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REVIEW PAPER

The application of internet of things in healthcare: a systematic literature review and classification

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Abstract
The Internet of Things (IoT) is an ecosystem that integrates physical objects, software and hardware to interact with each other. Aging of population, shortage of healthcare resources, and rising medical costs make IoT-based technologies necessary to be tailored to address these challenges in healthcare. This systematic literature review has been conducted to determine the main application area of IoT in healthcare, components of IoT architecture in healthcare, most important technologies in IoT, characteristics of cloud-based architecture, security and interoperability issues in IoT architecture and effects, and challenges of IoT in healthcare. Sixty relevant papers, published between 2000 and 2016, were reviewed and analyzed. This analysis revealed that home healthcare service was one of the main application areas of IoT in healthcare. Cloud-based architecture, by providing great flexibility and scalability, has been deployed in most of the reviewed studies. Communication technologies including wireless fidelity (Wi-Fi), Bluetooth, radio-frequency identification (RFID), ZigBee, and Low-Power Wireless Personal Area Networks (LoWPAN) were frequently used in different IoT models. The studies regarding the security and interoperability issues in IoT architecture in health are still low in number. With respect to the most important effects of IoT in healthcare, these included ability of information exchange, decreasing stay of hospitalization and healthcare costs. The main challenges of IoT in healthcare were security and privacy issues.

Keywords Internet of Things (IoT) · System architecture · Health · Home healthcare · Smart Hospitals

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1 Introduction

The Internet of Things (IoT) is clearly a major technological innovation in computing and communications [1]. Kevin Ashton in 1999 introduced the term IoT in the supply chain management domain [2]. He defined IoT as a network of uniquely addressable and interoperable objects with Radio-Frequency Identification (RFID) technology [3]. In the research community, IoT has been defined from different perspectives in the literature. RFID group as a leading forum defines IoT as the interconnected things that are exclusively identifiable relying on the standard communication protocols [4].

According to [3], IoT is a sophisticated network of “things” that is uniquely identifiable, where each of these objects connects to a server that efficiently provides suitable services. According to this definition, each of these ‘objects’ has some prominent characteristics and acts as active participant in different contexts. They are enabled to communicate with each other and with the physical world by transferring pertinent data from the physical and virtual world. These things are also able to respond autonomously to the events of the surrounding world. All of these processes can activate some actions and create services by human intervention or by means of machine-to-machine communication [5].

It is forecasted that by 2020, 25 billion "things" will be connected to the internet. This connection will promote the volume of derived data, and knowledge extracted from this data will be applied to manage and make intelligent decisions autonomously [6]. For years, several industrial and manufacturing domains have been used in machine-to-machine communication using technologies such as RFID and sensor networks [7–9]. Although IoT has existed for more than a decade, two developments have been the primary drivers behind the emergence of this technology. The first is the tremendous growth in mobile devices and applications; the second is wide availability of wireless connectivity [10, 11]. Furthermore, increasing knowledge-based capital (i.e., software, data, intellectual property, firm-specific skills and organizational capital) and the rise of the digital economy are among the key elements for rapid IoT revolution [11].

IoT consumers by means of augmented intelligence can vastly improve their decision-making abilities [12, 13]. Vast use of IoT technologies has enabled businesses to optimize the work process and increase efficiency by collecting and reporting related data, obtained from the environment. Based on the several previous researches, IoT will be the next big destination for investment by many industries [4, 14–16].

In the near future, healthcare environments will be revolutionized by means of IoT opportunities. This technology will play a prominent role in patient tele-monitoring in hospitals and more importantly at home [17–19]. Remote patient monitoring provides tremendous possibilities to not only increase healthcare quality but also reduce healthcare costs by identifying and preventing diseases and harmful situations [20, 21]. Nowadays, our healthcare services in many cases are costlier than ever before, while most of the patients are required to stay in the hospital for the entire duration of the treatment process. Using devices with a capability to remotely monitor patients can somehow overcome these challenges. IoT technologies, by collecting the patient's real-time health data and transferring it to caregivers, will not only reduce the cost of healthcare services, but also enable the treatment of health problems before they become critical [22]. In this domain, different papers have investigated various aspects of IoT application, architecture, and related technology in healthcare. To the best of our knowledge, there is no systematic review of the literature addressing IoT architecture in healthcare. The aim of this systematic review is to present a complete survey that determines IoT architecture in the healthcare sector. Hence, the research questions addressed are as follows:

1. RQ1: What is the main application area of IoT in healthcare based on architectures?
2. RQ2: What are the essential components of IoT architecture in healthcare?
3. RQ3: What are the most important technologies used in IoT architecture?
4. RQ4: What are the main characteristics of cloud-based architecture?
5. RQ5: What are the main security and interoperability issues in IoT architectures in healthcare?
6. RQ6: What are the main effects and challenges of IoT in healthcare?

The remainder of this paper is divided into the following sections: theoretical background of IoT architecture is presented in Sect. 2. The research methodology that is applied in this article is explained in Sect. 3. Section 4 presents the significant search results. A discussion of the gaps, implications for future research and limitations is presented in Sect. 5, while Sect. 6 concludes the paper.

2 Theoretical background

2.1 Application area of IoT in healthcare

In the coming years, IoT technology will be applied in the healthcare setting, at a great extend [23]. Healthcare sector always seeks new approaches for the services delivery, reducing the costs and improving the healthcare quality; therefore, reliance of this sector on IoT technology will be increased [24]. The use of these technologies empowers patients to follow self-care principles which lead to cost-effectiveness of healthcare services increased patient satisfaction and better self-management. Furthermore, IoT-based systems can be used for remote monitoring of physiological status in patients that need continuous attention [25–27]. Recently, smart healthcare system development has been possible by the convergence of various IoT architectures [28]. To get a complete picture of a patient's health status, IoT-driven solutions may be beneficial to create a comprehensive system with the interconnection of heterogeneous objects. The present section prescribes the main application areas of IoT in healthcare.

2.1.1 Home healthcare

According to the World Health Organization (WHO) report on aging and disabilities, the life expectancy of people has been improved and it is expected that most of the people globally will live beyond the age of 60 [29]. Aging people are more susceptible to chronic diseases, disabilities and higher hospitalization [30]. According to the researchers, in the near future, healthcare services delivery will be transformed into hospital–home balance in 2020, to the homecare services in 2030 [31–33]. Technological revolution embraces all aspects of a patient's life such as vital sign monitoring, emergency situation management, rehabilitation strategies in stroke, and medication management and telemedicine [34–36].

Home healthcare services based on IoT are among the promising solutions to overcome the difficulties associated with population aging [37]. In the coming years, the aging of the population, as a social phenomenon, and the revolution of IoT are two megatrends that will reform people's life extensively [38]. Home monitoring is among the outstanding applications of Wireless Sensor Networks (WSN), where heterogeneous sensors are used to identify people's activity [39]. In addition, technological advancements and smart objects such as video-based technology, near-field communication (NFC), and RFID by connecting different objects lead to effective communication among patients, objects, and objects themselves and also facilitate tele-monitoring processes in home healthcare [40–43].

For home healthcare monitoring, a number of different architectures have already been proposed. In this context, several efforts are aimed to monitoring patient condition. Integrating various IoT components into home care and medical systems becomes increasingly popular, mainly for events such as fall detection [44] and seizure detection [45]. In this way, caregivers can provide better treatment and take immediate action to prevent a dangerous situation during a seizure. Zgheib et al. [46] proposed a system for detecting the risk of bedsores using sensors. In addition, some potential applications of IoT technology in medical environment such as nursing homes in stroke rehabilitation, Parkinson's gait disturbance, cardiac, and neurologic monitoring are demonstrated by [47]. Detection and analysis of sleep patterns are another research area for IoT that deals with the assessment of sleep quality in different ages and the evaluation of the medications effect on sleeping patterns, as investigated by [48, 49].

2.1.2 Mobile health and electronic health

The development of communication devices such as smartphones and their integration with various types of sensors highlight the increasing usage of IoT technologies. Physiological signals of the human body are collected by means of different wearable sensors by the software application. These signals are then securely transferred to healthcare institutions. Depending on the situation, signals in the form of short messages can notify healthcare professionals about medical emergency institutions and assist them in taking the suitable actions [27, 50].

For the next generation of m-health solutions, the emergence of IoT provides a personalized approach in healthcare delivery. In the other words, this technology promises to define not only new solutions for patient and physician communications, but also create better tailored therapeutic strategies to the patients [51]. Moreover, instant access to health data offers more opportunities to increase the quality of healthcare, improves patient satisfaction, and supports timely intervention [52]. In addition, the explosion of e-health and self-management of health conditions will radically alter the manner of healthcare delivery and collection of related information [53]. In the e-health area, medical devices are connected to the internet to perform various telehealth services such as tele-monitoring, supervision of old people, tele-consultations, and robotically-assisted surgery [54–56].

Acceptability and usability of m-health tools for breast cancer and some long-term conditions such as obesity and diabetes were identified in [57]. Some researches concentrate on supporting self-management of diabetic patients such as blood glucose patterns and insulin calculation [58]. Mobile phone applications can contain various educational materials, which in turn allow patients to track their caloric intake for recording physical activity, and to connect with others who can provide essential information and support. Totally, these factors lead to changes in lifestyle and provide positive health outcomes. The concept of Internet of m-health Things (m-IoT) has been introduced recently as a developing field in some researches. Sung et al. [59] developed a simple physiological signal detection system for blood pressure, oxygen intake, and body temperature, that was combined in the cloud [59]. In another study conducted by [60], an IoT application for ophthalmology was proposed. In this model, the eyeglasses transmit the signals of the eye blood flow sensor and lens color to show the bleeding in the eyes.

2.1.3 Hospital management

In hospital management, responsibilities such as prevention of hospital infections, determining a complete plan for educating patients, management of emergency situations, and logistics systems, have been defined [61, 62]. IoT-based technologies such as sensors, ZigBee, RFID, and NFC can offer valuable solutions to overcome barriers in hospital logistic management. This revolution can enhance the supply chain management in hospitals by intelligently connecting people, processes, and data to each other. For instance, IoT innovations can provide technical development and support to the vaccine distribution system, and will affect how vaccine supply chain leaders' access the information needed to improve their services [63]. Moreover, in hospital management, careful planning for post-discharge care is essential. Meaningful planning and setting a reasonable decision-making framework are crucial elements to the overall flow of patients from admission to health institutions until discharge. To overcome this challenge, IoT technologies provide suitable solutions for patient tele-monitoring, continuously and effectively [64, 65]. For IoT application in hospital management, Esteban-Cartelle et al. [66] proposed a system for correct identification of patients and their corresponding medication based on RFID. This model assists in reducing medication and human error significantly. In addition, IoT technology is applicable for post-discharge planning. Bragg et al. [67] demonstrated a feasibility study for remote monitoring of patients discharged after colorectal surgery. This type of technologies may be helpful in early diagnosis and management of post-discharge complications and provides suitable interventions. In the following section, we will provide a short description of IoT technologies and their important features.

2.2 IoT technologies

Smart devices are playing an important role in forming the overall IoT vision. In fact, because of features such as low price, diminishing size and reducing energy consumption rates, steady advances of IoT in healthcare in coming years will be ensured. Because of these characteristics, this technological innovation has the potential to completely transform healthcare activities [68]. These technologies are briefly introduced in the following sub-sections.

2.2.1 RFID and NFC

Perception and identification technology is the foundation that supports the long-term growth of IoT. It is responsible for the acquisition of the environmental events and data, the realization of awareness, and recognition of the external world of information and solving the problem of accessing information [69]. Identification by assigning a Unique Identifier (UID) to a corresponding entity makes it retrievable and recognisable without ambiguity. In the healthcare environment, every resource such as a hospital, emergency center, rehabilitation clinic as well as caregivers are associated with a digital UID [70].

Radio-Frequency Identification is a communication technology aiming to address short-range communication. RFID consists of a tag and a reader that communicate with each other for receiving and transmitting the signals. In IoT applications, most of the data that have been used in RFID tags are electronic product code (EPC). EPC is used to uniquely identify objects. By means of these tags, we can ensure that each object has an exclusive identity in the IoT environment [71]. Nowadays, RFID technology with prominent distinguishing features like cheap and reliable tags, and tracking capabilities makes it a suitable solution for IoT [72]. Furthermore, NFC technology is another short-range communication protocol that creates simple and safe authentication mechanisms among different objects. This technology supports devices in three modes of operation including reader or writer, peer-to-peer, and card emulation modes. In reader and writer mode, the system operates as a contactless reader or writer to get information or trigger an action. In peer-to-peer mode, the system operates as a two-way communication channel. Finally, in card emulation mode, NFC enables devices to act like smart cards [73].

2.2.2 LR-WPAN

Wireless personal area network (WPAN) is one of the main components in short-range IoT applications. One of the subtypes of this technology is Low-Rate WPANs (LR-WPANs). LR-WPAN provides low-cost communication networks, consumes minimal power, and enables a reliable data transfer protocol [74, 75]. In general, two types of devices can be used in LR-WPAN network including full-function device (FFD) and reduced function device (RFD). FFD type is capable of serving in three modes including personal area network (PAN) coordinator, a coordinator, or a device. Furthermore, RFD can be used in applications that do not need to exchange large amounts of data [76].

2.2.3 Bluetooth

Bluetooth is a type of wireless communication network developed for short distances. This technology enables the creation of a network between two or more devices and implements protection methods that are based on authentication and encryption [77]. It uses 79 radio-frequency channels with a bandwidth of 1 MHz on the 2.4 GHz band. According to the Bluetooth device class, this technology is able to provide connectivity up to 100 m at a speed of up to 3 Mbps. Today, as IoT applications are mainly used in telemonitoring, all devices that are organized in this scenario are based on low-power solutions such as Bluetooth [78, 79].

2.2.4 ZigBee

Zigbee is a wireless technology developed to provide a foundation for IoT, by enabling objects to work together. The structure of this protocol is comprised of end-nodes, routers, and a coordinator and processing center. The processing center is responsible for data aggregation and data analyzing [80]. ZigBee is often one of the preferred technologies in IoT implementation because of its considerable features, such as security and network resilience, interoperability, and low power consumption [81]. This technology is based on a mesh network; this model enables the system to continue operation when an object is a fault, while the other objects continue to communicate with each other without interruption [82].

2.2.5 Wireless fidelity (Wi-Fi)

Wireless technologies are the main components of IoT. Wi-Fi is used in various fields such as home automation, wearable sensor devices, mobile devices, and smart grids [83]. Based on Wi-Fi, if a Wireless Local Area Network (WLAN) product meets IEEE 802.11 standards, it is considered as of Wi-Fi category [84]. Wi-Fi-based LANs are available in most hospitals.

2.2.6 Worldwide interoperability for microwave access (WiMAX)

Worldwide interoperability for microwave access is one component of 802.16 series standards for wireless metropolitan area networks (WMAN) [85]. One of the key features of the initial WiMAX standard IEEE 802.16a is that it can be executed in licensed and unlicensed frequency bands and has a frequency band spectrum range from 2 to 11 GHz. In IEEE 802.16a, WiMAX standard transceiver antennas of the source and destination devices do not require a direct line of sight between each other, as the devices operate in low-frequency ranges [86]. WiMAX forum introduced the IEEE 802.16b standard for providing good quality to real-time voice and data services customers. It has an operating frequency band range of 5–6 GHz. Besides, WiMAX IEEE 802.16c allows interoperability between different vendor devices and gadgets and has an operating frequency band range of 10–66 GHz [87].

2.2.7 Mobile communications

Mobile communication networks have undergone significant changes. The first generation was based on an analog system applied for real-time transmission of voice over the network. The second generation (2G) networks provide a digital network infrastructure that supports text messaging. In addition, online information exchange demands highlighted the need for development of the third generation systems (3G) [88]. 3G technology is able to create a global infrastructure which supports different services effectively. This infrastructure should be optimized in a way that can support technologies revolution during times. This requirement would be possible if data access equipment, transport infrastructures, and user application be separated from each other [89].

To overcome some limitations of 3G and enhance the quality of services and bandwidth as well as decrease the cost of resources, the 4th generation (4G) concept has been proposed. This wireless mobile network has the same quality of services as the fixed internet. In addition, the 5th generation (5G) internet networks can bring a perfect wireless communication without limitation. On the other hand, 5G networks, compared to the 4G, offer high system capacity and improved energy efficiency. In addition, the 6th generation (6G) network was proposed to unify satellites, to offer better coverage in a wider area [85, 90].

2.2.8 Wireless sensor networks (WSN)

Wireless sensor networks consists of heterogeneous sensors to monitoring physical worlds conditions. This model uses three key components (nodes, routers, and a gateway) to gather information from the environment [91]. WSN systems can be divided into two types, i.e., wearable and implantable. These types of sensors are tools frequently used in healthcare to monitor patient condition in home healthcare and home automation [92]. WSNs because of several benefits such as broad coverage, low installation cost, and real-time data gathering, have been applied in different fields such as emergency situations management, military operations, tracking the movement of animals, and healthcare monitoring systems [93–95].

Some capabilities of WSN for healthcare monitoring include the monitoring of human physiological data, drug, and device monitoring in hospitals and emergency situation management [96, 97]. Sensing technologies are essential tools for acquisition of physiological parameters from the patient [40, 98]. The main focus of sensors used in healthcare facilities is on point-of-care parameters measurements such as medical screening and diagnostic applications. Novel sensors equipped with wireless connectivity by biomedical signal acquisition, generate new opportunities for continuous monitoring of patient condition [59, 96, 99]. Nowadays, there is a growing interest to use sensors that perform food allergy detection, pregnancy monitoring and cholesterol level monitoring, as well as Deoxyribonucleic Acid (DNA)-based electrochemical analysis. Furthermore, results obtained from such sensors can be exploited for suitable decision-making about patients' situations [98, 100, 101]. Usually, sensors that can be used in healthcare monitoring include inertial sensors (e.g., accelerometers, gyroscope, and pressure sensor), biosensors [e.g., Electrocardiography (ECG) monitoring, temperature and heart rate sensor], and wearable sensors (like fitness band and mobile phone) [99].

Table 1 presents some of the IoT-related technologies according to key parameters such as communication standard, frequency band, max signal rate, channel bandwidth, battery life (days), transmission rate, and cost [102–104].

Table 1 Comparison of IoT communication technologies

Parameters	Wi-Fi	WiMAX	LR-WPAN	Mobile communication	Bluetooth	RFID	ZIGBEE	WSN
Standard	IEEE 802.11 a/c/b/d/g/n	IEEE 802.16	IEEE 802.15.4	2G-GSM, CDMA 3G-UMTS CDMA2000 4G-LTE	IEEE 802.15.1	ISO/IEC 15,693	802.15.4	IEEE 802.15.4
Frequency band	5–60 GHz	2–66 GHz	868/915 MHz 2.4 GHz	865 MHz, 2.4 GHz	2.4 GHz	860–960 MHz and 2.4 GHz	868/915 MHz 2.4 GHz	902–928 MHz
Data rate	1 Mb/s–6.75 Gb/s	1 Mb/s–1 Gb/s (fixed) 50–100 Mb/s (mobile)	40–250 Kb/s	2G: 50–100 kb/s 3G: 200 kb/s 4G: 0.1–1 Gb/s	1–24 Mb/s	106 k–424 kbps	20 k–250 kbps	20–250 Kb/s
Transmission range	20–100 m	< 50 Km	10–20 m	Entire cellular area	8–10 m	Up to 100 m (325 feet)	10–75 m	20–100 m
Energy consumption	High	Medium	Low	Medium	Bluetooth: Medium BLE: Very Low	Medium	Medium	High
Cost	High	High	Low	Medium	Low	Low	Medium	High

2.3 IoT protocols

2.3.1 Constrained application protocol (CoAP)

Sensor networks have a prominent function in IoT architecture by interacting with the web or via the cloud [52]. In this perspective, because most of the IoT devices have small storage and low computing capability, the Hypertext Transfer Protocol (HTTP), due to its complexity, cannot be used in IoT. The COAP standard, proposed by the Internet Engineer Task Force (IETF), has some outstanding features that can change HTTP properties to increase requirements of IoT. Some of the key features of this protocol are group communication, resource observation, direct interaction with HTTP and assessment of security requirement [105–107].

2.3.2 Message queue telemetry transport (MQTT)

Message queue telemetry transport is a messaging transport protocol that its main task is to aggregate sensed data from the environment and transmit it to servers [108]. MQTT is able to easily connect the “things” to the web and supports unreliable networks with low bandwidth [106]. This protocol is interoperable and can be implemented in different platforms to connect objects to the internet [106, 107]. Low overhead and power consumption are the key features that make MQTT a suitable solution for the IoT implementation [109, 110].

2.3.3 Extensible messaging and presence protocol (XMPP)

Extensible messaging and presence protocol is based on XML protocols; this protocol is mainly famous for key features such as open source and the public security mechanism and is completely free [106]. This messaging protocol permits end users to communicate with each other easily regardless of the type of operating system [107]. In XMPP, the three main elements are client, server, and gateway. Client by means of transmission control protocol/internet protocol (TCP/IP) protocol is connected to the server and transmitted context based on XML protocol. The server has the responsibility of message routing. The gateway manages the stable communication between heterogeneous systems. XMPP by supporting objects communication with each other can be used in IoT architecture effectively [110].

2.3.4 Low-power wireless personal area networks (LoWPAN)

Compared to other types of protocols, LoWPAN has numerous outstanding benefits such as smaller sized packets, low power consumption, and bandwidth that make it one of the ideal solutions for IoT implementation. In addition, the 6LoWPAN protocol was designed by combining the latest version of the internet protocol (IPv6) and LoWPAN [111]. This protocol is well organized to compress IPv6 network headers in IEEE802.15.4 small packets to reduce the error rate and facilitate data sharing. 6LoWPAN by having prominent features such as low cost and low power consumption is suitable for IoT implementation [106].

2.3.5 Z-Wave

Z-Wave is a protocol characterized by the use of minimum power to carry out the desired communication in a wireless network and has been broadly applied in remote monitoring in various domains [107]. Z-wave mainly supports short-range wireless communication and provides reliable data transmission. It is recommended for networks with low bandwidth [106]. Furthermore, this technology promises to revolutionize machine-to-machine communication in IoT applications in healthcare such as wearable device monitoring [109].

2.4 IoT communication models

Internet of Things is generally about connecting different objects to the internet. These objects can be deployed in different ways. Moreover, it is essential to determine how these devices communicate with each other. To network smart objects, the internet architecture board (IAB) published a set of guidelines based on which four communication models can be deployed by IoT including Device-to-Device, Device-to-Cloud, Device-to-Gateway, and Back-End Data-Sharing model, as is shown in Fig. 1 [112].

2.4.1 Device-to-device communication model

This form represents several connected parties that communicate with each other. These communications are mainly based on IP networks. To create a stable communication in this model, various protocols such as ZigBee, Z-Wave, and Bluetooth might be applied. In this model, devices, by adhering to a specific protocol, can exchange messages to get the proper functions [112].

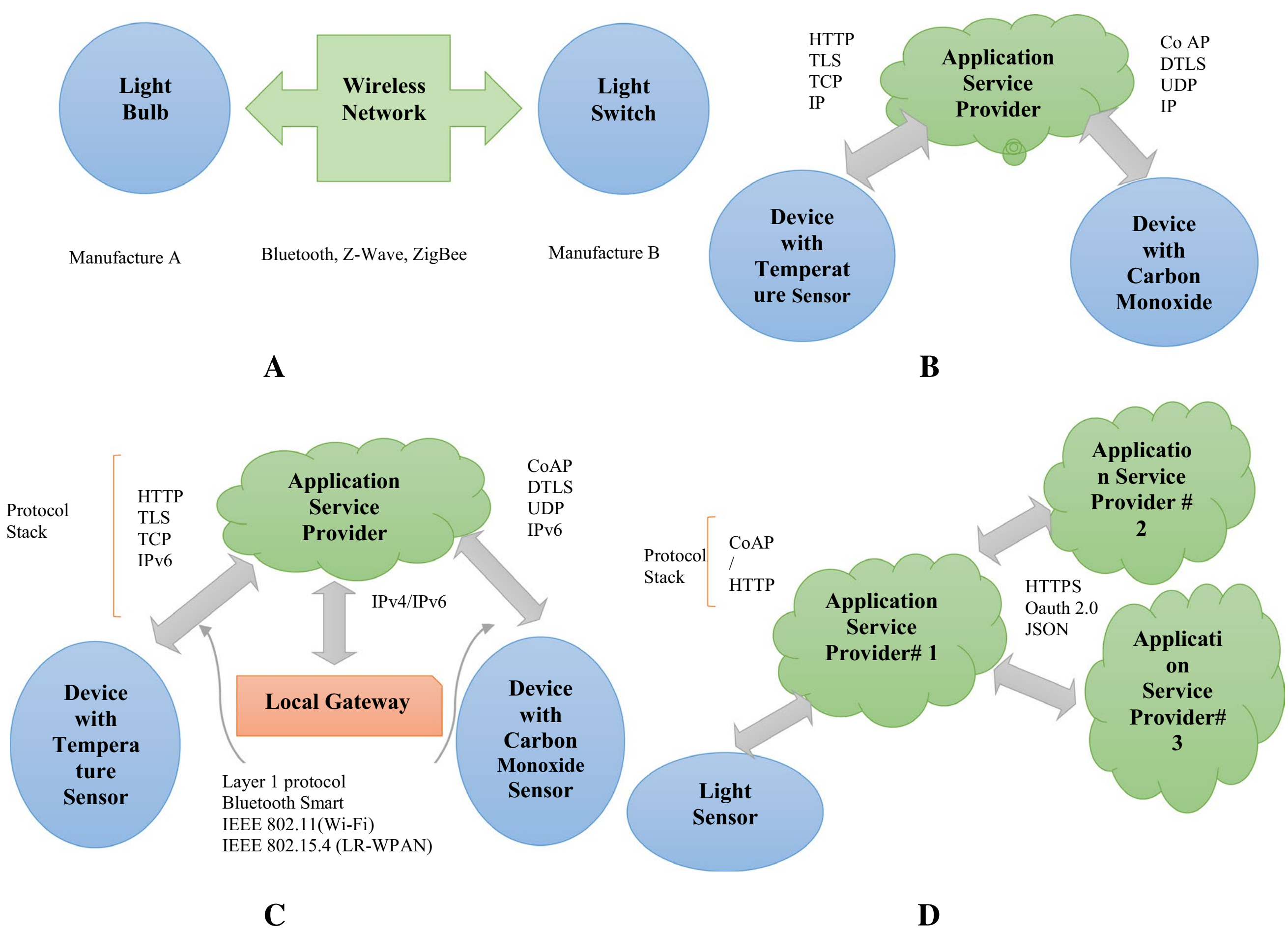

Fig. 1 Internet of Thing Communications Models (**a** Device-to-Device Communications Model, **b** Device-to-Cloud Communications model, **c** Device-to-Gateway Model, **d** Back-End Data-Sharing Model) [112]

2.4.2 Device-to-cloud communications

In this model, to exchange data, IoT-based devices are connected by the shortest route to the application service provider. Based on this approach, objects may establish a connection between devices and cloud services based on TCP/IP network or Wi-Fi connections [112].

2.4.3 Device-to-gateway model

In this model, an application software acts as a communication link among IoT objects and the cloud. In most cases, smartphone apps perform the function of the gateway to transmit data among the objects and cloud services. This approach is a suitable solution to address the interoperability issues occurring in the integration of new smart devices with legacy systems [112].

2.4.4 Back-end data-sharing model

Back-end data-sharing model is based on the idea that the sensed data from IoT devices can be accessed by authorized entities. Based on this framework, it is possible for users to aggregate, export, and analyze data from the heterogeneous environment and send it to another user securely for further actions. Back-end data-sharing model recommends an integrated cloud application which facilitates interoperability of smart devices in cloud environments [112].

3 Methods

Studies regarding IoT technologies and architectures have been carried out in various fields such as computer science, healthcare, and medical informatics. Therefore, published research papers have been scattered across various databases. We have nominated some popular electronic databases to create a complete bibliography of a research paper on IoT architectures in healthcare. The following eight digital databases were used: IEEE, Springer, Wiley, Science Direct, Emerald, Google Scholar, PubMed, and Scopus. We carried out a search of the literature published between 2000 and 2016 related to IoT architecture. Furthermore, studies were extracted from the databases using the following search terms: Architecture, Internet of Things, smart hospital, home healthcare, m-health, remote healthcare monitoring, and their effects. In the study selection process, we reviewed the papers through their abstract, introduction, and conclusion. To identify papers that would be more relevant to our research questions, inclusion and exclusion criteria were applied. Therefore, we defined inclusion criteria for selecting the most appropriate publications as follows:

1. Addressing technologies used in IoT in healthcare settings regardless of whether they were classified as the short or long distance.
2. Addressing IoT architectures in healthcare environments and their main components and structure.
3. Addressing the main effect and challenges of IoT application in healthcare.

We also considered exclusion criteria as follows:

1. Papers published in books, PhD or Masters' theses, meta-analysis, and other types of literature reviews.
2. Papers that were not related to healthcare domain and focused on IoT architectures for other purposes such as agriculture, aquaculture, road condition, traffic, smart city, urban management, home entertainment, smart sport, tourism and smart environment;
3. Abstracts or papers that were not available.

In the final stage, the necessary data were gathered from the papers. For each paper, the following data were retrieved: publication year, study type, main components of IoT architecture in healthcare, prominent technologies applied in architecture design, characteristic of cloud-based architecture, main application area of the proposed architecture, positive or negative effects of IoT technology in health and consideration of security and interoperability issues in IoT architecture.

4 Current state of the art of IoT in healthcare

In this study, a total of 2034 research papers were extracted according to the criteria mentioned in the previous section. Following the elimination of duplicate papers, 1010 potentially pertinent papers remained. Then, the titles and abstracts were evaluated and irrelevant papers were taken out; hence, 264 articles remained. Thereafter, the full text of the remaining papers was reviewed for eligibility. Eventually, we selected 60 papers regarding IoT architecture in healthcare. Figure 2 shows this study search flow.

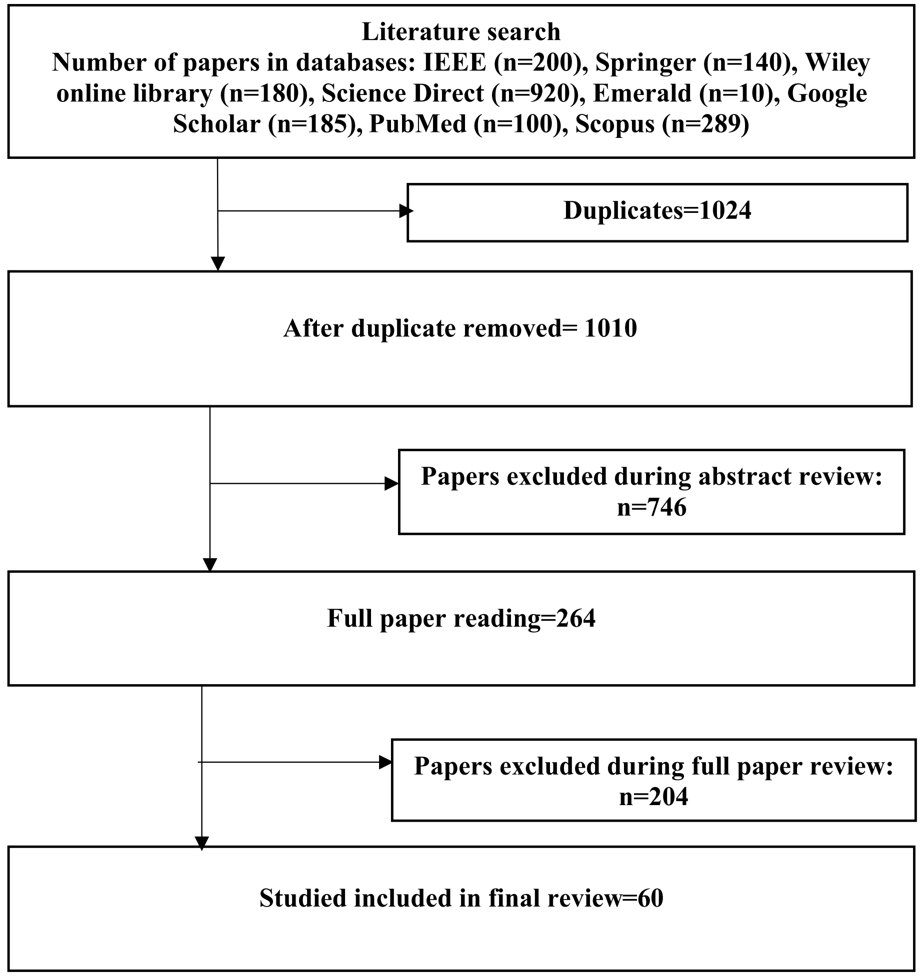

Fig. 2 Flow diagram regarding the systematic review, inclusion, and exclusion of studies in this review

4.1 Overview of selected studies based on research questions

4.1.1 RQ1: Application area of IoT architecture in healthcare

Studies regarding the specific domain of IoT architecture in healthcare, which were reviewed from the previous section, are summarized in the next sub-sections. The results of their analysis revealed that, generally, these articles can be classified into the categories briefly described in the following.

4.1.1.1 Home healthcare According to the analysis of research papers, most of the architectures were proposed for home healthcare monitoring. In this regard, Ambient-Assisted Living (AAL) technologies can create suitable solutions for disabled and elderly people suffering from different disabilities [113, 114]. AAL by means of a dynamic and interconnected environment has the potential to improve people's quality of life [115]. Based on Blackman et al. [116], three generations of AAL systems can be distinguished. The first generation includes wearable devices, usually alarms for emergency situations. The second generation is home sensors that provide automatic response to detection of hazards. Finally, the third generation is based on the integration of wearable devices and home sensors, applicable for monitoring of patient situation and prevention of health risks. In the following, some of these papers proposing IoT-based home healthcare monitoring are summarized.

Woznowski et al. [40] presented an AAL architecture by means of sensor technologies. The proposed platform, namely, SPHERE, is composed of three main components including body-worn sensors, video sensors for recognition and processing of inhabitant activities, and an environment sensor for sensing the home setting based on hardware. Sensing data are aggregated and transferred to a gateway by means of secure data transmission protocols. In addition, this system provides a suitable graphical user interface for main users such as caregivers and patients' family members. According to the analysis of sensed data, appropriate messages were transmitted to the user periodically or in an event-driven manner. This platform also provides the opportunity to design a 3D simulation of the environment and patient-specific situation. Moreover, the authors claim that despite previous architectures in AAL that concentrate on a single medical condition, SPHERE offers a comprehensive model for patient conditions.

The system proposed by Mainetti et al. [117], is able to aggregate environmental or biomedical data, collected from the various sensors and transmit them to a remote server for alert generation. This architecture is based on a Web of Topics (WoX) approach. The system is able to send the appropriate messages both to a family member or caregiver(s), and sometimes, based on the situation, set up notifications to the smart home appliance. The WoX middleware is composed of two main components that include capturing application and reasoning server. These components assure the constant monitoring of the elderly patient and generate specific events, when particular dangerous situations occur to elderly people in their home environment.

Coelho et al. [118] describe a system architecture for continuous monitoring of patients with disabilities. This system is designed to track and process the behaviour of residents at multiple time scales and also to provide suitable reports and alerts to the caregivers; its components include a smart home engine for local sensor management that is based on building control system developed by the iTech tool and a cloud-based analytics engine based on the Google cloud MySQL database. In addition, Al-Adhab et al. [119] developed a framework based on three parts consisting of input, context analysis, and view. The system is designed for identifying patient activities by means of sensors and monitoring patient situation. Then, by collecting data and processing special algorithms such as fuzzy logic, sensed data are transmitted to the server for an alert generation.

Ray [120] presented a model, namely, Home Health Hub Internet of Things (H3IoT) for continuous monitoring of elderly patients. The system in the first layer senses various physiological activities by different biosensors such as electrocardiogram, electromyogram, pulse oximeter, and blood pressure sensor. The communication layer transfers the sensed data to the information processing layer to process the data obtained. The user application layer immediately receives the information related to the older user's health condition. The authors mentioned some advantages for this framework, such as mobility, low set up cost, user-friendliness, clear layered design, and delay tolerant [120]. Fan et al. [121] demonstrate a smart rehabilitation system based on IoT by means of semantic network ontology, with four main sub-classes, namely, resource, prescription, hospital, and patient. This ontological data structure applied in rehabilitation system enables accurate reasoning and provides well-structured domain knowledge on rehabilitation engineering, leading to easy knowledge sharing and reusing. It consists of three levels including interfaces for human–machine interactions, the platform for automated design methodology, and the management of design information and applications. By implementing the proposed framework, new patients could be quickly diagnosed, and corresponding rehabilitation solutions could be provided. Furthermore, the essential medical resources can be available immediately.

4.1.1.2 M-health and E-health Mohammed et al. [122] developed a platform based on a mobile application, namely, 'ECG Android App'. This application enables users to visualize ECG waves. It collects ECG bio-signals and by uploading this data to the cloud and creates a specific medical record for each patient. Furthermore, the collected data are analyzed to provide suitable feedback to users. The proposed framework applied IOIO-OTG micro-controller that uses analog-to-digital converter, which converts ECG signals to digital numbers. Then, binary files uploaded to a cloud environment can be employed in for pattern analysis and detection of dangerous health situations based on bio-signal data. The authors claimed that this framework has the potential to decrease waiting time in hospitals' emergency departments and reduce visit time. Besides that, this model minimizes the administrative and personnel cost.

Santos et al. [123] presented a mobile gateway based on IoT technology, namely, "AMBRO". In this framework, they applied different sensors for falls detection as well as heart rate control and a GPS module to detect the people location. A GPS module was used for determination of patient location. Continuous monitoring and recording of patient heart rate were determined by the heart rate monitoring module. The patient's heart rate and the activities level information are forwarded to AMBRO every 5 min by means of a mobile gateway service. Moreover, tri-axis accelerometers service is used for detection of user fall. The AMBRO mobile gateway framework allowed that heterogeneous devices to communicate with each other, simultaneously.

Hussain et al. [124] developed a platform for urgent care for older adults and people with disabilities. This mobile application has the potential for real-time monitoring of health status, detecting physiological sign abnormalities and determining patient location. Based on the proposed model, the smart phone is a core device that acts as a gateway. This gateway not only transmits instructions between the source and destination nodes, but also provides a user interface among patients and their environment. In addition, Istepanian et al. [125] introduce m-IoT as a new healthcare paradigm that connects 6LoWPAN with the 4G network to provide services such as continuous measurement of glucose levels. This model is among the patient self-monitoring approaches that help hypoglycemia management in a diabetic patient. In this framework, non-invasive biomedical sensors through integration with IPv6 protocol transfer diabetic patients' data to a healthcare provider. This system has the potential to provide timely intervention for blood glucose monitoring in the diabetic patient.

Jara et al. [126], to reduce drugs side effects and increase medication adherence, introduced a drug identification and interaction checker based on IoT solutions. This model supports several IoT-based technologies such as barcode, NFC, and RFID incorporated into patients' personal devices, such as smartphones, etc. This framework comprises a drug database that consists of general drug information, list of adverse effects, and active and inactive ingredients. Moreover, the patient profile contains the medical history and list of medication allergies based on a predefined ontology. The data obtained are mapped to one or more ontologies, and a rule alerting engine that detect potential interactions between prescribed drugs, thereby suggesting appropriate solutions to patients.

IoT architecture can be implemented for people with disabilities. Some of the studies reviewed proposed models for disabilities such as deafness [127], blindness, and cerebral palsy [128]. Kumari et al. [129] presented a visitor alert system for hearing impaired people. This model consists of two main modules, i.e., a transmitter and a receiver. Based on this model, when a visitor presses the doorbell, the embedded camera captures the picture and transfers it to the wearable device. The image of the visitor along with a message is displayed on the home owner's phone. Eventually, details of this process are stored on the server for later retrieval.

4.1.1.3 Hospital management Catarinucci et al. [130] proposed a framework for automated detection and tracking of the occupants and devices in hospital environments. This system was also suitable for tele-monitoring of patients' conditions in an emergency situation. The model mainly relies on different IoT technologies such as RFID, WSN, and smartphones. These components cooperate together based on network infrastructures such as CoAP, 6LoWPAN, and REST protocol. Moreover, Bhatia et al. [131] presented a system based on IoT for tele-monitoring of Intensive Care Unit (ICU) patients. The proposed model addresses different issues related to the patient's environment in an ICU unit. The performance of an implementation of this system was evaluated in 3 ICUs. The obtained results revealed that the suggested system has better performance compared to other methods of monitoring.

Vargheese et al. [65] propose a cloud-based architecture for patients in 30-day re-admission to hospital. IoT technologies by obtaining vital information from the patient, help pro-actively to identify trends that could result in complications and re-admissions. They argue that as provider engagement in the first 7 days after discharging has a significant correlation with chances of patient re-admission, it is possible to take the data from sensors securely and transfer it to the cloud to generate suitable recommendations in a timely manner. Cloud-based e-health is a critical availability element ensuring the integrity of vital information to enable pro-active care to avoid 30-day re-admissions.

Gharote et al. [63] presented a model that demonstrates how IoT can be beneficiary in vaccine distribution planning in Public Health Centers (PHCs). A sensor can be attached to all the refrigerators and vehicles carrying vaccines. This sensor will connect to this device to monitor the temperature maintained in the refrigerator and alert the personnel. Using IoT, healthcare workers can check how much stock is left in the inventory of each public health center without any manual interference. If there is any sudden increase in demand for vaccine in some PHCs, then a large amount of that particular vaccine will be required. In such scenario, the system will first identify vehicles which are currently carrying the required vaccine. After that, recalculating and rescheduling the transportation can guide these vehicles from low priority PHCs to a high priority PHCs.

As mentioned in the work of Islam et al. [132], patient monitoring systems based on IoT can be categorized into two aspects, i.e., services and applications. The service is generic and has the potential to become the cornerstone of application in healthcare. In other words, service is used to create applications, while applications can be used by patients and healthcare providers. "Appendix A" (Table 5) lists academic papers based on specific domain of architecture, type of disease or condition, as well as their classification based on service or application.

4.1.2 RQ2: Essential components of IoT architecture in healthcare

The overall architecture of IoT-based healthcare systems consists of three layers including the identification layer, the gateway layer and the cloud layer [133]. The important function of the perception layer is the identification of devices and data collection. This layer is the lowest layer and has the most contact with entities such as patients, nurses, and devices. Medical devices such as heart rate monitors and tracking devices such as accelerometers are among the objects collecting related data in this layer. The essential role of the network layer is to transfer sensed data to the upper layer. The captured data are transmitted via different protocols to a gateway. The gateway layer is responsible for creating permanent connectivity and managing interruptions and transferring the collected data to the server for analysis. The cloud layer is the third layer of the IoT system. This layer can be obtained either via internet-connected remote servers or by local servers connected to local Hospital Information System (HIS) [25, 134–136]. Due to the fact that IoT should be able to connect heterogeneous things with each other, it is essential to develop a flexible and configurable architecture [133, 137]. Nevertheless, with respect to various architectures proposed in different research works, there is no consensus on a standard model [138]. Our investigation revealed that depending on the type of setting and infrastructure, a different type of architecture with several layers may be applied. Classification of articles based on the number of layers as well as IoT communications model is presented in "Appendix B" (Table 6).

4.1.3 RQ3: What are the most important technologies that are used in IoT architecture?

IoT technologies should provide continuous and safe internet connectivity. Communication technologies are the foundation of IoT systems and provide seamless connectivity to the internet allowing devices to exchange data over the network [139]. For short-range communication, RFID, Bluetooth, ZigBee, or Wi-Fi may be a reasonable solution. In addition, for long-range communication such as industrial automation, ZigBee [140], WiMAX, or Cellular technology for instance mobile phone could be the optimal choice [139, 141]. In addition, the most common obstacles in long-range communication technologies are high initial investment costs, a limited number of connections, and high prices for end users. On the other hand, short communication hardware devices have an advantage, since they are cheaper, smaller, and easier to set up [142]. E-health devices that have been utilized in IoT systems mainly have constraints in terms of processing and storage of healthcare data. In the e-health domain, low-range communication technologies such as RFID, Bluetooth, and ZigBee are more prevalent than long-range technologies such as cellular communication systems. As a result, there is a need to use the gateway service that translates messages among short-range and long-range communication technologies [143]. Therefore, IoT technologies such as sensors and smartphones have a unique identifier which enables them to interact with each other and also with the environment by means of direct communication or by an additional element such as gateway [144].

Previously, data gathering and analyzing in sensor-based applications were locally managed by software agents. Recently, sensors are monitored remotely through the web. For remote monitoring of these resources, the HTTP protocol is applied; however, this is not an appropriate solution because of its different headers which involve more central processing unit (CPU) power than sensors. As a result, to overcome these challenges, other standards have been proposed [144–146]. Nowadays, other protocols such as 6LowPAN, Representational State Transfer (RESTful), web services descriptive language (WSDL), and Simple Object Access Protocol (SOAP) have been proposed to create HTTP transactions to update and read the sensor data [147, 148]. The mentioned protocols determine the formats used for the exchange of different data, the process of data encoding, and assignment of IP headers for addressing devices in the network. The other functions of these standards include packets routing from their source toward their destination, data control, and managing the rate of data transmission between two nodes and resending of packets which have been lost [6, 107]. Table 2 classifies the papers reviewed based on different communication technologies and IoT protocols.

According to Table 2, the most important technologies in IoT architectures in healthcare were short-range communication technologies such as Wi-Fi (75%), Bluetooth (58.3%), RFID (37.5), and ZigBee (25%). In addition, 6LoWPAN was the main protocol used in the papers (33.33%). This protocol enables the connection of sensor networks with the internet and has been designed to ensure the interoperability of sensor networks and the internet [105].

4.1.4 RQ4: What are the main characteristics of cloud-based architectures?

Cloud computing is a technology which can be set as a base element for the use of IoT in healthcare [162]. This form of internet-based computing facilitates the execution of millions of commands per second and removes the technical complexities of hardware and software installation, maintenance, and scalability [163]. A cloud of things that integrates cloud computing with IoT technologies provides new capabilities such as storage, analyzing, networking, and real-time processing [164]. A cloud of things enables the use of networking standard for linking data storage facilities, providing service over the internet and executing web applications over the internet and managing computational capability [162, 164].

For health data analysis in a cloud of things environment, different types of machine learning techniques may be applied. Such algorithms can be divided into categories such as classification, cluster analysis, association rule mining, time-series analysis, and anomaly detection. The aim of classification algorithms is to group data into predefined categories. Cluster analysis determines the logical arrangement of a set of patterns, points, or objects. Association analysis aims to discover hidden patterns in data sets. Time-series analysis characterizes the properties of data over time. Outlier analysis reveals objects that are inconsistent or considerably deviating from other objects [165, 166]. Moreover, data visualization techniques provide an initial perception of data and determine patterns in given data set. Hence, the use of these methods leads to suitable recommendations and set the best policies for planning and analyzing cost efficiency for improving the quality of life for patients [167].

Based on the analysis of our data set papers, most of the cloud-based IoT solutions in healthcare include facilities such as real-time data capture and processing, data visualization, and data analytics (in Table 3 "Yes" indicates

Table 2 Comparison of existing communication technologies

No.	Authors	Wi-Fi	Mobile communication	Bluetooth	RFID	ZigBee	GPRS	IoT protocol
1	Sinharay et al. [149]			*				–
2	Rohokale et al. [150]				*			–
3	Lin Yang et al. [151]	*	*	*		*		COAP
4	Woznowski et al. [40]	*		*		*		MQTT
5	Santos et al. [123]	*		*				COAP
6	Mainetti et al. [117]	*		*				–
7	Jara et al. [152]	*		*				6 Low PAN
8	Khoi et al. [153]	*		*				MQTT, CoAP
9	Jara et al. [126]			* & NFC[a]	*			6 Low PAN
10	Sung et al. [59]	*	*	*				–
11	Leandro [154]	*	*					–
12	Hussain et al. [124]	*		*		*		6 Low PAN
13	Pang et al. [155]	*			*		*	–
14	Gelogo et al. [156]	*			*	*		6 Low PAN
15	Fan et al. [121]	*		*		*	*	–
16	Spanò et al. [157]	*		*	*			–
17	Lee et al. [158]	*				*		6LoWPAN
18	Mohammed et al. [122]	*		*				COAP
19	Rahmani et al. [159]	*		*				6LoWPAN
20	Bhatia et al. [131]				*			–
21	Zhang et al. [160]				*		*	–
22	Jara et al. [161]				* & NFC[b]			6LoWPAN
23	Adame et al. [43]	*			*			–
24	Istepanian et al. [125]	*	*					6LoWPAN

[a]In this table indicates that combination of Bluetooth and NFC were applied in the model

[b]In this table indicates that combination of RFID and NFC were applied in the model

the presence of characteristics in the models). Nowadays, healthcare systems are aiming to reduce costs and enable tele-monitoring of patients through the delivery of home healthcare services [23, 168]. Forming this environment requires real-time data capture and processing that leads to early detection of abnormal situations and proposes personalized treatments based on the patient situation [169]. Through utilizing a cloud of things, we have the opportunity to expand the use of the available technology provided in cloud environments. Applications that use IoT technology with this integration can be used through cloud storage [162, 170]. Through the cloud of things, cloud computing can fill some gaps of IoT such as limited storage and applications over the internet. In addition, IoT can fill some gaps in cloud computing such limited scope [164]. In other words, the cloud and IoT are mutually interdependent. To overcome constraints such as storage and processing limits, IoT can benefit from the cloud. Moreover, the cloud can exploit the IoT capabilities to delivering diverse services in a distributed environment [171].

4.1.5 RQ5: What are the main security and interoperability issues in IoT architectures in healthcare?

4.1.5.1 Security In remote healthcare delivery in IoT environments, considering security vulnerability not only for medical data sharing, patient privacy, and confidentiality but also for IoT setting is essential [132, 178]. Ida et al. describe IoT setting vulnerability in three main categories including hardware vulnerability (the smart devices should be secured from any physical attacks), network vulnerability (since this type emphasizes mainly data integration and data authentication), and application vulnerability (any damage to service delivered to users and unauthorized access to data) [171]. Therefore, in this section, the health security threats in the IoT settings are summarized based on the reviewed literature.

Based on the systematic analysis of literature, to overcome the security vulnerability issues, some requirements should be satisfied for IoT-based architectures in

Table 3 Main characteristics of cloud-based architecture

No.	Authors	Real-time data capture and processing	Data visualization	Cloud service type	Data analytics
1	Yang et al. [151]	Yes	Yes	–	Yes
2	Ivascu et al. [172]	Yes	Yes	–	Yes
3	Woznowski et al. [173]	Yes	Yes		Yes
4	Gupta et al. [174]	Yes	–	Hybrid [a]	Yes
5	Sinharay et al. [149]	Yes	–	–	Yes
6	Khoi et al. [153]	Yes	Yes	–	Yes
7	Sung et al. [59]	Yes	Yes		Yes
8	Mano et al. [154]	Yes	Yes	–	Yes
9	Hussain et al. [124]	Yes	Yes	Yes	Yes (Fuzzy logic)[b]
10	Al-Adhab et al. [119]	Yes	–	–	Yes (Fuzzy logic)[b]
11	Spanò et al. [157]	Yes	Yes	Yes	–
12	Lee et al. [158]	Yes	–	Yes	Yes
13	Mohammed et al. [122]	Yes	Yes	Private[a]	–
14	Rahmani et al. [159]	Yes	Yes	Yes	Yes
15	Istepanian et al. [125]	Yes	–	–	Yes
16	Bhatia et al. [131]	Yes	Yes	Yes	Yes (Time series)[b]
17	Santos et al. [175]	Yes	–	Yes	–
18	Doukas et al. [176]	Yes	Yes	Yes	Yes
19	Santos [177]	Yes	–	Yes	Yes

[a]In this table indicates the type of cloud services that was implemented in the architectures

[b]In this table indicates the type of machine learning algorithm that was applied to data analytics

healthcare. In this regard, some examples have been provided as described in the following.

Gupta et al. [174] presented a cloud of things model for the analysis of user's activities in healthcare. For a cloud-based security mechanism, they emphasized privacy, integrity, trust, and authentication principles in access to health data. To analyze security aspects of this architecture, the authors propose RSA and AES algorithms, for the private and public cloud environment, respectively. This protocol guarantees confidentiality of data in the cloud. In this article, to compare these two methods, encryption and decryption time were calculated. The results indicate that the RSA algorithm was more secure and robust than the AES method.

Kraijak et al. [179] detailed some of the security and privacy issues. Front-end sensors and equipment and network security are among the main concerns. They emphasized that privacy issues should be addressed during the whole data communication process. Furthermore, in their study, Maksimović et al. [180] aimed to present some of the security and privacy issues in healthcare settings. They introduced some authentication methods needed to verify the user's identity, like password, fingerprint scanning, signature, voice pattern, smart card, and tokens. They also emphasized that adequate regulation and standards such as the ISO/IEC 27,000-series including information security protocols should be satisfied. Moreover, socio-ethical considerations such as patient rights, information disclosure policy and consumer advocacy have to be considered.

Moosavi et al. [181] explained a security scheme for medical sensors. They analyzed the key features of the presented model, i.e., security and energy-performance through hardware and software prototype and simulation. The proposed model, namely, SEA, acts as a gateway in the fog layer to carry out the authorization mechanisms. The authors claimed that in comparison with the present end-to-end security models, this approach diminishes the routing process, routing table, and packet preparation by 26%. In addition, reducing the time, it takes for a data packet to be received by the remote computer, is 16%. Moreover, Santos et al. [182] introduced digital signatures and symmetric and asymmetric algorithms certificates, as the most suitable solutions to overcome m-health security concerns.

Based on Lee et al. [178], threats in service-oriented IoT platforms are divided into device threats, infrastructure threats, and service threats. In this study, a service-oriented architecture for the remote management of health services in IoT has been proposed. Furthermore, as in an IoT system, new tele-health things and services will always be added, and this framework can support most of the security requirement in such environment. Moreover, this framework enables data confidentiality, security, and availability for authorized users such as patients and caregivers.

4.1.5.2 Interoperability Usually, interoperability of hardware, software, servers, storage, and other infrastructures is based on standards [183]. Although during recent years, several practical solutions have been recommended to use with IoT technology, there is no unique standard for interoperability of IoT systems [184, 185]. Lack of interoperability creates problems including the growth of heterogeneous IoT platforms, low service reuse, and end-user dissatisfaction [28, 38, 147, 186]. Moreover, as IoT technology is still in its infancy, with no technical coordination among components, it is clear that in the near future, considerable heterogeneity among systems will occur due to the development of various standards [184, 187, 188].

The IoT environment is faced with a high level of diversity. Device, networking, applications and data are among the main components in IoT that should be considered for interoperability [108]. At the device level, the various communication protocols in use include cellular communications, Wi-Fi, RFID, Bluetooth, and NFC [163]. In addition, at the network level, different networking protocols such as ZigBee, Z-Wave, Bluetooth, and Wi-Fi are among the most used solutions [109, 189]. Furthermore, at middleware, there are certain cloud-based infrastructures. Moreover, at the semantics level, by applying interoperability standards, heterogeneous data can be aggregated and analyzed with appropriate communication protocol [53, 109]. In an IoT environment, because of the development of innovative solutions, infrastructure technologies will also be more heterogeneous.

IoT-based systems are usually described in a bottom–up approach, where the sensors and network gateways are in the lower layers, and the services and applications are in higher layers [183, 184]. The IoT domain is like vertical silos of various IoT applications without horizontal interconnectivity between them [187, 190]. Currently, lack of interoperability is one of the leading factors that influences wide adoption and acceptability of IoT application [103, 191, 192]. Based on our results, not many projects have addressed issues such as interoperability and integration in the healthcare domain. None of the reviewed works discussed mechanisms for standardization of health data in the IoT environment.

Santos et al. [123] proposed an architecture that enables Personal Health Devices (PHDs) to communicate with the internet based on SOAP along with the IEEE 11,073 standards. They also demonstrated that this system is capable to integrate with legacy systems to exchange data. Moreover, González et al. [193] describe how embedding of self-powered wireless sensors into cloud computing enables such a system to become a sustainable part of the work environment. Emphasis in their study was on data and semantics level. This was due to the fact that using classification systems that produce controlled vocabularies, ontologies and application of semantic technologies in the medical domain, allow IT systems to work homogeneously [193].

4.1.6 RQ6: What are the effects and challenges of IoT application in healthcare?

The analysis of our data set papers reveals that some of the articles concentrated on the effects and challenges of the IoT in healthcare. As an example, Sushilan et al. [194] demonstrate that IoT-based healthcare technologies can be used for real-time patient monitoring from anywhere around the world and to identify dangerous behavioural anomalies in the patient. In addition, Alharbe [195] proposes a smart hospital management system that may be applied to locate and monitor patients. They declare that use of this type of systems could be beneficial in improving hospital workflow management and enhancing an overall performance of patient care. In addition, Alharbe et al. [42] in another study express that IoT is a prominent emerging technology which will make communication between different sectors easier and more effective. In addition, this new phenomenon is useful in exchanging information and smart identification and location of objects, monitoring and tracking them efficiently, reducing healthcare costs and decreasing hospital stays of elderly people, which are the positive effects of applying IoT in the health domain [196].

On the other hand, some of the articles concentrate on the main challenges of IoT in healthcare. For example, Ding et al. [197] state that patients may prevent full monitoring or might be sceptical of health information disclosure to unauthorized people in IoT environment. Furthermore, one of the main challenges in the m-health system is related to data security. Protecting the identity of persons that access e-health services, guarantees the privacy of the physical location of the patients, and protecting data aggregated by healthcare systems is another challenge that have to be addressed.

4.2 Critical points obtained from the analysis of the papers

Internet of Things is useful in most medical domains, such as tele-monitoring of elderly people with chronic conditions, emergency situations and supply management in healthcare. In this systematic review, we have identified 60 papers related to IoT architecture in healthcare, published between 2000 and 2016. In addition, this study was carried out to determine the main application areas of IoT in healthcare, essential components of IoT architecture in healthcare, the most important technologies used in IoT architecture, the main characteristics of cloud-based architectures, security and interoperability issues in architectures, and finally the effects and challenges of IoT in healthcare. The results that were obtained in this systematic review have some important implications as presented in the following.

In this survey, it is revealed that the number of articles related to IoT architecture in healthcare, experienced a substantial growth over the last 6 years. It is estimated that the number of papers in this field will be increasing steadily due to the importance of this paradigm in healthcare. In other words, in the near future, IoT will be one of the main hubs between various healthcare sectors, by connecting smart physical objects together and allowing the different applications to support smart decision-making processes in healthcare.

Regarding the first research question, it is observed that most of the architectures were related to home healthcare monitoring. The growing numbers of the aging population and increased life expectancy necessitated the transition from traditional hospital-based care to patient- and home-based healthcare services. Based on the literature, IoT-based solutions for home healthcare empower patients and allow a greater degree of health self-management [163, 180, 198]. Furthermore, this technology can offer older adults better management of their health condition, enable them to stay connected to healthcare communities, and offer access to the services they need via e-health solutions. In addition, this emerging technology may significantly and positively influence the quality of life of people with disability [199]. In this way, the best architecture and methods to connecting efficiently all participants in the care process should be investigated. In addition, determination of physiological and environmental factors is essential to provide the best medical care to patients. On the other hand, applying signal processing and pattern recognition mechanisms to analyze the data and extract suitable information about the situation of the patient at home, should be explored.

As already described, the majority of papers included in this review were related to home healthcare, as this method of healthcare delivery has beneficial effects for patients' and care givers' quality of life. This technology would be really useful in analyzing physical activity patterns, sleep analysis and accidental fall detection. However, in a situation that needs continuous monitoring of patient's condition such as in AAL, specific challenges should be addressed.

Monitoring of a patient's health status is a sophisticated process. As patients may use a combination of mobile health, nursing home services and AAL facilities, creating an integrated infrastructure that is capable to support all these processes with minimum errors, is necessary. Moreover, AAL systems should have a high level of reasoning to suggest the correct advice to users. Furthermore, in emergency care and monitoring of vital signals, delivery of reliable messages from the patient to the healthcare provider is crucial. Thus, AAL systems have to be able to correctly distinguish users' needs and preferences [200]. In this way, defining standards and protocols for reliable delivery of patient health information should be addressed. Another issue is related to heterogeneous systems with different data formats, required to interact with each other. On the other hand, since most of the ambient-assisted living technologies run on mobile devices use batteries, power management of home health monitoring services have to be taken into consideration [201].

Thus, it can be concluded that with the growing number of elderly people, the ability to remotely monitor healthcare conditions can lead to less crowded health institutions and provide beneficial care for patients. Moreover, healthcare providers, by delivering home health services can achieve different significant objectives. Some of these achievements include reducing admission rates, reducing costs in healthcare, improving chronic disease care and increasing population health level. In this way, governments should support industries related to IoT convergence and invest in the home healthcare area. Hence, the result of this study can provide public bodies with valuable insight. However, to make IoT a reality, further research needs to be conducted in the healthcare domain.

To answer the second research question, regarding the main components of IoT architectures, the results show that depending on the type of setting and infrastructure, a different type of architecture with several layers should be employed. Usually, the three-layer architecture is the main idea for IoT model; however, this may not be satisfactory for investigations related to IoT, because researchers usually need to concentrate on more detailed features. In addition, five-layer architecture adds more details to models [199]. A cloud-based architecture provides some facility such as flexibility and scalability. This type of architecture also offers capability such as storage, software, and suitable facilities to machine learning and visualization [135, 167].

Most of the architectures proposed in our data set papers were cloud-based. Despite the wide utilization of cloud-based architectures, some of the literature revealed that part of the applications and devices in IoT may not be capable to completely benefit from the cloud model. Their results emphasized that probable reasons in this regard include the limitation of storage capacity in smart devices, the lack of network resources, and latency to connect to a centralized server. To overcome these challenges, fog computing is the promising paradigm that can extend cloud resources to address the above-mentioned issues as described in some of our data set papers [202–205]. In fog computing, part of the data analytics task is accomplished by sensors and gateways [206, 207]. Fog does not replace cloud computing, though it can provide location details for further analysis, enhanced mobility and support for real-time processing as described by [206, 208, 209]. To achieve these, the concepts of cloud and fog computing can be integrated into a single platform to provide solutions such as diminishing latency rate, geographic location awareness, and improving data-sharing capabilities and accessing the needed resources [210, 211]. It is estimated that the integration of such approaches can be beneficial for healthcare [212], mainly by strengthening tele-healthcare infrastructures that aim to alleviate issues related to elderly people, as well as improve chronic disease and emergency management as were illustrated in some of the reviewed papers [202–205]. As in real-time health monitoring systems, a large amount of data is acquired from a multitude of bio and environmental sensors, the large data is transmitted to networks for remote monitoring by end users such as caregivers. Therefore, fog computing fits these systems marvellously. Finally, we can argue that there was no universal consensus on IoT architecture, and various models have been suggested in different researches.

The classification of papers based on IoT communications model shows that 23.33% of studies presented a device-to-gateway model. Based on its definition, this model frequently relies on smartphone app software to connect to the cloud. This means that with the growth of mobile health services, distinguishing traditional approaches for maintenance of health, and new well-being solutions still remain blurred. Although m-health-based solutions can mainly address issues such as patients' life style to enable them to self-care, realization of all these outcomes strongly depends on the collaboration of healthcare providers, patients and policy makers.

Another research question was related to the type of technologies that were used in the architectures. Based on our analysis, the most important technologies in IoT architecture in health were Wi-Fi, Bluetooth, RFID and ZigBee. On the other hand, 6LoWPAN was the main protocol that has been used in selected articles (33.33%). Based on the literature, the efficient models in IoT-based healthcare should support a combination of low-cost technologies such as RFID sensors, Wi-Fi, ZigBee or mobile-based communication [180]. In other words, affordability of IoT services in healthcare is an important aspect, where low-cost technologies should form part of the baseline services [213]. The application of advanced sensing devices and launching IPv6, allow real-time health monitoring. In this regard, the collected data in this process will be transferred by means of standard protocols and made available to a healthcare provider to control health status. In this way, smaller, cheaper, and better performing sensors and smart controllers can efficiently acquire data from the physical environment to help optimizing operations and increasing productivity.

In certain large-scale applications, massive deployment of IoT technology may not be possible because of cost limitations. As demonstrated by several studies, cost may be a prohibitive factor in IoT adoption [214–216]. A new technology will be attractive for the potential consumer if investment on this service reveals a reasonable result. Therefore, the architectures should be designed in a way that not only facilitates the cost reduction of intellectual properties in health, but also encourages governments and policy makers to create competition towards better management of affordable services. As the use of low-cost technology in healthcare can improve the level of IoT acceptance, more studies in healthcare are needed.

Furthermore, the other important factors that should be addressed to attract users to adopt such technologies are ease of use and establishment of suitable infrastructures [216, 217]. Some of the studies reviewed verified that customer attitudes have a direct impact on the intention to use (e.g., uncertainty of the quality of services and security and privacy concerns are among the main elements for patient resistance in use of IoT services) [214, 215, 217, 218]. On the other hand, some studies [219, 220] concentrate on critical factors in IoT acceptance. Among several factors, learnability and social integration have significant effects on IoT-based applications adoption. Learnability, as sub characteristic of usability, focuses on the level of difficulty that patients experienced in using the technology. In addition, social integration refers to the extent to which the technology is familiar to the patients. Therefore, user interaction is one of the important factors in IoT paradigm. Good suitability, ultimately leads to minimize error rate, reduce training time for users and improve acceptance rate.

Since the target group of future IoT applications will reflect a different range of users, the users' requirements and preferences should be taken into account [221]. Among all user groups, older adults and people with disabilities have different needs compared to other groups. Defining strategies to design systems based on user's preferences will encourage the future use of the systems [222]. In a Human–Computer Interaction (HCI) context, the universal access concept introduces a new perspective that attempts to consider the user's skills, abilities, preferences and requirements into the overall steps of computer-based system development life cycle [223]. Disabilities and aging are associated with some physical and cognitive changes in people's functionalities. Hence, this alteration necessitated that computer and web interface have special features. These characteristics may include larger font size, sounds frequency ranges, and layouts that require less mouse movement. Ultimately, designing personalize and universally accessible interfaces requires technical and cultural changes and strategic commitment in healthcare organizations [200]. Since the combination of organizational, cultural and technological aspects may lead to IoT adoption, efforts have to be made to identify more effective approaches. In the healthcare industry, some specific factors may be beneficial in IoT acceptance, so more in-depth studies are required. In this regard, use of different technology acceptance models such as Technology Acceptance Model (TAM) and Unified Theory of Acceptance and Use of Technology (UTAUT) can be beneficial to the analysis of main dimensions in technology adoption.

One interesting finding obtained from the analysis, was the relatively wide usage of cloud-based architectures in healthcare. Based on the literature, the cloud-based architecture would lead to decrease in the financial burden of hospitals and rapid access to health resources, especially in an emergency situation [162, 174]. Moreover, this emerging field in healthcare is leading to the creation of massive amount of data. In this way, effective methods of data storage and ownership of this clinical data, cause a critical challenge. In addition, in this type of frameworks, easy and secure data collection methods from sensors and smart devices are essential for ensuring data precision. Moreover, it is important to apply machine learning algorithms for accurate analysis of sensor data to smart monitoring of patients' condition [65, 135, 224].

Often, in healthcare machine learning approaches lack transparency, since they are not able to explain why a decision has been made [225]. On the other hand, in an IoT environment, because of some intrinsic features such as high volume, high veracity and high volatility, traditional machine learning algorithms cannot be applied to process the resulting large amounts of data [226, 227]. Furthermore, in a healthcare context, the focus of smart environment is on real-time event detection. In recent years, there has been a growing interest in deep learning techniques [228, 229]. These techniques utilize some learning methods such as a conventional neural network (CNN), deep belief network (DBN) and deep neural network (DNN) [230, 231]. Deep learning can automatically learn high-level features and utilize unlabeled data samples for meaningful patterns recognition.

None of the reviewed studies about cloud-based IoT architecture in healthcare discussed details of real-time data gathering and processing in IoT environments. Some of the possible solutions in that context include the use of Apache Hadoop software for streaming and batch processing, Apache Storm and Spark for real-time data analyzing and Apache Kafka by the distribution of data that provides low latency platforms. Moreover, Apache Ambari can be applied to organizing and managing cloud platforms. However, more research is needed to demonstrate various algorithms which can be applied to the decision-making process in healthcare. Emphasis on this element is important for the successful implementation of such technologies in healthcare.

Another research question of this study was related to security issues. Although security challenges are among the most important issues in healthcare [106, 171, 197], it can be concluded that concentration on this topic is still low and only 10% of the papers reviewed discussed it. Privacy protection has been a critical issue for information security in healthcare. Authentication and cryptographic mechanisms can be applied to protect user privacy. This method ensures that only authorized users have access to medical data [232]. Furthermore, healthcare systems have to deal with both device and data heterogeneity in IoT ecosystems. Such heterogeneity may lead to some serious challenges in terms of confidentiality, reliability and transparency [233]. For the IoT concept to flourish in the health domain, extensive work has to be carried out in the field of security-related issues such as cryptography, packets routing and secure data transmission mechanism. In addition, some of the security concerns, related to the practical implementation of IoT in healthcare should be alleviated. In other words, deployment of suitable security mechanism guarantees the privacy of medical data, leading to successful IoT implementation.

Regarding interoperability, we found that only 3.3% of the included papers were dedicated to this issue in IoT-based healthcare architecture. Other literature reviews state that integration of heterogeneous systems is one of the main elements that will lead to wide adoption of IoT [170, 234]. In the IoT-related health area, it is essential to determine how the healthcare communities apply different protocols to communicate with each other. Without interoperability standards, the application of IoT in healthcare remains heterogeneous and complex. In addition, this phenomenon acts as an inhibitor to the wider diffusion of this technology. As this topic is among critical issues in healthcare, it can be the very reason why a high level of theoretical background is required for integration of IoT systems. Another achievement of this systematic review was related to the effect and challenges arising for IoT in healthcare. Based on these research findings, the most important positive effect of IoT in health was information exchange, the decrease in number of hospital stays of elderly people and the decrease of healthcare costs. On the other hand, the most critical challenges in IoT application in health were related to security and privacy issues.

4.3 Distribution of articles by publication year

The distribution of articles related to IoT architecture based on publication year is shown in Fig. 3. It is clear that IoT architecture in healthcare, was addressed in a high number of articles during the last 6 years, compared to the first 10 years (2000 and 2010). The frequency of articles related to IoT architecture in healthcare was approximately stable in the first 10 years (there was no article identified in these years). Nevertheless, it is revealed from the chart that there is an increasing trend in the number of papers, reaching the peak (20) in 2016.

4.4 Distribution of articles by IoT application area in healthcare

The distribution of articles based by IoT application area in healthcare is presented in Fig. 4. From this chart, it can be

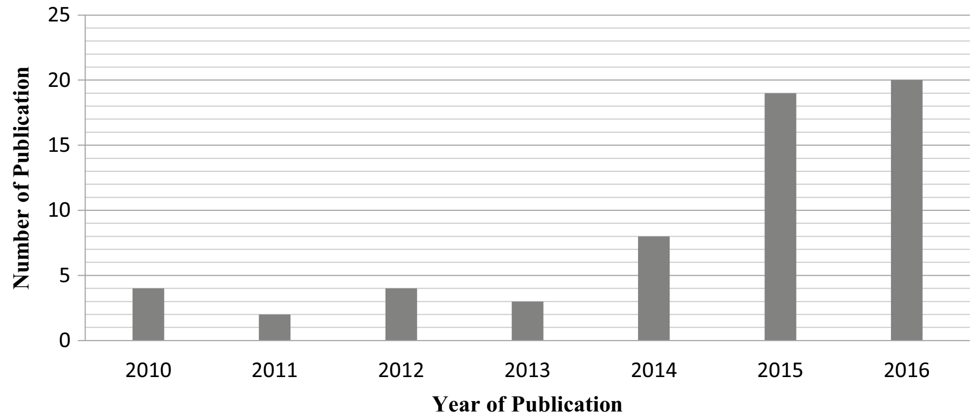

Fig. 3 Distribution of articles by publication year

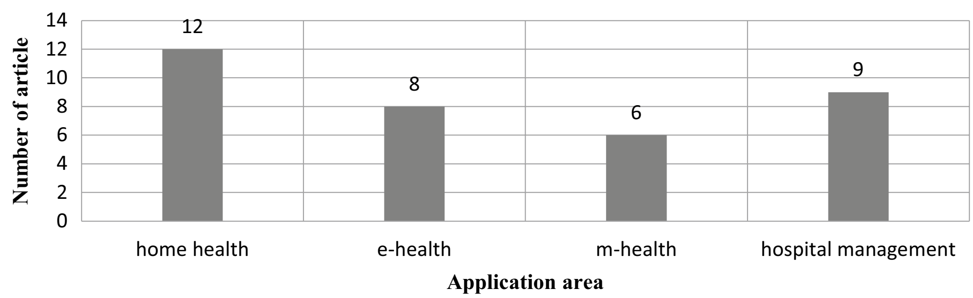

Fig. 4 Distribution of academic papers by IoT application area in healthcare

Table 4 Distribution of articles published by journal and conference

Journal or conference	Type of article	Frequency	Percentage
IEEE	International conference	31	51.6%
Journal of information systems engineering and management	Journal	1	1.6%
Journal of information, communication and ethics in society	Journal	1	1.6%
Procedia computer science	Journal	3	5%
Journal of network and computer applications	Journal	3	5%
Computers and electrical engineering	Journal	1	1.6%
Future generation computer systems	Journal	2	3.3%
Computer networks	Journal	1	1.6%
IFAC papers on Lin lamentation	Journal	1	1.6%
Sensors and actuators A: physical	Journal	1	1.6%
Computer communications	Journal	1	1.6%
The journal of systems and software	Journal	1	1.6%
Procedia technology	Journal	1	1.6%
Multimedia tools and applications	Journal	1	1.6%
Journal of medical systems	Journal	1	1.6%
Personal and ubiquitous computing	Journal	2	3.3%
Cluster computing	Journal	1	1.6%
Journal of medical systems	Journal	3	5%
Bio nano science	Journal	1	1.6%
ICACT transactions on advanced communications	Journal	1	1.6%
Journal of the ACM	Journal	1	1.6%
Healthcare informatics research	Journal	1	1.6%
Total	22	60	100

seen that home healthcare architecture has been the most popular area for IoT architecture in healthcare. As illustrated in Fig. 4, hospital management is another area that papers have concentrated on it. In addition, m-health and e-health have an equal frequency in papers distribution.

4.5 Distribution of articles by journal and conference

Research papers were selected from a total of 22 different journals. The distribution of articles by journal is presented in Table 4. IEEE conference papers have the higher number of contributions regarding IoT architecture in healthcare (51.6%). Procedia Computer Science, Journal of Network and Computer Applications and Journal of Medical Systems have published, on average, 5% of the total papers related to IoT architecture in healthcare.

5 Gaps, implications for future research and limitations

Studies addressing interoperability issues in healthcare are still rare. In the healthcare domain, different vendors exist that provide various products, devices and protocols. Usually, they do not have any obligation to follow regulations. This ongoing means of variation of protocols and standards causes a number of interoperability issues. Hence, it is important to consider a wide range of topics such as device, networking, applications, data and semantic level for standardization. In addition, a variety of software and hardware with multiple communication protocols were deployed, although there is no evidence regarding their technical interoperability. However, semantic interoperability research in IoT in healthcare is still in its infancy. Some of the most important standards for health data are systematized nomenclature of medicine (SNOMED) and read codes and logical observation identifiers names and codes (LOINC). None of the reviewed studies on IoT architecture in healthcare used these interoperability standards. Furthermore, the process of interoperability deals with re-engineering work processes to take full advantage of electronic systems, and is interdependent with technical and semantic interoperability where all three are needed to get significant benefits from healthcare services. Nonetheless, the steady development of IoT applications makes standardization a complex issue. There was no evidence in the reviewed studies addressing these topics comprehensively. Hence, detailed studies have to be performed in this regard.

Patients' medical data are distributed across diverse data sources. Increasing the volume and complexity of health data necessitate the formation of suitable methods for integrating heterogeneous data sources. Extracting knowledge from such data provides a holistic view of patient status and thereby facilitates the delivery of personalized healthcare. Furthermore, communications and information flow patterns in healthcare often involve multiple groups of healthcare providers over a wide geographical area. Therefore, providing a whole view of this situation for IoT implementation is essential. In our study, none of the reviewed studies describe a data model to provide such a holistic view. From this perspective, deployment of the appropriate methods for identification and integration of data sources and effective data handling mechanisms in healthcare are necessary.

None of the studies included in this systematic review provide a cost analysis about devices introduced in the models. Since in IoT architecture, a variety of high and low-cost technology can be used, finding an accurate though cost-effective solution to collect and store medical data is essential. Besides, power management and energy consumption assessment are relatively rare. More studies in this area are needed to create high-quality evidence about energy consumption, battery capacity, and power generation in IoT devices in healthcare.

IoT-based patient monitoring requires continuous healing relationships. In a large number of papers included in this review, the requirement for this type of monitoring, particularly for patients with a chronic disease has not been strongly emphasized. Furthermore, most of the models introduced in this review were service-oriented, while with the rapid increase in mobile healthcare, most of them have the potential to be sole applications. Therefore, there is a need to propose a new architecture for single and multiple conditions.

Recently, the idea of a Social Internet of Things (SIoT) has been proposed [235]. This novel concept in healthcare describes an environment where objects in healthcare environment are intelligently networked with each other. While most of the articles included in this systematic review deployed cloud-based architectures, there is no evidence to demonstrate a SIoT architecture that is applicable to healthcare environment. Therefore, more studies need to be conducted in that context.

This research has some limitations. First, there were some parameters that we could not access as most of the papers were conference proceedings; therefore, their authors did not mention them in details. Second, despite the deployment of a thorough search strategy, some of the studies on IoT architecture in healthcare could not be identified, such as grey literature and reports that were not published in the 8 selected databases which we reviewed. Therefore, it is suggested that an additional systematic review of papers should be conducted to cover other important databases.

6 Conclusion

Our study investigated the different aspects of IoT architecture in healthcare. We have addressed issues concerning the application of IoT in healthcare, and how the different components in IoT architecture communicate with each other. For deeper insights, different technologies used in different models were surveyed and the main characteristics of cloud-based architectures were debated. In addition, critical issues such as security and interoperability were discussed and depicted. Finally, this paper presents the main effects and challenges of IoT in healthcare. In sum, it is hoped that the outcome of this research will be beneficial for researchers, policy makers and healthcare providers in the area of the IoT in healthcare.

Since IoT has the potential to change the economy and society globally, making health more connected, networked and data driven is the cornerstone in the future e-health vision. Planners, managers and policy makers in healthcare tend to rely more on information infrastructure to keep the patient more informed, engaged and empowered. Furthermore, the use of IoT infrastructures enables the patient to actively contribute to, and become part of sustainable healthcare development, and self-management of their own health and well-being to live longer, and healthier. It is essential for stakeholders to observe this rapidly evolving technology and share their attitudes, knowledge and experience to accurately deploy this phenomenon in healthcare. In this way, they will be equipped with extensive knowledge essential to migrate from small projects to large-scale deployments.

With the continuous increase of healthcare data, a major challenge is to design suitable platforms for data analysis. The cloud environment has numerous advantages that make it an appropriate solution for large-scale complex computing. Due to diverse data sources, heterogeneity is an inherited characteristic of health data. Therefore, selection of the appropriate data model for data analysis is essential. Efficient data analysis tools and technologies are required to process such data. Real-time data capturing and processing are also key challenges in health data analytics. Defining the life cycle and intervals of data capturing will influence the analysis result. Moreover, determining the context of unstructured data is necessary, especially when meaningful information about the patient is required. However, some challenges and barriers need to be overcome for IoT acceptance in healthcare. The main obstacles to widespread growth of IoT in healthcare industry are interoperability, standardization and security issues. Fulfilling the user requirement is the main factor affecting the wide adoption of IoT. Since, as a whole, IoT is a new technology, there is a need to teach users about its operations and capabilities. Thus, the system should be simple and user-friendly, to facilitate interactive learning for patients. One of the possible solutions to overcome the issues identified is actively involving potential users in all phases of system development.

The findings of this study will help government officials and health policy makers to formulate strategic decisions regarding the most effective IoT investment and deployment. This study has illustrated that home healthcare services and AAL are the main application areas of IoT in the healthcare sector. In addition, the use of IoT technologies is one of several strategies for improving public health, chronic diseases' self-management and preventing patient hospital re-admission. In the long term, deployment of IoT in health can improve productivity, enhance quality of life, and contribute to poverty alleviation and overcoming health inequities.

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Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interests regarding the publication of this article.

Appendix A

See Table 5.

Table 5 Classification of papers based on specific IoT architecture domain, type of disease or condition, and service or application

No.	Authors	Type of Disease/condition	Service/application	Home health	E-health	M-health	Hospital management
1	Lin Yang et al. [151]	Chronic disease	Service	*		*	
2	Ivascu et al. [172]	Mental disorders	Service		*		
3	Woznowski [173]	Elderly people	Service	*			
4	Zgheib et al. [46]	Bedsores	Service	*			
5	Mainetti [117]	Elderly people	Service	*			
6	Jara et al. [152]	AAL	Service	*			
7	Khoi et al. [153]	Elderly people	Service		*		
8	Coelho et al. [118]	Physical disabilities	Service	*			
9	Catarinucci et al. [130]	Patients, personnel, devices tracking	Service				*
10	Bazzani et al. [236]	Elderly people	Service		*		
11	Ray [120]	Elderly people	Service	*			
12	Pir et al. [237]	Health management information system	Service				*
13	Al-Adhab et al. [119]	Elderly people	Service	*			
14	Fan at al [121]	Elderly people	Service				*
15	Jara et al. [238]	Knowledge management	Service			*	
16	Spanò et al. [157]	ECG monitoring	Application		*		
17	Rahmani et al. [159]	Data processing	Service				*
18	Mohammed et al. [122]	ECG monitoring	Application			*	
19	Istepanian et al. [125]	Diabetes	Application			*	
20	Santos et al. [177]	Patient monitoring	Application			*	
21	Shamim Hossain et al. [239]	ECG monitoring	Application		*		
22	Blazek et al. [240]	Device monitoring	Service				*
23	Sung [59]	Elderly people	Service	*			
24	Hussain et al. [124]	Elderly people	Service	*			
25	Jara et al. [126]	Drug identification	Application			*	
26	Distefano et al. [26]	Patient monitoring	Service		*		
27	Bhatia et al. [131]	ICU monitoring	Service				*
28	Fazio et al. [241]	Patient monitoring	Service				*
29	Pang et al. [155]	Medication management	Application			*	
30	Roy et al. [242]	Children monitoring	Service	*			
31	Moosavi et al. [22]	Remote health monitoring	Service		*		
31	Stefanov et al. [243]	Physical disabilities	Service	*			
32	Zhang et al. [160]	Emergency management	Service				*
33	Jara et al. [161]	Drugs interaction	Application			*	
34	Ray [244]	Physical activity	Service		*		
35	Thang et al. [245]	Emergency management	Service				*
36	Qi et al. [246]	Physical activity	Service		*		
37	Jara et al. [247]	Drug adverse reaction	Application			*	
38	Mazhar et al. [248]	Emergency management	Service				*
39	Zhang et al. [249]	Chronic diseases	Application				*
40	Al-Taee et al. [250]	Diabetes management	Application				*

Appendix B

See Table 6.

Table 6 Main components of IoT architectures in healthcare and their main functions

No.	Authors	Number of layer	IoT communications model	First layer	Second layer	Third layer	Fourth layer	Fifth layer
1	Ivascu et al. [172]	3	Device to gateway	Data collecting: heterogeneous body sensors for data collection	Data processing: processing data by data mining algorithms	Diagnosis: analyzing and processing sensed data	–	–
2	Woznowski et al. [173]	3	Device to gateway	Sensing layer: bringing together sensor data from home environment	Data aggregation layer: secure access to data through graphical user interface	Data analytics layer: analyzing and processing sensed data	–	–
3	Gupta [174]	4	Device to cloud	Implementation layer: capture and storage of data	Evaluation layer: representing usage of the application by the user	Feedback layer: using the outputs of the evaluation	Security layer: concentrating on security issues related to data	–
4	Sinharay et al. [149]	3	Device to gateway	The first layer: is hardware to collect physiological data	The second layer: is used to anomaly detection	Third layer: cloud-based environment to mapping abnormalities and trigger an event	–	–
5	Zgheib et al. [46]	3	Device to cloud	Semantic engine: is used to integrating devices	Middleware engine: assuring the security of medical data	The analysis engine: alarm generation in high-risk situations	–	–
6	Khoi et al. [153]	5	Device to cloud	Sensing layer: comprises of different sensors	Home gateway: data collection, filtering and processing	Network infrastructure: capturing data from the gateway and transferring to monitoring part	Cloud computing: data storage in a cloud environment	Application layer: providing a complete picture of patients' situations
7	Bazzani et al. [236]	4	Device to gateway	Wearable devices: collecting patient activity data	Middleware: enables the interconnection between various modules	Smart device: an interface among user and the remote server	Project manager software: creating daily reports	–
8	Rahimi Moosavi et al. [181]	3	Device to cloud	Device layer: implantable or wearable medical sensors to collect contextual and medical data	Fog layer: a network of interconnected smart gateways	Cloud layer: comprising of big data analytics and other facilities	–	–
9	Sung et al. [181]	4	Device to gateway	Physiological signal acquisition equipment: includes physiological signal modules	Transmission equipment: transmission of physiological data	Display devices: demonstration of events	Cloud server	–
10	Mano et al. [154]	3	Device to gateway	Sensor module: controlling and managing sensors	Web service module: receiving data from the user's mobile	Mobile module: communicating with the web suitable protocols	–	–

Table 6 (continued)

No.	Authors	Number of layer	IoT communications model	First layer	Second layer	Third layer	Fourth layer	Fifth layer
11	Fazio et al. [241]	4	Device to gateway	Input devices: detecting physiological or physical world data	Telecommunication system: transmission of data to the repository	Data management system: storing, processing and retrieving of data	Application software: interpretation of data	–
12	Hussain et al. [124]	3	Device to gateway	Data access layer: SOAP web service is used for collecting data from different resources	The physical layer of transformation: event management and real-time processing	Data-sharing layer: sharing data with a mobile application	–	–
13	Ray [120]	5	Device to gateway	Physiological sensing layer: sensing various physiological activities by biosensors	Local communication layer: transferring the collected data	Information Processing layer: processing the received data	Internet application layer: transmitting data to the cloud environment	User application layer: receiving real-time data about the patient
14	Pang et al. [155]	4	Device to cloud	Wireless internet link: sharing data by communication protocols	Global Positioning System (GPS) link: determination of patient location in an emergency situation	WBSN link: data collection from the environment	RFID link: medical inventory management	–
15	Gelogo et al. [156]	3	Device to gateway	Body sensor: a collection of data	Mobile phone: processing the received data	Monitoring center: analyzing and transferring result	–	–
16	Al-Adhab et al. [119]	3	Device to cloud	Input: body sensor senses the data	Context analysis: data storing in, by Apache server	View: obtaining the result	–	–
17	Fan et al. [121]	3	Back-end data-sharing model	Things layer: the things are connected with each other by WAN protocol	Server layer: is responsible for data storing, data analyzing and permission control	Master layer: represents caregivers, and patients and providing specific permissions to the system	–	–
18	Jara et al. [238]	4	Device to gateway	Electronic personal record: aggregating clinical data	Pro-active monitoring: tracking data transmission	Remote diagnosis: creating a treatment plan to patients	Other services: intelligent analysis of patient data	–
19	Spanò et al. [157]	3	Device to cloud	Sensor and Actuator Nodes (SANs): collecting and transferring data	The IoT server: converts the raw data into "universal" format	User interfaces	–	–
20	Lee et al. [158]	3	Device to gateway	Tier 1: the wearable sensors sense the data	Tier 2: the mobile phone is used to processing the data	Tier 3: data analyzing in monitoring center	–	–

Table 6 (continued)

No.	Authors	Number of layer	IoT communications model	First layer	Second layer	Third layer	Fourth layer	Fifth layer
21	Gómez et al. [251]	2	Device to gateway	Server: consists of a detector, reasoning engine, and the server	Client: consists of two layers; visual interface and search engine	–	–	–
22	Rahimi Moosavi et al. [22]	5	Device to cloud	Sensor interface: the ZigBee based architecture consists of several patient nodes	WSN implementation: collecting data from various sensors	Database application: is connected to a local PC and save data	Webserver application: updates the web page data	–
23	Rahimi Moosavi et al. [22]	4	Device to cloud	Sensor interface: reads data from the medical sensors and perform analog-to-digital conversion	WSN implementation: a user datagram protocol client application sends data packet to a remote server through Wi-Fi	Database application: server application collects the incoming data	Web server application: updates the web page data	–
24	Mohammed et al. [122]	3	Device to gateway	Hardware layer: sensing data from ECG	Application layer with 3 sub layer Service layer: retrieving and storing data. Platform application layer: viewing and managing mobile app. File transfer and writing layer: reads and writes ECG data	Cloud layer	–	–
25	Rahmani et al. [159]	3	Back-end data-sharing model	Medical sensor network: collecting biomedical data	Smart e-Health Gateway: performs the connection between sensors and internet	Back-end system: containing cloud computing platform	–	–
26	Bhatia et al. [131]	4	Back-end data-sharing model	Data acquisition and synchronization: data collection	Event classification and cloud storage: storage of clinical data	Information mining: information extraction	Information presentation: alert generation	–
27	Ullah et al. [252]	4	Device to cloud	Sensor layer: collects different data from patient	Network layer: connecting devices with WAN by protocols	Internet layer: data storage and management	Services layer: access to data	–
28	Salah et al. [253]	3	Device to cloud	Sensor access module: patient monitoring in real time	Communications module: transferring data to the upper layer	Data analytic module: real-time analytics, clustering, and classification methods	–	–

Table 6 (continued)

No.	Authors	Number of layer	IoT communications model	First layer	Second layer	Third layer	Fourth layer	Fifth layer
29	Dong Lee et al. [178]	5	Back-end data-sharing model	Perception layer: sensor creates the data	Perception support layer: data storing and supporting authentication mechanism	Network layer: handling data communication	Service support layer: receiving data and storing in the database	Application service layer: providing methods for data access for users
30	Doukas et al. [176]	5	Device to gateway	1. Gathering patients biomedical and movement data	2. Collecting signal and transferring to the internet	3. The communication protocols	4. Visualization of health data	5. The cloud infrastructure that provides CPU, storage and application
31	Monteiro et al. [202]	3	Device to gateway	Smartwatch: the android application is used for the acquisition of clinical speech data	Fog computing Platform: extraction of clinical features from speech data	Cloud: sending data to the cloud storage environment	–	–
32	Gia [203]	3	Device to gateway	Medical sensor node: implantable or wearable sensors	Gateway: connecting sensors to the cloud server	Back-end part: representing data for visualization	–	–
33	Cao [204]	3	Device to gateway	Front-end module: collection of data	Back-end module: preprocessing and analyzing data	Communication module: transferring data	–	–

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