stakeholders [27,28]. The BAN supports the delivery of on-demand health services information to stakeholders that have data access authorization.

The enabling technologies for BAN include: Wearable devices, energy harvesting, ultra-low power wireless communication network protocols [29], Wireless Sensor Networks (WSN), 6LoWPAN.

A few of the challenges for Body Area Networks are intra-human body transmission safety, signal attenuation, resource optimization routing strategy, energy constraint, security and privacy, and medical ethics.

2.4. Big data

Big data analytics combines two or more previously disparate sources of data and structures them in a way that further insights and knowledge can be extracted by analyzing them. Analysis could be by comparison or examination of the new or expanded data sets. In healthcare, there are multiple and disparate data sources. These sources include the Electronic Health Record (HER), Health Information Exchange (HIE) data, public health data, clinical outcome data, and patients' data generated from the vast network of IoT-based healthcare devices [30].

IoT-based healthcare solution supported by big data: Big data analytics allows the health data to be presented in a meaningful, understandable way which will allow healthcare providers to make accurate, well-informed decisions on patients' treatment plan and management. Particularly, with big data technologies, a short time analysis of a large collection of data from thousands of patients is possible. Such technologies allow the identification of clusters and correlations, and the development of predictive models using statistical or machine-learning models [31]. In addition, big data technologies make it feasible to incorporate the data collected in the past with current data for various healthcare research studies. For example, a pharmaceutical research can continue to enrich its research database with different types of information from new patients for new research studies that aids in the improvement of medical drug manufacturing.

The enabling technologies include: fog computing [31], cloud computing, and data virtualization platforms.

Some of the challenges include: data interoperability, the lack of seamless integration of the large-scale and disparate health databases, integrating legacy data sources with state-of-the-art database systems, new skill set/experts to understand and provide accurate data analysis and interpretation of the medical data records.

2.5. Artificial intelligence

Artificial intelligence (AI) systems are designed and implemented with intelligent systems so that they can perform tasks without receiving instructions directly from humans [32]. These AI systems use vast amounts of data, intelligent algorithms and decision-making models to provide a solution or response to a user request or situation. The integration of AI and data analytics systems with the IoT ecosystem can enable automation of the healthcare system such that some major treatment or diagnosis decision about a patient are being made by the system instead of healthcare professionals. Leveraging AI in

Table 2
Technical functional services required by healthcare services.

Functional service	Healthcare service				
	Monitoring	Remote patient healthcare	Assisted living	Mobile/remote access	Coaching system
Notification (warning or alert)	Medium	High	High	Medium	High
Internet connection	High	High	High	High	High
Device discovery and connectivity	High	High	High	High	High
Security	High	High	High	High	High
Artificial intelligence	Low	Medium	High	Low	High
Data analytics	High	High	High	High	High
Real-time streaming	High	High	High	High	High
Mobility service	Medium	Low	Low	High	Low

healthcare has a lot of potential benefits including convenience, improvement of patients' safety, minimizing medical costs (e.g. doctors' and laboratory test charge), improvement of diagnosis and avoiding repeated tests.

IoT-based Healthcare solutions supported by AI: AI has the capability to support and improve assisted living through a Personal Health Virtual Assistant System [33]. AI systems can serve as personal coaches for a patient when he/she is outside of the hospital environment by motivating him/her to take certain actions for necessary for his/her well-being. AI systems can deliver medication alerts and use human-like interactions to gauge patient's current mental state. They can monitor patients' behavior when clinical healthcare professionals are not available and then generate proactive alerts which are sent to patient's physicians and clinical professionals [32]. In addition, AI systems can assist in performing remote surgery [34], create customized medical treatments for patients by providing treatment recommendations based on aggregated data and detecting abnormalities in X-ray results [32].

The enabling technologies are Cloud computing, machine learning, healthcare software decision making applications, big data.

Some challenges of AI in healthcare includes the lack of data exchange between health stakeholders, interoperability, regulatory compliance requirements and standards. As with any new technology and due to security and trust issues the adoption of AI by patients and healthcare providers has been slow. One of the trust issues is system failure, which could be catastrophic. Another issue is the fact that it is almost impossible for the AI system to mimic the physician's gut feeling and intuition even with sophisticated algorithms and lots of computational resources [32].

For all these technologies discussed above, a significant challenge that remains is the provision of high-quality services in all areas of healthcare via the IoT ecosystem. Some design issues that need to be addressed include bandwidth requirement for healthcare facilities and patients, accurate data storage, data ownership, generating systems requirements, operational standards and policies. In addition, most of the healthcare applications/services where the technologies (discussed above) are used will generate real time streaming data while others will generate burst of data as needed [33]. Therefore, devising smart communication protocols to ensure the provisioning of quality of service within the network, optimized resource allocation and data routing are paramount to the delivery of high-quality healthcare services through the IoT ecosystem.

3. Review of proposed IoT design architectures for healthcare solutions

The benefit of leveraging various types of technologies to improve healthcare delivery systems cannot be overemphasized. Strong connectivity among all networked systems and devices that are part of the healthcare environment is vital. To reinforce the importance of a connected healthcare system and to illustrate how it can be achieved through the IoT concept, in this section, we analyze some recently proposed architectures, which use the IoT fundamental technologies to better manage and deliver healthcare services. These architectures vary from one service to another. For each architecture, we outline its goal and the targeted healthcare solution, the basic architectural design components and their operations along with their functional services. These functional services include notification, which provides a warning or an alert, network resource sharing between components of the architecture, Internet connectivity, device discovery and connectivity, security, artificial intelligence, data analytics, real-time streaming and mobility. Table 2 summarizes the functional services for each of these architectures. These functional services are required for the IoT architecture to provide the targeted healthcare solutions and goals. The overall outcome is the realization of an IoT-based healthcare solution. Moreover, each of the functional services has varying levels of importance in the different IoT-based healthcare architectures with some services being more important in some architectures than in others. Internet connection, device discovery, connectivity, real-time streaming, data analytics and security services are high priority for all the architectures presented. These services can be supported cost-effectively by leveraging the IoT concepts and technologies.

3.1. IoT Healthcare Network (IoThNet) architecture

Fig. 1 shows the IoThNet architecture, a basic reference architecture recommended by Continua Health Alliance. The goal of this architecture is to facilitate the monitoring of personal health and wellness by providing an end-to-end connected

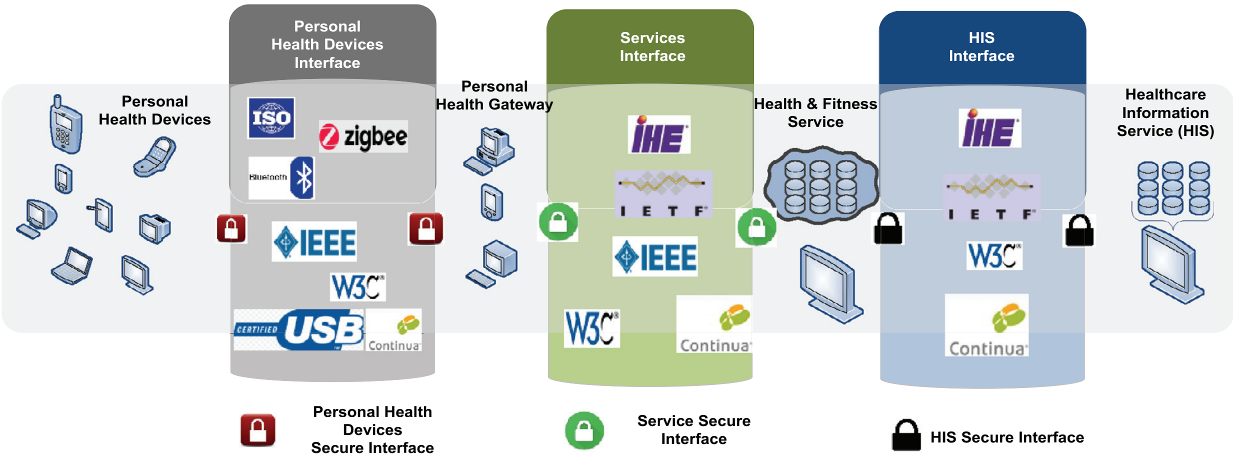


Fig. 1. IoT-based architecture by Continua Health Alliance [35].

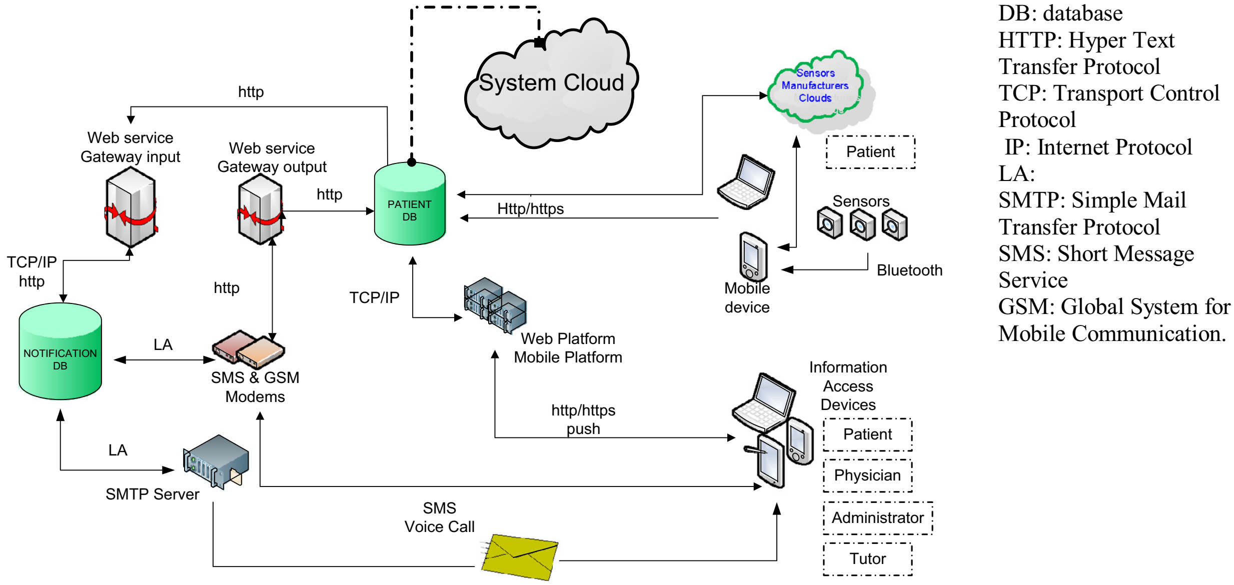


Fig. 2. IoT-based architecture by IPHealth [39].

architecture for the transmission of patients' data from their health devices to medical offices, hospitals, patient information systems, and so on [35,36]. The functional structure of the architecture comprises of WBAN, Wireless Local Area Networks (WLANs), Wireless Wide Area Networks (WWAN) and the Data center [37]. The physical elements operating in each functional section include devices such as wearables, smartphones, tablets and data storage devices. These devices make use of IPv6 and 6LoWPAN as the main network layer protocols, while the physical layer transmission uses the IEEE 802.15.4 protocol [37]. However, since for the IoT healthcare, some services require healthcare providers to have full access to the data for the continuous monitoring of patients regardless of their location, real-time continuous and seamless communication is necessary. Thus, mobility support is crucial for the success of IoT in healthcare. Mobility support protocols for communication within the IoThNet can be provided by using the 6LoWPAN protocol for exchanging messages between mobile patient devices, home networks, and visited networks which are described in [38,39].

3.2. IoT architecture for remote patient healthcare

Fig. 2 illustrates the architecture implemented in the IPHealth project [39]. The goal of the architecture is to assist healthcare professionals when they make remote clinical decisions or give chronic and dependent patients access to relevant information about their health to prevent acute episodes and emergency situations due to health degradation. It also provides support-based training evidence of medical students [39]. Medical students can access and view real-life patients' data during their training. This architecture facilitates high-performance, effective and scalable data collection by monitor-

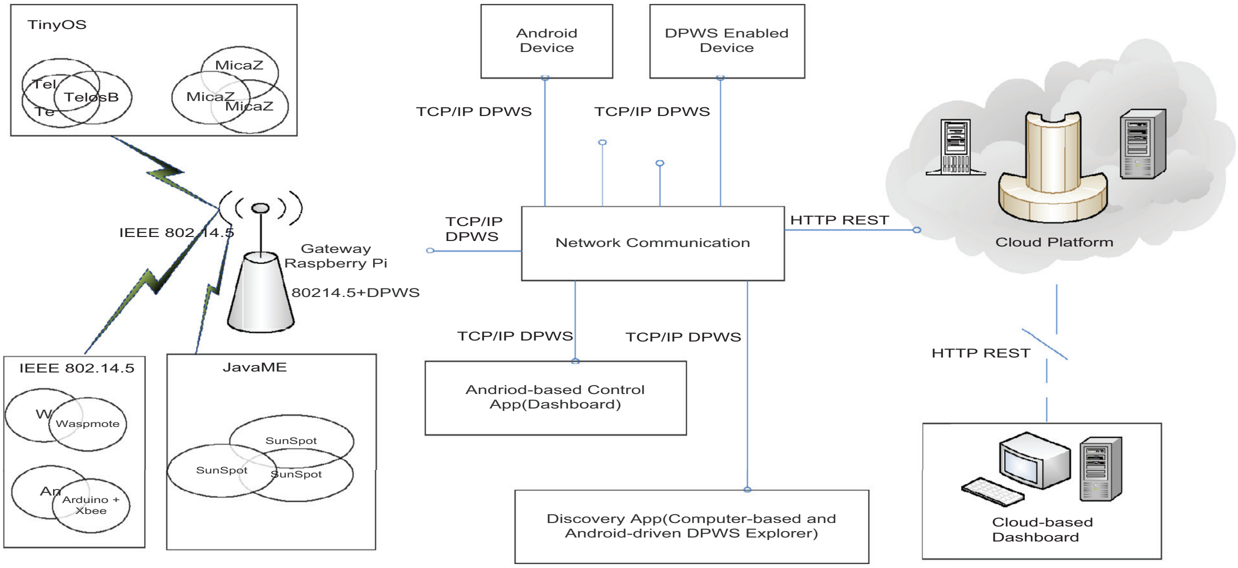


Fig. 3. Open source IoT-based architecture [40].

ing a patient's activities and the processing, sharing and storage of this data. Activity monitoring can be done by authorized stakeholders such as patients, healthcare professionals, emergency systems, caregivers and relatives. It incorporates the implementation of non-invasive sensors coupled with the concept of big data and cloud computing, thus allowing the processing of high volumes of sensor data and data from other sources. The architecture enables searching and retrieval of medical related information about the patient who is being monitored and provides appropriate visualization interface for all stakeholders.

The architecture allows smartphones to accept data from wearable devices and activity sensors. A cloud-based infrastructure is used for data storage and an analytic module to generate alarms (when an emergency is detected) to the patient and/or the patient's caregivers. A message delivery platform such as Short Message Service (SMS), email, voice automated systems are all PUSH technologies that are used for sending information to all users of the system. Access to a patient's information is possible via a website from a desktop computer or a mobile device.

3.3. IoT architecture for Ambient Assisted Living (AAL)

Fig. 3 shows a proposed open source cloud-based architecture called DEEP (Devices Profile for Web Services (DPWS)-enabled devices platform) for supporting Ambient Assisted Living (AAL) [40]. The architecture uses the DPWS protocol stack [41] to describe devices as services. The aim is to integrate and manage multiple heterogenous health and homecare devices in an assisted living environment efficiently and seamlessly.

Ambient intelligence (AmI) systems consist of medical sensors and devices, computers, wireless networks and software applications, which are used to perceive stimuli and generate data from the users and the environment. The data generated enables the monitoring of patients. Thus, AmI systems facilitates the realization of AAL healthcare application [40]. AAL applications facilitates user-dependent services for elderly and disabled people. These user-dependent services include monitoring the vital signs or controlling the tracking of a patients, through the analysis of diverse sensed information and detecting and reacting to abnormal situations. Therefore, AmI systems must deal with a diverse range of devices, from smartphones and tablets, that have medium capacity, to sensors, actuators, consumer electronics and wearable devices, that have critical resource limitations.

AmI systems use the capability of smart sensing devices to sense typical normal human behavior and environment and identify any critical changes or anomaly. If an anomaly exists, the devices communicate with each other to enable the use of available home automation system to create an alert. These smart sensing devices help elderly/aging/senior citizens in their daily routine at home to allow an independent and safe lifestyle.

When AmI systems are deployed within an architecture powered by the IoT concept, AI, and cloud computing, the resulting architecture enables the realization of an AAL health service [40]. The personal communication between elderly people, their environment and their relevant groups of care givers is an important aspect of Assisted Living [29]. As such, communication among stakeholders of an Assisted Living service is facilitated with smart devices in a smart home. These devices can communicate with remote caregivers and health professionals [37,40]. In this architecture, devices are abstracted as services and the features of a device are exhibited as web services. The first level of the architecture consists of sensors and gateways which transform the messages received from the different types of sensors to DPWS-compliant services. The second level is the network communication, which allows all heterogeneous devices such as the sensors, gateway, DPWS-enabled devices and the Android devices to discover and connect with each other. The last level is the cloud platform, which collects the sensed data via the network and allows users to access and effectively analyze available data in order to react to situations based on the data collected. Remote monitoring is supported by using the push messages of the Google Cloud Messages [40] to recommend the appropriate diagnosis and treatment to medical personnel.

3.4. IoT architecture for mobile healthcare

Mobile health (m-health) is a concept that allows the provisioning of appropriate healthcare services to patients that are highly mobile. It combines mobile computing, sensors, and communications technologies [43]. It uses sensor embedded connected and mobile health devices. Thus, mobility as a service, is an intrinsic feature of m-health for continuous connectivity with participating stakeholders. Consequently, device-to-device and cellular communication network infrastructures are vital components for current and future mobile health services. Fig. 4 shows a high-level architectural model that provides m-health services. The generic components required within an m-health architecture includes [43]:

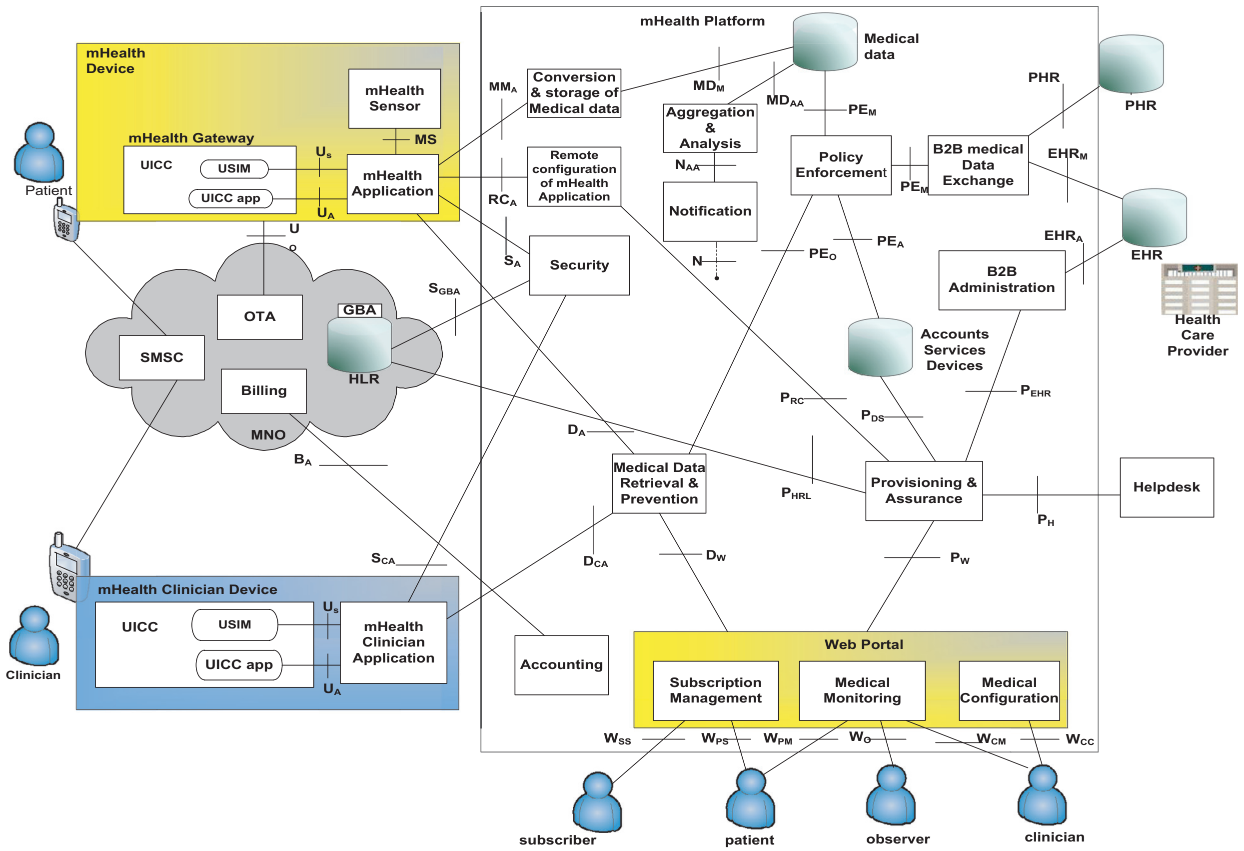
- *The patient's mobile device*: this includes embedded sensors, a gateway device and a smart phone with an appropriate health service mobile application installed.
- *The health provider's mobile device*: this is likely to be a smartphone or tablet that will enable the healthcare professional to view and interpret the data that is being transmitted from a patient's mobile device.
- *The mobile network and its components*: this is a cellular mobile network that provides mobile and ubiquitous connectivity for the devices. Its components include a sim card, the Home Location Register (HLR) and all other cellular network components.
- *The mobile health platform*: this platform utilizes the data collected via the mobile operator network to provide a mobile health service. The main components of this platform perform: the conversion and storage of data sensed by the patient's device, the synchronization of data, administrative services (e.g. accounting information about patients and clinicians, billing and pricing). These components also guarantee Service Level Agreement (SLA) compliance. The mobile health platform also provides a web portal interface and sends notifications to mobile healthcare participants whenever preset thresholds for certain health related data are reached.

The goal of the reference architecture in Fig. 4 is to support mobile network operators in the development of mobile health products and services [43]. The architecture helps them to identify and reuse tried and tested network capabilities and operations to provide value-adding, differentiated and tailored healthcare services. For example, a disease management health service can be a value-added mobile service for a mobile network user. Consider a diabetes patient who requires a management program. Such program assists in the measurement of blood glucose, the amount of insulin and recommends an adjustment of lifestyle accordingly if needed. The management program includes a blood glucose sensor connected to the patient's mobile device. To use the program, the patient and his healthcare provider ensures that the patient has the appropriate mobile network service subscription. Such subscription is provided as a differentiated service for the patient and the healthcare provider by the mobile network operator. The differentiated service ensures that a reliable network connectivity is available to transmit the patient's blood glucose and insulin data to the healthcare provider. Under the differentiated network service, the patient and his healthcare provider are always connected even when they are both mobile. Thus, the healthcare provider is always updated with the patient's diabetes related data, which is used to ensure that the patient's condition is properly managed.

3.5. An IoT architecture for smart healthcare coaching systems

Home healthcare and rehabilitation has become increasingly important due to the fast aging population and some chronic diseases that require patients to have continuous healthcare attention to aid their recovery [44]. Chronic diseases such as dementia and Alzheimer's disease need patients to be cared for in their home environment. The IoT ecosystem offers a potential to provide quality healthcare solutions by facilitating the building of coaching systems. Such systems can use collected data to proactively manage patients' health by setting challenging activities for the patients [44]. Benefits of coaching systems to dementia patient include maintaining and stimulating mental and physical capacity and facilitating night sleep. They help patients to remain active and to do movements that can help them to live as normal as possible. These coaching systems rely on computational cognitive models of human memory, which when combined with the IoT concept has the possibility to improve patients' daily living.

Fig. 5 shows an IoT architecture that enables the realization of a coaching system for daily living activities. The coaching system models human cognition so as to solve users' problems as a human would [44]. Thus, the architecture assists in caring for cognitive impaired patients' by recognizing and dealing with activities ranging from those that may involve potentially dangerous situations to abnormal behaviors of patients. Such abnormal behaviors are due to memory impairments, anxiety, psychotic symptoms or alteration in sleep and wake cycles. Sensed data from devices are processed and analyzed by the components of the cognitive architecture [44]. The architecture uses frameworks that model the brain structure and foster the study of the mind and it how it works [44]. The healthcare goal of this architecture is to give guidance and coaching to cognition-impaired patients. Overall, the service provided is the tutoring of patients to avoid performing incorrect actions



SMSC: SMS Centre (SMSC)	U_S: USIM to mHealth Application	P_W: web portal to the provisioning and assurance capability
OTA: Over The Air	U_A: UICC to mHealth application	D_W: web portal to the presentation capability
GBA: Generic Bootstrapping Architecture	M_S: Mobile sensor to mHealth application	W_{SS}: subscriber to the subscription management functionality
HLR: Home Location Register	U_c: UICC to OTA	W_{PS}: patient to subscription management functionality
MNO: Mobile Network Operator	MM_A: receives raw data from mhealth application	W_{PM}: patient to medical monitoring functionality
UICC: Universal Integrated Circuit Card	R_{Ca}: remote configuration module to mHealth application	W_O: observer to medical monitoring functionality
USSM: UICC Security Service Module	MD_{aa}: medical devices to aggregation and analysis module	W_{CM}: clinician to medical monitoring functionality
GSMA: GSM Association	N_{AA}: notification module and aggregation and analysis module	W_{CC}: clinician to medical configuration functionality
B2B: Business to Business	EHR_A: for a Health Care Provider to manage accounts and services through its own EHR system	P_W: Web Portal to provisioning and assurance capability
PE:	EHR_M: to exchange information with the Electronic Health Record database of the Health Care Provider.	P_H: helpdesk to provisioning and assurance capability
PHR: Personal Health Record		P_{HLR}: HLR of the Mobile Network Operator
EHR: Electronic Health Record		P_{RC}: for remote configuration of mobile health devices, applications and sensors
MD_{in}: stores medical data converted to database format		P_{DB}: to the database with information about user accounts, mobile health services and devices
B_A: Billing to accounting database		P_{EHR}: for B2B administration
S_{ca}: security module to mHealth Clinician application		
S_{GBA}: Security module to GBA		
S_A: Security module to mHealth application.		

Fig. 4. IoT-based architecture by Continua Health Alliance [42].

or missing the sequence of corrected behavior. The system interprets the sensed data and suggests or directs patients on actions to take. The components of the architecture are:

- *Sensor layer*: devices on this layer perform continuous real-time measurement of signals and medical vital (e.g. blood pressure, heart and respiratory rate and muscle activity).
- *Sensor network*: comprises of heterogeneous device-to-device short range network technologies that allow the sensor layer devices to disseminate the data collected.
- *Drivers*: they are the bridge between the sensor layer and integration platform, which enables inter-operation between different technologies.
- *Integration layer*: this layer also comprises of the data layer. The layer integrates the data coming from the drivers to present a uniform model for the storage and management to data at the Data layer.

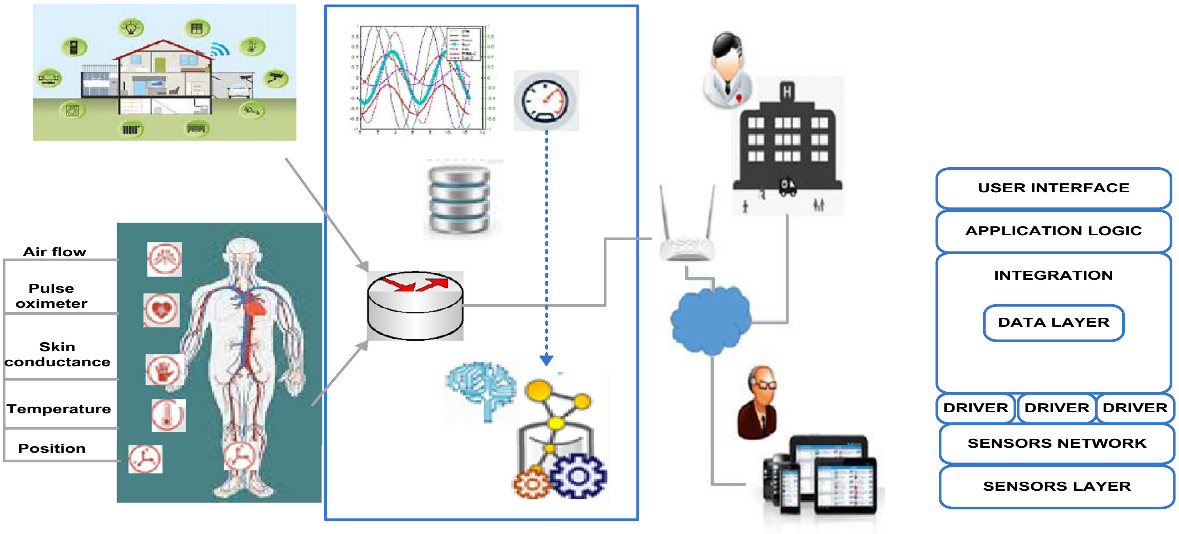


Fig. 5. IoT-based architecture for coaching [44].

- *The application logic*: this is the core of the coaching architecture. It uses the in Adaptive Control of Thought-Rational (ACT-R) cognitive architectures [45]. The application logic layer processes data and generates messages, which are sent to the User Interface to notify users about dangerous situations or recommend correct behaviors. In addition, it issues real time command to control smart devices in patients' home. For example, when there is an imminent dangerous situation, commands can be sent through the device drivers to switch on or switch off devices.
- *User Interface*: used for the interactive control, configuration and use of the system. It provides an interface for the user to trigger an alerts/alarms, which may cause an action or communication with other users.

4. Potential IoT-based healthcare solutions

4.1. Current IoT-based healthcare services

There are many areas in healthcare that could benefit from IoT technologies. Next, we discuss how IoT technologies can help deliver improved healthcare by focusing on the following four categories of healthcare service:

- *Symptom analysis and early diagnosis:* Most individuals suffer from health conditions that would probably have been avoided if symptoms were identified and diagnosis made early enough for quick treatment. Thus, it is critically important to find precise and quick ways to identify the individuals who are at high risk of developing a disease [38]. Symptom analysis and early diagnosis can be achieved through the continuous measurement of relevant vital signs such as glucose level, heart rate, heart rhythm pattern, body temperature, blood oxygen saturation and others. The data resulting from these measurements are analyzed with appropriate medical data analytics tools using predictive analysis and if an individual is prone to a disease, it will be detected early. For example, an individual with re-occurring high blood pressure measure level can be diagnosed early if they are nearing a potential or an imminent risk of a stroke or heart attacks. Application of the IoT in healthcare can provide information through predictive analysis of the data generated by the wearable devices and thus allow early diagnosis and enable clinical professionals to decide whether aggressive treatment is required or not.
- *Monitoring:* Hospital visits, setting up appointments are the norm for several individuals with healthcare needs. This can be quite inconvenient at times and may be costly due to associated travel expenses especially for specialized treatments for chronic diseases. With the IoT concept being deployed for monitoring patients, tailored healthcare monitoring devices will generate vast amount of data. The high volumes of data that will be generated by the healthcare/medical devices and made available through secured communication network connectivity and data storage will allow an effective analysis of such data. Therefore, real-time and continuous monitoring of patients' conditions anytime anywhere becomes possible. Consequently, the development of improved health management solutions, better strategies and support systems for treating and managing chronic disease and identification of medical emergencies will be achieved. In addition, patients' treatment regimen for medication compliance can be monitored and potential overdose or under-dose issues are prevented. Another major benefit of the application of the IoT concept for patients' monitoring is the ability to achieve of precision medicine, which enables the development of personalized/customized healthcare treatments. Some patients may not respond to a normal treatment course due to their genetic make-up and thus require a customized treatment plan. The information analyzed from the data gathered via an IoT-based monitoring platform can help in the develop-

ment of a specialized treatment regimen for such a patient. Patient-based IoT monitoring platforms can help patients to become quickly aware when symptoms are returning and provide them with a prompt treatment course to prevent potential hospital re-admission and thereby helping patients to save on healthcare cost. Moreover, the use of artificial intelligence on the data generated from an IoT platform can enable an early diagnosis of symptomless but serious and chronic diseases such as Atrial Fibrillation (AF) [32].

- *Mobile/remote access services*: Increasing patient engagement through smart mobile phones can improve the quality of care given to patients and their satisfaction. The mobile devices within the IoT ecosystem enables continuous streaming of up-to-date and accurate patients' medical data to healthcare providers. Traditionally, a patient's vital medical data would have been 8 or 12 h old by the time it has been recorded in the database. Thus, the data may not accurately match the current state of the patient's health. However, with the integration of IoT in healthcare, real-time and up-to-date information about a patient's health can be accessed regardless of the location of the patient. Thus, various types of medical information are available on-demand and accurate, on-time treatment decisions can be made. Since most patients who need healthcare will be mobile (either at home or in the office), certain healthcare devices can be considered as mobile in nature and connect to the Internet via the mobile cellular network. The availability of data analytics technologies and platforms will in turn foster independence and empower individuals to manage their health and wellness from anywhere at any time, thus making health and wellness a convenient part of their daily lives [30].
- *Hospital management*: Hospital management is concerned with patient management, medical supplies management and work-flow management [7]. The outcome of good hospital management is an efficient and effective hospital work-flow which results in improved hospital quality, patients' welfare and safety. The use of smart devices within the IoT ecosystem can enable an effective patient management to be achieved. For example, a sudden increase in the number of patients under treatment after a surgery can be reduced or totally prevented. Such an increase may be due to infection, which could be avoided if appropriate data were available for analysis using intelligent algorithms that can detect patient's plummeting vitals that are not detected early by humans (medical staff). As for medical supplies, the IoT concept can facilitate cost-effective inventory management, logistics and storage of medical supplies by correctly identifying optimal times for replenishing medical supplies to enable continuous and smooth hospital operations [27]. In terms of work-flow, hospital bottlenecks can be prevented especially in the Emergency Room (ER) section by using IoT-generated data to analyze patient flow during peak times so that additional staff can be scheduled on time.

4.2. Future healthcare opportunities in the IoT ecosystem

- *On-demand health service to reduce appointments:* IoT support for healthcare can implement architectures and platforms that will help clinicians and health professionals react quickly and effectively to patients' medical needs remotely or face-to-face if necessary thus enabling early treatment of high-quality care.
- *Public health:* In the health sector, the area of public health is very important for any government in any country. The IoT concept, when combined with big data technologies and intelligent predictive analytics algorithms can help harness and strengthen public health management.
- *Remote surgery:* Remote surgery makes it possible to extend quality healthcare to underdeveloped areas that lacks access to surgical care. Remote surgery also has the potential of enabling healthcare surgical experts in different regions of the world to collaborate effectively when performing a surgery without meeting. A reliable wireless and satellite communication channel, Machine learning, Imaging technology, Artificial Intelligence and tele-surgical robotics are a few of the technologies that enables and IoT-based remote operation [34]. To perform a basic remote surgery, the patient to be operated on and the surgical expert to perform or supervise the operation are in different regions. The surgical expert uses a special console to continuously control every action and movement of the tele-surgical robot and thus can remotely command/supervise the surgical robots that operates on the real patient [46]. Remote surgery that involves advanced level of surgical operations may take some time for it to be fully integrated into the healthcare system. However, the IoT ecosystem with full-fledged and robust security services can assist in the delivery of accurate and reliable surgical operations anywhere and anytime in the world [32].
- *Sustained patient engagement:* Often patients are not actively involved in their treatment plans. Moreover, those who are monitoring their vital signs with wearable devices do not have an integrated and a unified meaningful view of all the data being gathered [29]. IoT technologies can motivate healthcare providers to act quickly toward adopting the right data standards that allow the integration of heterogeneous data sources. The adoption and implementation of the correct data standard is critical for chronic disease management, remote monitoring, and predictive analytics, so that care givers can easily engage with patients who will be motivated to adhere to their individual treatment plans. Due to sustained patient engagement, we are likely to have a lasting behavioral change on the mitigation or reduction of the impact of common chronic diseases, such as heart failure and diabetes. In short, a unified view of the data originating from various sources will contribute to the delivery of optimized healthcare cost-effectively.
- *Remote hospital-level treatments and services:* A well-integrated IoT platform with AI has the potential to deliver efficient and precise health services to patients [32]. These include automated prescription, medication delivery and auto-diagnosis. Patients can interact directly with an always-available system to schedule appointments, obtain prescription, access billing information and obtain automatic diagnosis. Consequently, healthcare providers will reduce the overall administrative and running costs of operations. An IoT-based healthcare system can also provide remote and accurate

diagnosis independent of or along-side clinicians. This can give more some time to clinicians to attend to more critical patients. The pharmacy can also use such IoT-based systems to schedule, dispense and deliver prescribed medication to the patient's address automatically without any human intervention.

- *Advanced delivery of prescription medication:* Currently, Zipline [47] operates the world's only medical supply drone delivery system, which offers direct delivery of medications to patients. Urgent medical supplies including blood and vaccines are delivered to near and remote clinics and hospitals. Adding an IoT-based architecture to the system can ease the automatic delivery of prescription medications to home and offices for those who subscribe to the IoT-based healthcare system.

5. Conclusion

In this paper, we emphasize that, providing high, reliable connectivity for medical devices and sensors through the IoT ecosystem is the key to unlocking the true potential of a smart, connected digital healthcare system. These medical devices are typically portable, wearable, implantable, miniature and mobile wireless devices. The main value associated with a smart healthcare system is the availability of continuous and real-time up-to-date data, which is used by stakeholders to make informed and timely decisions. Such continuous and real-time information requires strong ubiquitous connectivity if a reliable technology-based healthcare system is to be delivered. We have showed how the IoT concept can enable ubiquitous connectivity that can meet the requirements of all healthcare industry stakeholders. Though there are several complex challenges such as security and privacy, interoperability and standards, connectivity and architecture that are associated with IoT deployment, in this paper we have focused on the IoT connectivity and architecture. To achieve IoT-based connectivity in the healthcare ecosystem, we need a reliable and robust IoT architecture. An IoT-based healthcare solution is composed of several underlying technologies including medical wearable devices, wireless communication networks (mostly, low-powered), data storage and data analytics. In this paper, we reviewed some of these technologies and then discussed a few IoT architectures that have been proposed recently for some healthcare applications such as patient monitoring, Ambient Assisted Living and m-health.

It is worth noting that since the healthcare industry provides a variety of services to patients there cannot be a generic IoT architecture for all possible IoT-based healthcare applications. To address this design challenge, we have identified and presented some of the most important functional services that are required by different healthcare applications. These functional services vary from critical ones to those with low priorities. In addition, to achieve the full potential of IoT architectures, we need to leverage other technologies such as AI, cloud computing, fog computing and others to provide a specific health service. Finally, we discussed the impact of IoT on healthcare delivery and the potential benefits that we can reap from IoT-based healthcare solutions in the future.

Conflicts of interest

We do not have any conflicts of interest.

Acknowledgments

We thank the anonymous reviewers for their valuable comments which helped us to improve the quality and presentation of this paper.

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Please cite this article as: S. Zeadally and O. Bello, Harnessing the power of Internet of Things based connectivity to improve healthcare, Internet of Things, https://doi.org/10.1016/j.iot.2019.100074