IoT-Based Healthcare Applications: A Review

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Abstract. The high cost of healthcare services, the aging population and the increase of chronic disease are becoming a global concern. Several studies have indicated the need for strategies to minimize the process of hospitalization and the effects related to the high cost of patient care. A promising trend in healthcare is to move the routines of medical checks from a hospital (hospital-centric) to the patient's home (home-centric). Moreover, recent advances in microelectronics, wireless, sensing and information have boosted the advent of a revolutionary model involving systems and communication technology, enabling smarter ways to "make things happen". This new paradigm, known as the Internet of Things (IoT), has a broad applicability in several areas, including healthcare. The full application of this paradigm in healthcare area is a common hope because it will allow hospitals to operate more efficiently and patients to receive better treatment. With the use of this technology-based healthcare approach, there is an unprecedented opportunity to improve the quality and efficiency of the medical treatment and consequently improve the wellness of the patients, as well as a better application of government financial resources. Based on this context, this paper aims to describe a review to comprehend the current state and future trends for healthcare applications based on IoT infrastructure, and also to find areas for further investigations.

Keywords: Healthcare · Internet of Things (IoT) · Patients · Technology · Review

1 Introduction

The high cost of healthcare services, the aging population and the increase of chronic disease are becoming a global concern. Many studies have indicated the need for strategies to minimize the institutionalization process and the effects of the high cost of patient care [19]. With the aim to minimize this concern, a promising trend in health treatments is to move the routines of hospital medical checks to the patient's home. But, to effectively achieve this, we need systems and communication technology to allow the patient's remote health monitoring.

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On the other hand, recent advances in microelectronics, wireless networks, sensing devices and information techonologies have fueled the advent of a revolutionary model involving systems and communication technology, enabling smarter ways to "make things happen". This new paradigm, known as the Internet of Things (IoT), has a broad applicability in several areas, including health. In this trend, it is estimated that by 2020 there will be around 20 billion "things" connected [14] and uniquely identifiable [17]. These "things" promote the basic idea of IoT that is pervasive computing around this kind of devices, such as RFID tags, sensors, actuators, mobile phones, etc. [5].

Fig. 1. IoT applications markets [2].

As presented in Fig. 1, the IoT will enable the development of applications in many markets, such as agriculture, industry, smart cities and healthcare. In particular in the healthcare market it is expected to see the development and application of this trend as part of its future, because it has the ability to allow hospitals to operate more efficiently and patients to receive better treatment. A type of healthcare application which will be focused on in conjunction with this new paradigm is the application of mobile health. The main objective of mobile health is to allow for the remote monitoring of the health status and the treatment of patients from anywhere [23].

In this context, the potential for change in the quality of life that can be promoted by IoT is unquestionable. Creating integrated utilities will lead to a qualitative change in the services to integrate information systems, computing and communication with extensive control [8]. Therefore, there is an urgent need for the development of technologies and applications related to IoT infrastructure for healthcare.

Thus, before the proposal of new platforms and solutions IoT-based for healthcare, it is essential to understand the state-of-art of the applications of this area and to realize that we performed a review based on Systematic literature reviews (SLR) method. According to Wohlin et al. [40], SLRs are conducted to identify, analyze and interpret all available evidence related to a specific research question, as it aims to give a complete, comprehensive and valid picture of the existing evidence, both the identification, analysis and interpretation must be conducted in a scientifically and rigorous way. So, this paper presents a review based on SLR method that was performed aiming to comprehend the current state and future trends for healthcare applications IoT-based, and also in order to find areas for further investigations.

Finally, in Sect. 2, we present the method for this review, focusing on the research questions, search process, inclusion and exclusion criteria, quality assessment and data collection. Continuing, in Sect. 3, we present the results for this method, regarding search results, quality evaluations and factors. In Sect. 4, we present discussion about the results, and in Sect. 5, we present the conclusions and future works of this research.

2 Method

This study has been undertaken as a systematic literature review based on the original guidelines as proposed by Kitchenham and Charters [26]. In this case, the goal of the review is to comprehend the current state and future trends in IoT-based healthcare applications. The steps in the systematic literature review method are documented in the following subsections.

2.1 Research Questions

Considering the context of this review, the research questions addressed by this study are:

RQ1. What are the main characteristics of healthcare applications based on IoT infrastructure?
RQ2. What are the patterns and protocols used in healthcare applications based on IoT infrastructure?
RQ3. What are the challenges and opportunities related to healthcare applications based on IoT infrastructure?

Regarding RQ1, about the characteristics of healthcare applications, we intend to analyze the functional and nonfunctional requirements, and for which area of healthcare the applications are intended.

2.2 Search Process

The studies selection was made on Scopus from Elsevier[1], as it indexes the main sources of computing in the academic area. The example of sources indexed by Scopus are presented in Table 1.

To define the search string we used terms related to health and Internet of Things (IoT). The main goal was to obtain the major number of researches of this particular applications. Thus, the defined search string was: ("Internet of Things" OR "IoT") AND health.

[1] http://scopus.com.

Table 1. Example of sources indexed by Scopus.

Source	Link
ACM digital library	http://dl.acm.org
IEEExplorer	http://ieeexplore.ieee.org
Science direct	http://www.sciencedirect.com
Springer link	http://link.springer.com

2.3 Inclusion and Exclusion Criteria

This review included works published at any year because we intended to find the biggest number of researches regarding the development of healthcare applications based on IoT infrastructure.

2.4 Quality Assessment

Each selected study was evaluated according to the following quality assessment (QA) questions:

QA1. Is the paper based on research (or is it merely a "lessons learned" report based on expert opinion)?
QA2. Is there a clear statement of the aims of the research?
QA3. Is there an adequate description of the context in which the research was carried out?
QA4. Is the study of value for research or practice?
QA5. Is there a clear statement of findings?

These criteria were based in Dybå and Dingsøyr [11] and they are grounded in three points that need to be addressed in the appreciation of the studies of the literature review:

– Rigour. Has a thorough and appropriate approach been applied to key research methods in the study?
– Credibility. Are the findings well-presented and meaningful?
– Relevance. How useful are the findings to the software industry and the research community?

These five quality assessment questions were scored as follows: 0 - in case of not attend the criteria; 0.5 - in case of partial attend of the criteria; and 1 - in case of fully attend of the criteria.

2.5 Data Collection

The data extracted from each study were: authors country, publication year, venue (journal of conference), goal, app characteristics, functional requirements, nonfunctional requirements, transfer protocols, formatting pattern, IoT platform, define ontologies?, communication protocols, application domain, hardware, interoperability with other systems?, application deployment, challenges and opportunities and additional comments.

3 Results

This section summarizes the results of this review. It specifies each stage of its execution and also presents an overview of the studies that were useful for answer the research questions. Finally, it describes the quality evaluation results of the read studies.

3.1 Search Results

We began to obtain the results by the execution of the search with the string described in Sect. 2.2 at Scopus (stage 1). This search returned 1355 studies, and then, we performed the analysis of the titles and abstracts of each one of them (stage 2). After this analysis, only the 46 studies presented in Table 2 remained. Finally, we performed a carefully read of these 46 studies and 33 of them were useful to answer the proposed research questions (stage 3). The Fig. 2 presents these stages of the study selection process. The results of the extraction of the 46 studies are presented in https://goo.gl/skZmns.

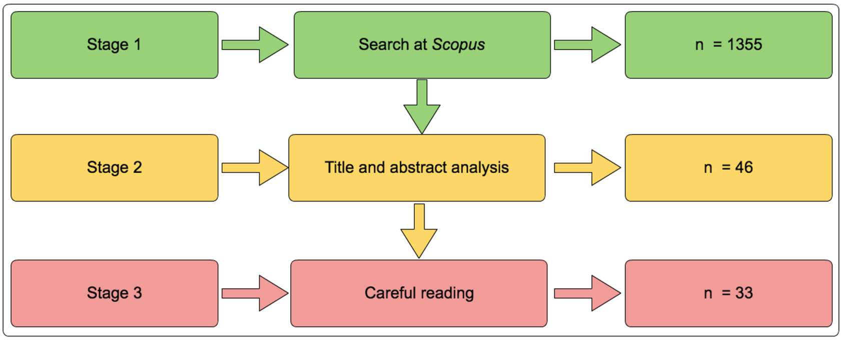

Fig. 2. Stages of the study selection process.

3.2 Overview of Studies

Considering the venue (journal or conference) of the selected studies, 72.7% are from conferences and 27.3% are from journals. Moreover, 6.1% of these papers are from 2017, 12.1% are from 2016, and we believe that in 2017 there will have more publications about healthcare application IoT-based than 2016, once we are at the beginning of 2017 and the number of publications of this year is

Table 2. The 46 carefully read studies.

Id	Authors	Year	Venue
S1	Yang et al. [43]	2014	Conference
S2	Jara et al. [23]	2013	Journal
S3	Fan et al. [12]	2014	Conference
S4	Castillejo et al. [6]	2013	Journal
S6	Doukas and Maglogiannis [10]	2012	Conference
S7	Poenaru and Poenaru [32]	2013	Conference
S8	Yang et al. [42]	2013	Conference
S9	Swiatek and Rucinsky [36]	2013	Conference
S10	Lopez et al. [29]	2013	Conference
S11	Trcek and Brodnik [38]	2013	Journal
S12	Hu et al. [21]	2013	Conference
S13	Le Moullec et al. [28]	2014	Conference
S14	Mohammed et al. [31]	2014	Conference
S18	Kevin et al. [24]	2014	Conference
S19	Sebestyen et al. [35]	2014	Conference
S20	Hassan et al. [18]	2014	Conference
S21	Hassan et al. [18]	2014	Conference
S24	Khattak et al. [25]	2014	Conference
S25	Jara et al. [22]	2014	Journal
S26	Tabish et al. [37]	2014	Conference
S27	Gia et al. [16]	2014	Conference
S28	Ray [34]	2015	Conference
S29	Raad [33]	2015	Conference
S30	Gao et al. [13]	2015	Conference
S34	van der Valk et al. [39]	2015	Conference
S35	Maksimović et al. [30]	2015	Conference
S37	Abdullah et al. [41]	2016	Conference
S38	Abawajy and Hassan [1]	2017	Journal
S39	Chen et al. [7]	2017	Journal
S40	Yang et al. [44]	2016	Journal
S41	Archip et al. [4]	2016	Conference
S42	Kodali et al. [27]	2015	Conference
S43	Gia et al. [15]	2015	Conference
S44	Al-Taee et al. [3]	2015	Conference
S45	Datta et al. [9]	2015	Conference
S46	Hossain and Muhammad [20]	2016	Journal

already about 50% of 2016. At the other side, only 3% are from 2012 and we did not find healthcare applications IoT-based before 2012. We believe that this is because of the maturity of IoT area. The Fig. 3 presents this distribution of the selected studies by year.

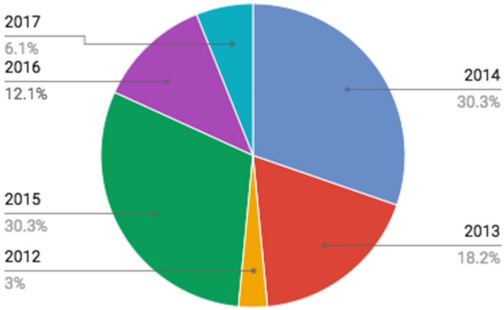

Fig. 3. Distribution of the studies by year.

Regarding the applications described in the studies, 63.7% of the papers do not specify where the healthcare application are deployed. Considering the other 36.3%, 12.1% presents solutions deployed at hospitals and 24.7% deployed at home. Moreover, these studies describe that main characteristics of these healthcare applications are the body and ambient monitoring. From the applications presented, only two studies, S6 and S34, presented the use of IoT Platforms, in this case, the ThingSpeak Platform[2]. Another observation is that seven of them define ontologies, they are S2, S3, S4, S10, S19, S25 and S45. One important point of these applications is that only S1 and S2 present interoperability with other systems, in the case of S1, with medical supply chain, emergency center and hospital, and S2 with clinical devices. So, the consequence of it is that the use of most of the presented healthcare applications in 93% of the selected studies would demand the change of existing systems of the hospitals.

3.3 Quality Evaluation Results

We evaluate using the criteria described in Sect. 2.4. The score of each study is presented in https://goo.gl/skZmns. All disagreements with scores were discussed and resolved. The results show that all studies scored more than 1, and only 7 of them had the maximum score (5): S1, S2, S18, S34, S35, S40 and S41.

4 Discussion

In this section, we discuss the answers to our research questions and then, we present the limitations and conclusions of this review.

[2] https://thingspeak.com/.

4.1 What are the Main Characteristics of Healthcare Applications Based on IoT Infrastructure?

Regarding the main characteristics of healthcare application based on IoT infrastructure, we collected their functional and nonfunctional requirements from the studies. Thus, the functional requirements described in the studies are the body and ambient monitoring for the patient. Considering the body monitoring, the data monitored by sensors attached to patient's body are the pulse oximeter, heart rate, galvanic skin, transpiration, muscle activity, body temperature, oxygen saturation, blood pressure, airflow, body movement, blood glucose, breathing rate and ECG. Moreover, the ambient monitoring is about sensors deployed in the patient's environment that capture data from temperature, light, humidity, location, body position, motion data, SPO2, atmospheric pressure and CO2. The Table 3 presents the studies and the patient's body and ambient data captured by the healthcare applications. We can note that the most frequent captured data of the healthcare applications are from ECG, body temperature, heart rate and blood pressure.

About the features of healthcare applications, there are some important nonfunctional requirements that represent a concern in this kind of applications. Thus the nonfunctional requirements cited by the studies are scalability, reliability, ubiquity, portability, interoperability, robustness, performance, availability, privacy, integrity, authentication and security. The Table 4 specify the nonfunctional requirements and the studies. We can note that the most cited nonfunctional requirements are security, interoperability, reliability and privacy.

Finally, we conclude that the main characteristics of healthcare applications in terms of functional requirements are the patient's body and ambient monitoring, with the mainly capture of data from ECG, body temperature, heart rate and blood pressure. With respect to nonfunctional requirements, the most important are security, interoperability, reliability and privacy.

The Fig. 4 presents the word clouds regarding the requirements of IoT-based healthcare applications.

4.2 What are the Patterns and Protocols Used in Healthcare Applications Based on IoT Infrastructure?

With respect to protocols, the collected data of the studies showed that there are two categories of protocols: communication, regarding network protocols, and application, regarding data transfer protocols. Thus, the communication protocols cited by the studies on the healthcare applications are 6LoWPAN, IEEE 802.15.4, Zigbee, Bluetooth, RFID, WIFI, Ethernet, GPRS, IEEE 802.15.6, 3G/4G, NFC and IrDA. Regarding the applications protocols, the studies cited: REST, YOAPY, HTTP, CoAP, XML-RPC and Web Services. The Table 5 presents the communication protocols and the studies. We can note that the most used communication protocols are Bluetooth, WIFI, 6LoWPAN, Zigbee and 3G/4G.

Table 3. Patient's body and ambient data captured by healthcare applications and the studies.

Data	Freq.	Studies
ECG	22	S1, S2, S6, S7, S10, S14, S19, S20, S26, S27, S28, S29, S30, S35, S37, S38, S39, S40, S41, S42, S43, S46
Body temperature	17	S1, S2, S4, S6, S7, S19, S20, S21, S24, S26, S28, S34, S35, S39, S41, S42, S45
Heart rate	11	S2, S4, S6, S18, S21, S24, S27, S29, S34, S39, S46
Blood pressure	9	S2, S8, S19, S20, S22, S28, S29, S35, S44
Oxygen saturation	6	S6, S19, S21, S24, S29, S39
Ambient temperature	5	S6, S8, S21, S30, S34
Body movement	4	S28, S30, S34, S37
SPO2	4	S27, S35, S41, S42
Pulse oximeter	3	S24, S28, S35
Breathing rate	3	S4, S21, S27
Muscle activity	2	S19, S35
Galvanic skin	2	S34, S35
Blood glucose	2	S7, S36
Ambient humidity	2	S8, S21
Airflow	2	S19, S35
Body position	2	S19, S35
Motion data	2	S6, S21
CO2	1	S8
Transpiration	1	S19
Ambient light	1	S30
Location	1	S6
Atmospheric pressure	1	S21

The Table 6 presents the application protocols and the studies. We can note that the most used application protocols are REST, HTTP and CoAP.

About the data format, the studies presented that the healthcare applications use HL7, XML, EHR, CSV, JSON and PHR. The Table 7 presents the data format and the studies. We can note that the most used are JSON, XML, HL7 and EHR.

The Fig. 5 presents word clouds regarding the technologies related to the patterns and protocols of IoT-based healthcare applications.

Table 4. Nonfunctional requirements of healthcare applications and the studies.

NFR	Freq.	Studies
Security	13	S2, S3, S6, S9, S10, S14, S19, S20, S28, S30, S38, S45, S46
Interoperability	10	S2, S3, S4, S6, S24, S27, S35, S38, S43, S45
Reliability	8	S2, S9, S20, S27, S30, S35, S37, S40
Privacy	8	S2, S6, S14, S19, S20, S28, S35, S38
Scalability	6	S2, S6, S14, S39, S44, S46
Availability	4	S2, S6, S9, S45
Performance	2	S14, S20
Authentication	2	S35, S46
Ubiquity	1	S10
Portability	1	S14
Robustness	1	S2
Integrity	1	S35

Fig. 4. Word clouds of the requirements of healthcare applications IoT-based.

4.3 What are the Challenges and Opportunities Related to Healthcare Applications Based on IoT Infrastructure?

The studies presented that are many challenges related to healthcare applications based on IoT infrastructure. In S6, the authors presented that health information management through mobile devices introduces several challenges: data storage and management (e.g., physical storage issues, availability and maintenance), interoperability and availability of heterogeneous resources, security and privacy (e.g., permission control, data anonymity, etc.), unified and ubiquitous access are a few to mention. Thus, according to S6, the vast amount of sensor data generated by the capture of these applications need to be managed properly for further analysis and processing. Another challenge regarding the data is the unstructured format of it, that, according to S14, the huge volume of data produced by the sensors is in an unstructured format, which is very complex to understand and requires different data storage mechanisms than the typical database management system (DBMS).

Table 5. Communication protocols of healthcare applications and the studies.

Com. protocols	Freq.	Studies
Bluetooth	19	S1, S2, S4, S6, S10, S14, S18, S19, S20, S28, S34, S35, S38, S39, S40, S43, S44, S45, S46
WIFI	17	S1, S3, S6, S19, S21, S29, S31, S34, S35, S37, S38, S39, S40, S43, S44, S45, S46
6LoWPAN	11	S2, S10, S17, S21, S24, S25, S26, S27, S28, S30, S43
Zigbee	11	S1, S2, S4, S8, S18, S28, S35, S40, S42, S43, S45
3G/4G	10	S1, S7, S20, S26, S31, S35, S37, S38, S40, S44
RFID	7	S1, S2, S3, S18, S25, S29, S37
IEEE 802.15.4	6	S4, S7, S9, S26, S35, S41
GPRS	3	S21, S35, S40
NFC	2	S10, S25
Ethernet	2	S1, S21
IEEE 802.15.6	1	S7
IrDA	1	S25

Table 6. Application protocols of healthcare applications and the studies.

Com. protocols	Freq.	Studies
REST	7	S4, S6, S14, S20, S35, S41, S45
HTTP	5	S34, S35, S40, S44, S45
CoAP	4	S2, S24, S30, S45
Web services	2	S27, S46
YOAPY	1	S2
XML-RPC	1	S9

Table 7. Data format and the studies.

Data format	Freq.	Studies
JSON	9	S4, S6, S18, S24, S34, S35, S41, S44, S45
XML	6	S6, S8, S18, S19, S27, S45
HL7	3	S2, S8, S24
EHR	3	S2, S25, S45
CSV	2	S6, S34
PHR	1	S25
HTML	1	S40

Fig. 5. Word clouds of technologies related to the patterns and protocols of IoT-based healthcare applications.

Still about challenges, in S18, the authors highlight that the existing home healthcare systems have drawbacks such as simple and few functionalities, weak interaction and poor mobility, and IoT is considered an effective method for healthcare monitoring system of the disabled and elderly people by the people-object interaction. Moreover, the authors in S18, describe that their future work is focused on the wireless body area networks combined with social networks, exploring the mobility impaired healthcare services based on social networking, and sharing the information of smart object more security and accuracy.

The authors in S19 describe an interoperability, political and administrative challenges, since the communication protocol of the devices is not open and a given device cannot be integrated in other (or multiple) applications. Moreover, according to S19, the implementation of these applications is a technical as well as a political and administrative challenge, once it implies not only in a technical infrastructure but also a number of regulatory measures, such as standards, regulations and institutional reorganization. Any regional or national implementation of such system must fulfill not only quality and safety requirements but also economical efficiency conditions.

In S20, the authors present the need for the development of new protocols that are reliable and energy efficient in data transmission, since routing protocols are critical for the system to work efficiently. In addition, they say that even though several protocols have been proposed for various domains, none of them has been accepted as a standard, and with the growing number of things, further research is required. Still, in S20, the authors also describe the need for the development of efficient data mining techniques for extracting useful knowledge from IoT data. Moreover, sometimes IoT-generated data are not always ready for direct consumption using visualization platforms and, therefore, new visualization schemes need to be developed. Another key challenge described by the authors in S20 regards the need to protect privacy information. They say that more innovative solutions need to be developed in privacy and security aspects.

The authors in S24 highlight the interoperability challenge, once there have been different studies and proposals for patient monitoring at hospital or at home for personal monitoring, a shared goal to produce an interoperable system adopting open standards for healthcare, for example HL7, and a seamless framework to be easily deployed in any given scenario for healthcare is still missing.

4.4 Limitations of This Review

The main limitation of this review is on the bias in the selection of publications and inaccuracy in data extraction. We strict follow the defined protocol, described in Sect. 2, to ensure that the selection process was unbiased. Another limitation is the used search string, described in Sect. 2.2, that although it was defined guided by the research questions, that there is a risk that some studies were omitted. The final limitation of this review is that we used Scopus from Elsevier to proceed with the search of the studies and, although it indexes others scientific repositories, inclusion in Scopus once a paper has been published takes some time, and so there is a risk that some already published studies were not yet included.

5 Conclusion and Future Works

This review was made aiming to comprehend the current state and future trends of healthcare applications based on IoT infrastructure, and also in order to find areas regarding it for further investigations. We started this review defining the method with research questions, search process, quality assessments and data collection. Then, we performed the search using the defined search string at Scopus from Elsevier (stage 1), resulting in 1355 studies. After this search, we performed the analyses of the titles and abstract of the studies (stage 2). Then, 46 studies remained in this review and they were carefully read (stage 3). For these 46 selected studies, we evaluate them according the quality assessment and 7 of them had the maximum score. From these 46 selected studies, 33 studies were useful to answer the research questions.

Using the extraction data, we were able to answer the research questions and provide the characteristics of healthcare applications based on IoT infrastructure (Sect. 4.1). We also described the protocols and data formats used in the studies (Sect. 4.2). Moreover, using the extract data from studies, we were able to find some challenges and opportunities for healthcare applications (Sect. 4.3). The challenges are related to the development of new solutions to resolve interoperability problems, data mining techniques for extraction of knowledge for IoT data, privacy and security problems. Regarding opportunities, there is an industry opportunity for companies that develop IoT-based healthcare applications, since healthcare industry is estimated to be more than $2 trillion by 2020 with an annual consumer market for remote/mobile monitoring devices at $40 billion globally [32].

Finally, with this review we were able to define a layered architecture for healthcare applications based on IoT Infrastructure. It considers the characteristics of these applications, functional and nonfunctional requirements, used protocols and patterns, and is composed of a layer of patients, monitoring, requirements, communication, middleware, systems and services, and users. As future works, we will present and improve this architecture, and it will be used for the development of a platform for remote health monitoring that will address issues like security and interoperability.

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