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Review

Internet of Things Architectures, Technologies, Applications, Challenges, and Future Directions for Enhanced Living Environments and Healthcare Systems: A Review

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Abstract: Internet of Things (IoT) is an evolution of the Internet and has been gaining increased attention from researchers in both academic and industrial environments. Successive technological enhancements make the development of intelligent systems with a high capacity for communication and data collection possible, providing several opportunities for numerous IoT applications, particularly healthcare systems. Despite all the advantages, there are still several open issues that represent the main challenges for IoT, e.g., accessibility, portability, interoperability, information security, and privacy. IoT provides important characteristics to healthcare systems, such as availability, mobility, and scalability, that offer an architectural basis for numerous high technological healthcare applications, such as real-time patient monitoring, environmental and indoor quality monitoring, and ubiquitous and pervasive information access that benefits health professionals and patients. The constant scientific innovations make it possible to develop IoT devices through countless services for sensing, data fusing, and logging capabilities that lead to several advancements for enhanced living environments (ELEs). This paper reviews the current state of the art on IoT architectures for ELEs and healthcare systems, with a focus on the technologies, applications, challenges, opportunities, open-source platforms, and operating systems. Furthermore, this document synthesizes the existing body of knowledge and identifies common threads and gaps that open up new significant and challenging future research directions.

Keywords: ambient assisted living; enhanced living environments; healthcare; health monitoring; internet of things; ubiquitous and pervasive computing

1. Introduction

In order to maintain and improve people's life quality in all periods of life but particularly for older adults, ambient assisted living (AAL) remains a multi-disciplinary field that is strictly related to an ecosystem of different technologies and applications for personal healthcare monitoring and pervasive and ubiquitous computing [1,2]. The concept of enhanced living environments (ELEs) refers to the AAL area that is more associated with information and communications technologies (ICTs). ELEs include all ICT achievements to support AAL. ELEs incorporate several ICT solutions, which require algorithms, platforms, and systems to design and develop innovative applications and services to maintain an independent and autonomous living. Moreover, an ELE includes the latest technological achievements related to Internet of Things (IoT) to create ICT solutions to improve people's health and well-being. A healthcare system can be defined as a set of hardware and software tools designed to provide a broad range of healthcare services and applications to individuals, such as medical staff and patients, aiming to promote health and well-being in in an effective and often pervasive manner. Healthcare systems are closely related to ELE and AAL. AAL systems present an efficient potential to address several healthcare challenges through ICT. Moreover, ELEs incorporate an ecosystem of healthcare systems, which include medical sensors, microcontrollers, wireless communication technologies, and open-source software platforms, for data visualization and analytics. AAL systems provide pervasive methods and ambient intelligence to design ELE applications that incorporate healthcare systems able to provide 24/7 continuous monitoring and control of the environment. ELE include healthcare systems that directly or indirectly help to maintain people within their home environments instead of being moved into institutionalized environments. Moreover, these systems provide efficient methods to improve individuals' independence and facilitate medical treatments. Currently, there are different healthcare systems that incorporate several technologies to monitor several human physiological status and environmental parameters using different wireless communications technologies, such as ZigBee, 3G, Bluetooth, Ethernet, and Wi-Fi [3]. On the one hand, human physiological status monitoring provides medical state perception and is particularly important for at-risk individuals, such as older adults and newborns, to detect symptoms in useful time. On the other hand, environmental conditions also play a major role in well-being and can be monitored in real-time to detect and prevent dangerous situations. Both monitored data (physiological and environmental) can be analyzed by doctors in order to support clinical diagnostics. In particular, indoor air quality (IAQ) is a significant factor to be monitored and controlled in real-time for ELEs and occupational health as people typically spend about 90% of their time inside buildings. IAQ assessment supports decision making on possible interventions to improve productivity and a healthy indoor environment by identifying multiple situations or habits that affect well-being.

There are several open issues in both the planning and implementation of healthcare systems, such as usability, user interface, data structure, ubiquitous design, ergonomics, and data access [4]. Although there are a number of social and ethical issues, such as acceptance by the users, the privacy and confidentiality of information are already recognized by most healthcare systems [5]. It is likewise imperative to guarantee that technological innovation does not replace human care, and instead it should be used to support medical decisions and monitoring health/diseases anywhere and anytime [6]. By 2050, 20% of the total population will be 60 years old or more [7], and that will bring an increase of healthcare systems' costs and lead to a high dependency on healthcare systems [8]. Likewise, 87% of the general population prefers to stay in their homes instead of moving to a retirement home so they can have better quality of life, and therefore, healthcare systems are also expected to support the high cost of nursing care [9].

IoT architectures refer to the connectivity of physical objects connected to the Internet that support sense capabilities. These objects can be accessed through unique addressing schemes with interaction and cooperation features. IoT architectures incorporate numerous types of devices, such as microcontrollers, sensors, actuators, smartphones, and wearables. Furthermore, open-source platforms, hardware, and enhanced software solutions for data analytics, consulting, management, and storage are required to design and develop IoT architectures. IoT architectures involve people who use these IoT devices and should contribute and cooperate with IoT systems synergistically. Therefore, IoT architectures must be aware of the human context and consider people as an essential part of the system. IoT can support healthcare systems and allow people to stay at home and be supervised in real-time, instead of being sent to nursing homes or clinics [2]. Numerous IoT architectures incorporate personal healthcare devices (PHDs) for remote patient monitoring. These devices are portable systems with relevant features for patient biomedical signal sensing and measurement. The number of PHDs are increasing and must incorporate efficient methods for healthcare servers' connection [10,11]. PHDs are used for activity, blood pressure and pulse oximeters monitoring, medication dispensers, and fall detection [12,13]. These portable devices are used in IoT environments by healthcare staff and allow patient monitoring at home. Moreover, healthcare systems cannot be designed and implemented without the relevant role of PHDs. Moreover, PHDs' integration in healthcare environments is proposed by several studies [14–16]. Several monitoring activities, such as measuring cardiac frequency and blood pressure, that in the past were only available at the hospital, can now be continuously performed by using wearable sensors incorporated in, e.g., smartwatches. However, hospital measurements cannot be completely replaced with wearables, such as smartwatches, for several reasons, such as reliability, accuracy, and the context of the measurement. These wearable sensors should be used as an important complement and will never replace human integration and the relationship between the doctor and the patient.

Healthcare solutions that allow real-time monitoring can avoid unplanned hospitalizations that result in expensive emergency costs. IoT incorporates several advantages for the design and development of healthcare systems. IoT can provide networks of connected devices, Cloud applications, and services to facilitate the patient's monitored data transmission and storage. IoT applications are closely related to healthcare systems through remote monitoring, smart-homes, wearable devices, and smart medical equipment. Numerous academic and industry research studies have been conducted about IoT interoperability and therefore several methods and technologies to address interoperability challenges are available in the literature. These methods focus on the standardization of communication protocols to provide interoperability of heterogeneous devices, networks, and data structures. Therefore, these methods and technologies can also be applied to IoT in order to provide interoperability to the healthcare domain. Furthermore, numerous applications for healthcare have been developed based on IoT, which demonstrates the relevant advantages of this architecture to provide efficient and cost-effective healthcare systems [17]. In order to support high-quality healthcare systems, IoT must adopt standardization, including efficient wireless protocols, improved mobile and wearable sensors, and cost-effective and low-power microprocessors [18]. A study presented by [19] demonstrates that individual approval of IoT advances are broad and growing. The current accessibility of remote wireless medical systems and the emerging diffusion of electronic healthcare database records can make the IoT communication framework the fundamental empowering agent for distributed ubiquitous healthcare applications [20].

This paper aims to provide an introduction to healthcare systems, review the current state of the art, and focus on the technologies, applications, challenges, opportunities, IoT open-source platforms, and operating systems. At this stage, a comprehensive understanding of IoT from a healthcare background is significant in order to support future research. This paper will also present an effective analysis of the key enabling architectures, main applications, challenges, and opportunities for ELEs and healthcare systems. While several survey papers regarding IoT for the healthcare domain are available in the literature and the recent proliferation of IoT platforms is evident, it can also be observed that these surveys do not focus on the examination of existing IoT platforms and operating systems. Therefore, the key novelty of this paper is that it performs a comprehensive and comparative study of the available IoT platforms and operating systems and recommends one of them to specifically address solutions for the healthcare domain. Furthermore, this document synthesizes the existing body of knowledge and identifies common threads and gaps that open up new significant and challenging future research directions for healthcare systems. Taking into account the importance of security, privacy, and quality of service (QoS) open issues in the healthcare field, the paper highlights various insights surrounding healthcare systems. The discussion on numerous key future research topics, with the potential to accelerate the progress and deployment of IoT in healthcare, is expected to provide an important background for future research initiatives. In conclusion, this review article aims to be useful by introducing the topic to not only academics or engineers but also o healthcare professionals, which is essential for the development of future healthcare systems.

The rest of this paper is structured as follows: This paragraph ends Section 1; Section 2 focus on IoT visions, elements, open-source platforms, smartphones, and wearable applications; Section 3 refers to IoT applications in healthcare, and Section 4 focuses on important open issues, such as QoS, security, availability, and interoperability; Section 5 discusses several key future research topics with the potential to accelerate the progress and deployment of IoT in healthcare systems; and Section 6 concludes the paper.

2. Internet of Things for Healthcare

Healthcare systems are extremely necessary to enhance the global access to healthcare and medical information. Technological innovations facilitate the access to healthcare in an ageing population and also provide new opportunities and methods for processing and knowledge of medical data [21]. Despite all the advantages of healthcare systems, a complex and important open issue associated with the confidentiality and safety of the patients' data still exists [22,23]. Healthcare systems have several other main challenges, e.g., normalization, network setup, business models, QoS, and data security as referred by [24]. Several research fields are relevant to the design and implementation of healthcare systems, such as mobile and wearable sensors, wireless technologies, and open-source platforms (Figure 1). Numerous healthcare systems incorporate mobile and wearable sensors for data collection used for human physiological status monitoring and use wireless communication technologies for data transmission. Moreover, open-source platforms not only support data storage, visualization, and analytics but also provide numerous features for device management and security. This section aims to specify a comprehensive summary of the most important areas of research trends in IoT.

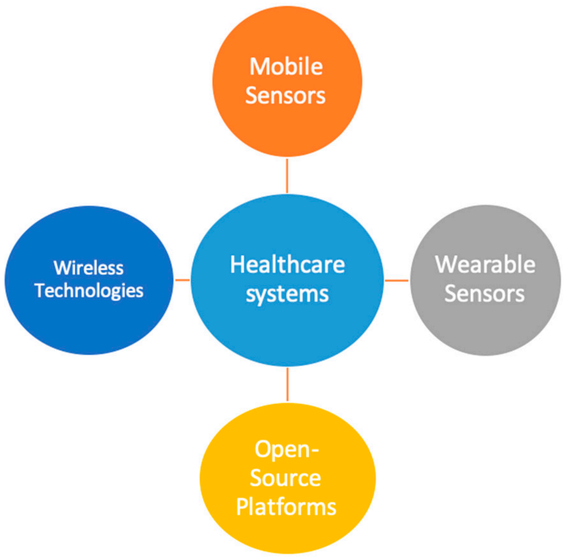

Figure 1. Important areas of research for healthcare systems.

2.1. Visions

The IoT represents one of the main paradigms in information and communication technologies. IoT has three different points of views: Things-oriented vision, Internet-oriented vision, and semantic-oriented vision as referred by [25] (Figure 2). Semantically oriented vision refers to a universal network of unified objects, which supports storage, searches, and organizes information. The things-oriented vision refers to intelligent autonomous things applied to our daily lives that are connected to the Internet. The Internet-oriented vision focuses on systems linked to the network, with a unique address that supports standard protocols.

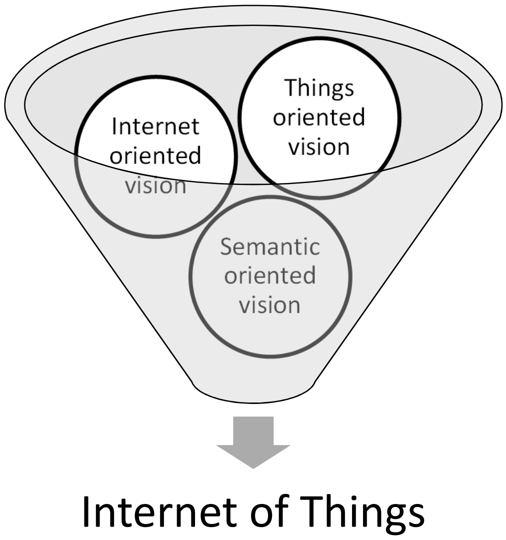

Figure 2. IoT visions.

Regarding the healthcare systems and applications, the things-oriented vision concept is related to the identification of a high diversity of objects, such as sensors and actuators. The Internet-oriented vision is related to methods and procedures to satisfy the data transmission requirements of healthcare systems. Healthcare systems incorporate a high number of sensors, which are responsible for the collection of a massive amount of data. The semantic-oriented vision is related to the methods used to process this vast amount of data in order to extract knowledge to support medical activities.

2.2. Elements

Identification, sensing, and communication are the main elements of IoT, elements that will be explained briefly below. Healthcare systems need to be properly identified in order to match services with their demand. Moreover, not only the identification of the physical "things" but all the interaction entities also have to be clearly acknowledged in IoT solutions to ensure the correct composition and operation of the system. Nevertheless, identification has a significant extended scope and is important for all IoT applications and entities. Identification is a major topic for communication in order to address the items, services, users, data, and locations. The "identifiers" are applied to provide identification and can be assumed as a pattern to uniquely identify a single entity in a particular context. Electronic product codes (EPCs) [26] and ubiquitous code (uCode) [27] are identification methods that currently exist. Object identification refers to the hostname and IP address for communication on the network.

Several addressing techniques are present in the literature, such as IPv4, IPv6, and 6LoWPAN, that apply compression on IPv6 headers [28]. With the colossal address space offered by IPv6, all the addressing requirements of the IoT are supposed to be met. Sensing is the capture of information from the environment through a collection of data; this data can be saved in a remote, local, or cloud database. Communication is a major element of IoT, as for specific applications, such as healthcare systems, communication is crucial for patients' data sharing. Currently, there is a vast diversity of communication protocols with different battery dependability and data range transmissions, such as Wi-Fi, ZigBee, and mobile networks [29]. Most IoT devices adopt the message queuing telemetry transport (MQTT) and constrained application protocol (CoAP). These two open standards are designed to provide mechanisms for asynchronous communication. MQTT is a publish/subscribe messaging protocol designed for lightweight machine to machine (M2M) communications. CoAP is a web transfer protocol for use with constrained nodes and constrained networks designed for M2M applications [30,31]. The IEEE 802.15.4e standard was announced by IEEE in 2012 to improve and complement the previous 802.15.4 standard [32], to address the emergent requirements of manufacturing and industrial requisites [33]. In particular, the IEEE 802.15.6, is a wireless body area network (WBAN) standard developed for enhanced health monitoring, which supports QoS data rates up to 10Mbps, low power, and high reliability [34,35]. Furthermore, other communication technologies are used for short-range communications, such as radio frequency identifications (RFIDs) [36], near field communication (NFC) [37], and Bluetooth low energy (BLE) [38]. A memoryless-based collision window tree plus protocol for simplified computation on anti-collision RFID was proposed by [39]. Other technologic enhancements are provided to NFC, such as a flexible and cost-effective NFC tag to allow smart devices and daily object communication in IoT environments was referred by [40]. Currently, Bluetooth 4.2 provides a suitable power efficient protocol for IoT and is applied in 6LoWPAN networks [41]. The 6LoWPAN has been projected to support WPAN devices with reduced battery specifications to the Internet and can be used in IoT healthcare systems to facilitate and improve energy efficiency.

The referred IoT elements play an even more important role when applied to the healthcare domain. In fact, healthcare applications based on IoT can significantly enhance patient care, optimize resource consumption, and therefore lead to a decrease in healthcare cost. Regarding the healthcare field, privacy is of principal importance as patients' data must remain confidential. Therefore, identification, sensing, and communication elements must incorporate enhanced methods to offer high-quality medical services, while at the same time ensure privacy.

2.3. IoT Open-Source Platforms and Operating Systems

Currently, there are numerous open-source platforms and operating systems that aim to provide support for different systems, data confidentially, safety, fusion, and dissemination. This section presents the most relevant IoT platforms and operating systems (Figure 3), which are recognized by their significance for the improvement of the state of the art and creative highlights, which can likewise be utilized to create secure and scalable healthcare systems.

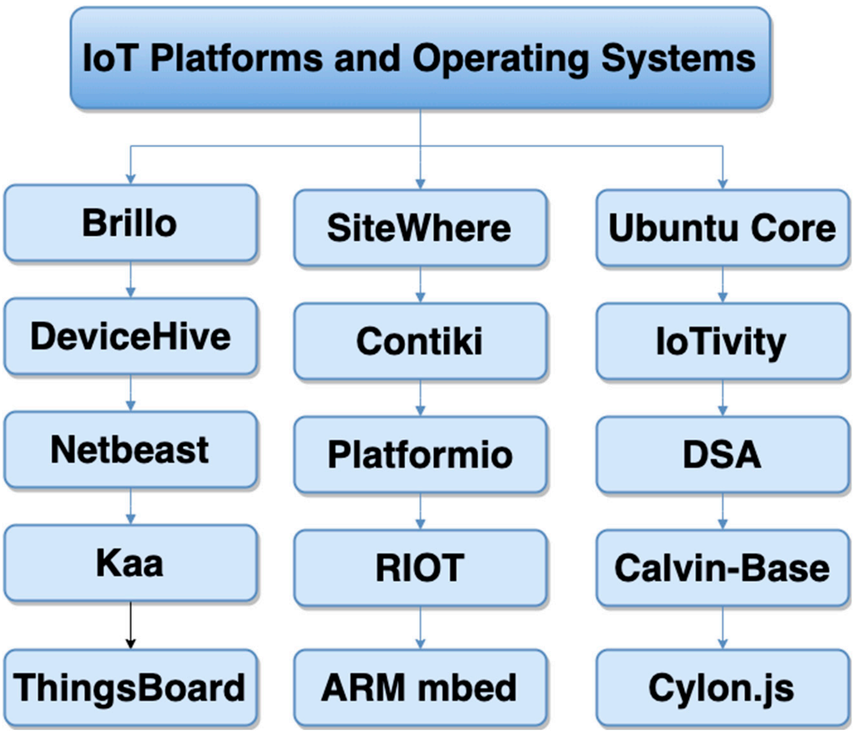

Figure 3. IoT platforms and operating systems.

(1) **SiteWhere:** An open-source IoT platform. It offers a system that accelerates the storage, handling, and incorporation of device data. SiteWhere provides an IoT server platform, device management, and third-party integration frameworks. This IoT platform aims to provide IoT functionalities for monitoring, automation, and analytics for healthcare systems [42].

(2) **DeviceHive:** An open-source IoT data platform that aims to connect devices to the cloud and device data stream. It also provides creation and customization of IoT/M2M (machine-to-machine) applications with a secure, scalable, and cloud-ready functionalities [43].

(3) **Platformio**: An integrated development environment for IoT. It supports cross-platform build functionality without external dependencies to the operating system software, having compatibility with 200+ embedded boards, 15+ development platforms, and 10+ frameworks. It also provides a built-in serial port monitor and configurable build flags/options and automatic firmware uploading for IoT system development [44].

(4) **RIOT**: A free, open-source operating system for the majority of the relevant open standards supporting the IoT. It provides code compatibility for 8,16,32-bit platforms, energy-efficiency, real-time capability due to an ultra-low interrupt latency, multi-threading with ultra-low threading overhead but also 6LoWPAN, IPv6, an IPv6 routing protocol for low-power and Lossy networks (RPL), UDP, CoAP, and concise binary object representation (CBOR) protocols [45].

(5) **ARM mbed**: An IoT platform that delivers the operating system, cloud facilities, tools, and designer ecosystem in order to develop scalable systems based on IoT. It implements safety functionalities, such as transport layer security (TLS) as well CoAP and RESTful API to design M2M networks [46].

(6) **Ubuntu Core** (Snappy): A development version of Ubuntu for IoT systems that offers safety and extensibility of an Ubuntu operating system. It also delivers management systems for safe, reliable, transactional updates controlled by Canonical's AppArmor security system [47].

(7) **IoTivity**: An open-source software framework that provides device-to-device communications to the IoT systems. The IoTivity project is sponsored by the Open Connectivity Foundation (OCF), a specification and certification program to address IoT open issues [48].

(8) **Distributed Services Architecture** (DSA): An open-source IoT platform that aims to join the heterogeneous hardware and software in IoT and provide a scalable, resilient decentralized solution. DSA is composed of DSBroker, DSLink, and nodeAPI. DSBroker acts as a router for incoming and outgoing streams. NodeAPI provides node compatibility and bi-directional control and monitoring ability between connected things. DSLink is connected to the DSBroker that acts as the source of the data streams [49].

(9) **Calvin-Base:** An open-source platform built with a centralized architecture that supports REST API and it is particularly scalable implementing a variety of plugins for interoperability [50].

(10) **Cylon.js:** A JavaScript framework for the IoT that uses Node.js. This framework provides code compatibility between different hardware for IoT. Supports multiple platforms, such as Arduino, Intel Galileo, Intel Edison, and Raspberry [51].

(11) **Brillo:** An Android-based operating system, with core services that provide a developer kit and developer console to build IoT applications. It aims to provide scalability with OTA updates, metrics, and error reporting. It is supported by the ARM, Intel x86, and MIPS-based hardware but also provide secure services [52].

(12) **Contiki:** An open-source operating system for the IoT that provides standard IPv6, IPv4, 6lowpan, RPL, and CoAP protocols. This OS provides a network simulation environment for agile IoT development [53].

(13) **Netbeast:** An open-source IoT platform that aims to connect IoT devices and to provide agile development for IoT solutions. It is supported by 30 different types of smart home devices and 10 brands, such as Philips Hue, Belkin Wenmo, Google Chromecast, Parrot, etc. [54].

(14) **Kaa:** A multi-purpose middleware platform that delivers tools for software development for IoT with enhanced features that decrease related cost, risks, and time-to-market. It is an agnostic hardware solution that supports an SDK for a diversity of programming languages, such as C, C++, and JAVA [55].

(15) **ThingsBoard:** An open-source IoT platform for data collection, processing, visualization, and device management. This platform supports device connectivity using standard IoT protocols, such as MQTT, CoAP, and HTTP. Moreover, ThingsBoard support data processing rule chains and alarms configuration based on events, attribute updates, device inactivity, and user actions [56].

The achievements of platforms and frameworks are related to different requirements, such as [57]:

1. Providing security and privacy APIs with easy configuration and management in order to be adopted by third-party systems.
2. Providing interoperability and extendable protocols to be adopted by third-party systems.
3. Providing efficient size bandwidth, energy consumptions, and low processing requirements.
4. Providing easy management and governance of heterogeneous networks of devices and applications.

Comparison of the IoT Platform Architectures

An IoT platform is a software designed and developed for specific application domains. It can support several domains, such as device management support, security, data collection, integration, analytics, visualization, and storage. On the one hand, an IoT platform can provide enhanced features to decrease the development time of IoT applications as it can provide scalability and heterogeneous device compatibility. One the other hand, an IoT platform can connect IoT devices to user applications and provide interaction management between the hardware and application layers. Regarding the extensive number of IoT platform and operating systems available in the literature is not possible to discuss all related IoT platforms and operating systems. The IoT platforms and operating systems researched in this study were selected according to the criteria used by the authors of [58] and [59]. Therefore, 15 IoT platforms and operating systems were chosen and analyzed in this paper. In this section, the authors compare the presented open-source IoT platforms and operating systems. Table 1 presents the comparison results referring to device management support, security, data collection, integration, analytics, visualization, and storage features.

After the review of the presented platforms, the authors conclude that the majority of IoT platforms support device management. Considering not only the increase of IoT device numbers but also the need to store the atomic attributes of each device, the device management feature is extremely important for IoT architectures. These attributes could be the serial number, mac address, location, and device firmware version. Is important to note that these attributes can include complex, structured objects, such as a list of connected peripherals and their properties. In addiction, is also important to create groups of IoT devices that are in a specific location and communicate with other devices of the same group. Another important feature related to device management is the authorization mechanism to allow or disable access remotely. With the exception of RIOT and DSA, all the presented platforms support device management.

Regarding security protocols, RIOT, Calvin-Base, Cylon.js, Brillo, and Contiki do not support native security features. Although, there are third-party plugins to manage the security issues of these platforms. In general, all the platforms use MQTT and REST APIs to provide data collection and integration features support, with the exception of Calvin-Base that uses a specific language syntax script for device configuration and Platformio that use CI (continuous integration). CI is the practice, in software engineering, of merging all developer working copies with a shared mainline several times a day. The data analysis and visualization are extremely important features as IoT devices generate a lot of data. Platformio, RIOT, ARM mbed, Ubuntu Core, and Cylon.js platforms do not have analytics support. The raw and unstructured data collected by IoT devices must be processed in order to create structured data for analytics, pattern analysis, visualization, and charting. Consequentially, these platforms are not recommended by the authors for healthcare applications as the analytics feature is significant for clinical analysis and diagnosis. Platformio, RIOT, ARM mbed, IoTivity, Calvin-Base, Cylon.js, and Contiki platforms do not provide storage features.

Table 1. IoT platforms and operating systems comparison (√: apply; ×: not apply).

IoT Platform	Device Management	Security	Open-Source	Data Collection	Integration	Analytics	Visualization	Storage
SiteWhere	√	SSL, Spring Security	√	MQTT, JSON, AMQP, WebSockets	REST API	√	×	√
DeviceHive	√	JSON Web Tokens	√	REST API, MQTT	REST API, MQTT	√	√	√
Platformio	√	SSL	√	REST API, MQTT	Continuous Integration Software	×	×	×
RIOT	×	×	√	COAP, MQTT	REST API	×	×	×
ARM mbed	√	SSL/TLS, X.509 Certificate	√	REST API, MQTT	REST API	×	×	×
Ubuntu Core	√	RSA, SSH	√	MQTT, AMQP	REST API	×	×	√
IoTivity	√	DTLS/TLS	√	Message Queue	REST API	√	×	×
DSA	×	Basic Authentication	√	HTTP	REST API	√	×	√
Calvin-Base	√	×	√	REST API, HTTP	Calvin Script	√	×	×
Cylon.js	√	×	√	REST API, MQTT	REST API	×	×	×
Brillo	√	×	√	REST API	REST API	√	√	√
Contiki	√	×	√	REST API	REST API	√	×	×
Netbeast	√	TLS/SSL	√	HTTP, MQTT	REST API	√	√	√
Kaa	√	TLS/DTLS	√	MQTT, CoAP	REST API	√	√	√
ThingsBoard	√	TLS	√	MQTT, CoAP, HTTP	REST API	√	√	√

For healthcare applications, the authors recommend the Kaa platform. This platform supports open protocols, encryption channels for data security, and provides data analytics, visualization, and storage. This platform has important third-party integrations based on microservice architecture; is scalable; supports open IoT protocols, such as MQTT, CoAP, and JSON encoding; has gateway support; the communication with devices is secured with TLS or datagram transport layer security (DTLS); features flexible credentials lifecycle management; supports flexible application versioning; and incorporates well-tested open-source components. IoT architectures have been extensively applied in the healthcare domain to implement effective healthcare systems for older adults and patient monitoring. Moreover, these healthcare systems have been incorporated in ELE to improve users' health and well-being. IoT platforms can provide an efficient functional basis to develop enhanced healthcare systems. These platforms have relevant embedded features for device management, security, data collection, visualization, and analytics. Furthermore, IoT platforms implement important features that considerably accelerate healthcare systems' development and incorporate embedded scalability and interoperability methods. IoT platforms offer standardization methods for data collection from heterogeneous devices through distinct network protocols. Additionally, some of these platforms support not only remote device configuration and control but also over-the-air firmware updates.

2.4. Smartphones

Currently, smartphones provide considerable processing capabilities and a great diversity of sensors that can be used to develop mobile healthcare systems. A survey of healthcare software for smartphones was presented by [60] and concludes that the use of smartphones in healthcare systems is increasing and are useful applications for patient training, sickness self-administration, and remote supervising. Mobile applications support symptom evaluation, psychoeducation, source position, tracking of treatment development, and mental tele-health. Consequently, it is necessary to define and delineate the difference between mobile applications that support healthcare decisions and those with the goal of intervening in clinical decisions [61]. Commercial smartphone applications for healthcare allow patient participation in effective disease prevention and management, which leads to significant cost savings in personalized healthcare [62]. Smartphones provide activity recognition through the detection of physical activities, such as walking and running, climbing stairs, travelling, and sedentary behavior, without the need for extra devices that can be used for patients' activity monitoring for personalized healthcare [63,64]. A distributed particle filter simultaneous localization and mapping (DPSLAM) process that offers restrictions towards a simple recent mounted inertial measurement unit combined into the mobile phone and specifies the core information on the movement of the user was presented by [65], which can be used to monitor a patient's activity at home after medical intervention. An intelligent communication approach for AAL that uses information collected by sensors, data traffic patterns, and the behavior of a person for providing decisions, and sends notifications via smartphone applications was proposed by [66] and demonstrates the importance of smartphones in personalized healthcare. The accelerometer, gyroscope, or light sensor incorporated in a smartphone can be used for activity recognition and monitoring. The camera and microphone can be used as multimedia sensors for personalized healthcare systems [67]. Smartphones are equipped with short-range communication technologies, such as Bluetooth and Wi-Fi, but also long-range technologies, such as GPRS, UMTS, and 3G/4G, that can be used for monitoring co-morbid patients remotely using short-range communication inside hospitals and long-range communication inside patients' home [68]. The NFC and RFID identification technologies can accelerate healthcare and medicine care procedures, and develop enhanced identification protocols that can lead to a reduction of errors in medical diagnostics [69,70]. The preceding paragraphs are intended to provide facts that support the importance of smartphones in healthcare systems. Smartphones incorporate sensors, communication technologies, and processing power that can be used to complement healthcare systems, enabling better data accessibility and notifications to the patient but also to collect data from the environment.

2.5. Wearables

Wearable sensors are used on a large scale for healthcare systems, such as diagnostic procedures and visualization software, to measure and define living environments and real-time personal activity [3]. Wearables have a remarkable diversity of applications in healthcare, such as real-time monitoring of pediatric patients with cardio-metabolic problems [71], headband for electroencephalogram (EEG) feeling recognition aiming to estimate the life quality of individuals [72], and to detect situations of behavioral anomaly in smart AAL through the collection of movement data combined with the local context [73]. Wearable technologies can be used to reduce the costs of personalized healthcare by providing patient monitoring in their own homes [74]. Wearables are also used for blood pressure monitoring, ring-type heart rate monitoring, and Bluetooth-based electrocardiogram (ECG) monitoring. A tele-home medical solution that incorporates wearables, wireless technologies, and sensor data fusion techniques was presented by [75]. Healthcare systems can be very important to provide ubiquitous healthcare services because they allow continuous access to patient information [76]. Healthcare systems for symbiotic and bio-inspired architectures may enhance the health circumstances and living expectation of an enormous number of individuals [77]. A wearable pervasive medical supervising solution that utilizes unified ECG, accelerometer, and oxygen (SpO2) sensors that provide biological records to be communicated in wireless sensor network using IEEE 802.15.4 to a PC where the data can be displayed and stored was presented by [78]. Non-invasive sensors incorporated in wristbands are used to measure and supervise several biological parameters, such as ECG, EEG, electrodermal (EDA), breathing, and biochemical procedures [79]. These wearable sensors can offer cost-effective answers for remote supervision of ageing individuals at domestic or nursing homes but also increase patient monitoring and care [80]. Wearable computing devices with an embedded camera can determine the user position and orientation by using visual odometry and SLAM (simultaneous localization and mapping) techniques to design assisted living systems capable of offering such guidance with on-site augmented reality, without introducing changes in the environment and using off-the-shelf equipment [81].

A system that aims to provide an active and healthy routine for individuals and to advise them with recommendations and important life behavior information that incorporates wearable bio-signals sensors and artificial intelligence algorithms was presented by [82]. HealthMon is a mobile healthcare framework towards access that proposes an affordable, retail wristband for clinical monitoring of scenarios, e.g., dementia, Parkinson's, or ageing, and it is used to provide health monitoring and contextualized alerts in real-time, as presented by [83]. Wearable sensors are used to predict and monitor patients by combining clinical observations, resulting in identification of "abnormal" biological information resulting from patient deterioration [84]. Wearable sensors are used for monitoring academic, sleep, and mental behavior using mobile phones with classification accuracies ranging from 67% to 92% [85] (Figure 4).

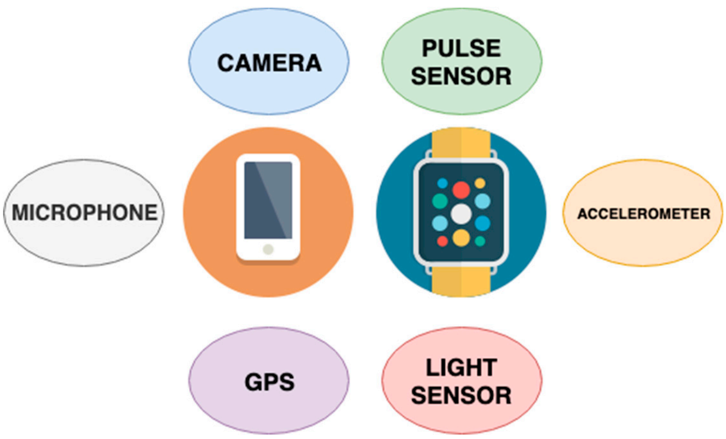

Figure 4. Mobile sensors.

3. Internet of Things Applications for Healthcare Systems

Smart homes should have cyber-physical content permanently linked to the Internet to provide data collection from environment that can be correlated and to produce effective knowledge that is used to improve the quality of life of occupants. The MIT Media Lab was responsible for the development of the first smart home project [86]. Smart homes can be classified into different categories depending on their main purpose. On the one hand, several smart homes aim to identify and distinguish the movements of its occupants to improve their health. On the other hand, some smart homes aim to store and retrieve multi-media captured data in the indoor environment and other activities are centered on surveillance, and are processed in order to obtain information to create real-time notifications and alarms to safeguard the family and house. Moreover, another group of smart homes is classified based on energy efficiency concerns by providing energy consumption supervising and gadget control [87]. A smart home intends to deliver an ELE to its occupants through the incorporation of numerous sensors to monitor indoor environmental conditions and the inhabitants' activities. Furthermore, smart homes aim to add intelligent functionalities to a home in order to incorporate healthcare systems to assist and improve occupants' health and well-being.

As referred by [88], several visions of smart homes are proposed, such as a social view, an instrumental view, and a functional view. Smart homes can be seen as an enhanced method to improve the life quality of occupants; this is referred to as the functional view. Another point of view is the smart home prospective for supervising and decreasing energy consumption and consequently lowering carbon dioxide emission; this is referred to as the instrumental view. Likewise, smart homes can be seen as a way to improve and enhance the digitalization of our daily routine; this is referred to as the socio-technical view.

An example of a smart house that provides breathing and heart rate supervision is presented by [89]. This smart home offers occupants breathing and heart rate supervision with a typical accuracy of 99%. Several projects based on smart homes are available in Europe, such as iDorm [90], Gloucester Smart Home [91], and CareLab [92], which remains notable through its significance for the enhanced state of the art and advanced qualities. A unified architecture for supervision and management of smart houses that recurs to ZigBee is recommended by [93].

The SPHERE Project [94] provides environment, video, and wearable data collection to offer an architecture that uses sensor data fusion to provide identification and administration of several healthcare conditions. An IoT architecture that provides management of the integration and behavior-aware orchestration of devices as services and is cloud based was proposed by [95].

Home Health Hub IoT (H3IoT) provides an architecture for health supervision of ageing home occupants that is cost-effective, easy to use, incorporates a simple layered design, and is delay tolerant [96]. A healthcare system for diabetes therapy was proposed by [97]. This system provide connectivity between the developed patient's device based on 6LoWPAN and the medical team's desktop software to process individual health conditions and a glycemic index information system. Several projects for remote healthcare based on IoT that can improve the process and intelligence of information collection in the medical industry are reported in the literature. One has been proposed by [98]. IoT allows the correct tracking of devices and their identification, patient and clinical team validation, and data collection that produces important information for personalized healthcare [25]. IoT platforms are able to support pervasive healthcare by adopting wearable devices for data collection and mobile devices to upload the data to servers, for communication and interfacing with sensors that allow measurement of physiological parameters [99]. Healthcare systems based in IoT architectures provide an effective way to monitor and store health and well-being continuously [2] but further offer protocols to be ubiquitous and fully modified for personalized healthcare [100,101]. UT-GATE offers native capabilities for well-being supervision software, such as the local repository, compression, signal processing, data standardization, web services, protocol translation and tunneling, firewall, data mining, and notifications, being proposed by [102]. The Health-IoT (in-home healthcare IoT architecture) delivers a business technology with co-design organization for cross-boundary incorporation for in-home medical systems based in IoT but has a deficiency of interoperability [103]. The correlation of a diversity of healthcare systems and sensors could provide earlier medical interventions rather than a detection of advanced stage diseases and provide preventive care [100].

Table 2 aims to analyze a number of studies of the current state of the art, which are categorized by application, sensing, configuration setting, connectivity, access to data, results, and limitations. Furthermore, Table 2 presents a comparison summary, which will be analyzed afterwards in order to extract lessons and common threads on the enhanced healthcare systems research.

Table 3 presents a review summary on the communication technologies used for the design of healthcare systems. The Wi-Fi communication is commonly used to provide Internet connection; however, due to energy consumption concerns, it is not used in battery-powered systems. The GPRS/3G/HSDPA and 4G are incorporated in the majority of smartphones and are significant to provide Internet connection when Wi-Fi networks are not available. Several healthcare systems are designed to use the smartphone as a gateway, where the data is collected using wearable sensors and is transferred to the smartphone. In these scenarios, the interface commonly used is Bluetooth since this is a low-consumption communication technology. Furthermore, RFID and NFC are used to provide identification of the patients or the devices and rarely serve the purpose of transmitting data from one device to the other.

From the analysis of Table 3, it is possible to conclude that the least-used technology for data communication in these scenarios is cabled Ethernet, followed by ZigBee, this being used in three studies. The most used technologies, used in six studies, are the Bluetooth protocol and the GPRS/ 3G / HDSPA / 4G, with Wi-Fi in second place. The conclusions are aligned with the requirements for low power consumption, portability, and lightweight of data communication technologies.

Table 2. Comparison summary on the presented healthcare systems (×: no support).

Application	Sensing	Configuration Setting	Connectivity	Access to Data	Results	Limitations	Ref.
Smartphone-centric AAL platform to monitor patients suffering from co-morbidities	Smartphone sensors (accelerometer, GPS, microphone) and external medical devices	Smartphones and others external devices	Wi-Fi, 3G/4G, GPRS and Bluetooth	Mobile application	Smartphone simultaneously used for data collection using built-in sensors and external medical devices but also as processing unit to extract information of interest.	The study does not address the issue related with power consumption and smartphone autonomy.	[68]
Wearable for EEG based detection of emotions	EEG	Head band	ZigBee	×	Wearable headband prototype can harvest sufficient energy to supply power consumption. The proposed study can achieve a classification accuracy of 90%.	Wearable protype size and data accessibility.	[104]
Anomaly detection in human daily activities using wearable sensors	Accelerometer and passive infrared sensors	Mobile robot, fixed sensors and wearable sensors positioned on hand, foot, and belt	ZigBee	×	Coherent detection of four different types of daily activity anomalies, such as falling to the ground, not following the normal schedule, working overtime, and sleepwalking.	The study needs further tests on more human subjects and in more realistic environments.	[73]
Wearable ubiquitous healthcare monitoring	ECG, accelerometer and oxygen saturation sensors	Sensor belt and wrist oximeter	ZigBee	Desktop application	The proposed system allows physiological data to be transmitted in wireless and have low power consumption. The collected data can be consulted and stored in real-time.	The study needs further experimental validation. The proposed systems do not have remote data access.	[78]
A system for promoting an active and healthy lifestyle using wearable bio-signals sensors	Blood pressure sensor and accelerometer	Wearable sensors positioned on wrist and smartphone used as a gateway	Wi-Fi, 3G /HSDPA and Bluetooth	Mobile application	This study uses a smartphone to receive data from the wearable sensors but also for data sharing with the backend cloud-based infrastructure for data storage. The proposed system incorporates a website for patient data sharing with both, medical personnel and family caregivers.	No obvious disadvantages	[82]

Table 2. *Cont.*

Application	Sensing	Configuration Setting	Connectivity	Access to Data	Results	Limitations	Ref.
Mobile health real-time monitoring framework using wearables	Accelerometer, gyroscope, skin temperature, GPS, contact sensor, ultraviolet light and LED-based heart rate sensor	Wearable sensors positioned on wrist and smartphone used as a gateway	Bluetooth, Wi-Fi and 3G	Mobile application	This study proposes a low-cost mobile monitoring wristband for real-time monitoring of physical activity levels, posture detection and heart rate measurements. This solution incorporates instant notification alerts on critical situations and user evaluation tests ensure high acceptability.	Further validation should be done to reliably posture detection for fall detection. The remote notifications should be enhanced in order to provide more intrusive, urgent notifications for family and doctors.	[83]
Personal diabetes management device	Glucometer	Mobile glucometers for data collection and RFID and NFC cards for patient identification	Ethernet, GPRS, Bluetooth, RFID and NFC	Web and Desktop application	This personalized system allows that the measurements and interactions with the patient are done at home. This architecture provides a web portal, and the management desktop application for data consulting.	This study doesn't include a context management framework in order to get additional information about the physical activity, and communication with electronic health record from the hospital information system.	[97]
Intelligent medicine box for in-home healthcare	GPS, compass sensor, accelerometer, video camera, microphone and ECG	Fixed sensors installed in the medicine box and ECG sensor positioned on chest	RFID, NFC, Bluetooth, Wi-Fi and 3G/4G	Web and mobile application	This intelligent medicine box can effectively integrate the in-home health care devices and services. It incorporates a tablet for sensing and connecting.	The proposed methodology needs to be validated in business practices and also to improve the detection speed and accuracy of medication activities.	[105]

Table 3. Communication technologies used for the design of healthcare systems.

	Wi-Fi	GPRS/3G/ HDSPA /4G	ZigBee	Bluetooth	RFID	NFC	Standard Ethernet
EEG	-	-	[104]	-	-	-	-
ECG	-	-	[78]	-	[105]	[105]	-
Smartphone	[68], [82]	[68], [82]	-	[68], [82]	[105]	[105]	-
Wrist	[82], [83]	[82], [83]	[78], [73]	[82], [83]	-	-	-
Medicine box	[105]	[105]	-	[105]	[105]	[105]	[105]
Glucometer	-	[97]	-	[97]	[97]	[97]	-

4. Internet of Things Challenges and Open Issues for Healthcare Systems

Healthcare-based applications should incorporate improved mechanisms in order to provide privacy of the patient's information. Several safety weaknesses persist in an M2M communication of IoT architecture because the majority of M2M and IoT systems do not require specifications to perform encryption techniques [106]. There is also a need to ensure correct access to the right individuals at the right time and support safe architectures. Several challenges are related to security, privacy, and legal aspects [107,108]. Healthcare systems are normally wireless and presented to people in general; the responsibility of the collected data must be protected and provided only with correct authentication and availability. For that, healthcare systems based in IoT should incorporate hardware and software encryption methods and support privacy policies. The data handled by a PHDs is very sensitive in terms of patient privacy, therefore there is a significant need to provide secure storage methods to prevent its exposure to unauthorized individuals. In this study, two security schemes are proposed. Furthermore, the protocol conversion methods must provide efficient authentication procedures. The protocol conversion proposed by KeeHyun Park et al. [109] implements two security schemes for patient privacy. The biomedical data obtained are not stored as a single unit but stored in parts in the IoT server. Furthermore, the divided data is saved in the IoT authentication server. Therefore, in order to access the data, it is necessary to violate both servers. Moreover, the proposed protocol conversion method incorporates an authentication scheme named the Buddy-ACK. This authentication scheme ensures that a specific part of biomedical data can only be accessed if a patient and the medical staff are authorized.

Individuals will remain the essential parts of the IoT architecture and consequently will touch all characteristics of our lives. Specifically, medical systems, and due to the enormous scale of devices, some safety and privacy challenges will subsist, so therefore teamwork between research communities is indispensable [110]. IoT has several QoS challenges, such as availability, reliability, mobility, performance, scalability, and interoperability, as presented by [25,100,111,112], and are representative challenges for healthcare systems (Figure 5).

On the one hand, availability in IoT platforms intends to present everyplace and anytime services to clients. IoT requires interoperability, therefore, it must follow protocols, such as IPv6 and 6LoWPA, which is preponderant for healthcare systems where availability must always be provided. On the other hand, reliability aims to aggregate the achievement rate of IoT service distribution and is essential to be applied in software and hardware through every part of the IoT layers, which are of particular importance for monitoring patients. In addition, mobility intends to relate users with their desired services uninterruptedly, while on the move. Interruption for mobile devices can happen when, for example, these devices change from one gateway to another. It is essential to develop pervasive and ubiquitous healthcare systems. An IoT-based platform that is compatible with mobility and safety in hospitals was presented by [113]. Performance is a relevant challenge for the implementation of healthcare systems. These systems incorporate a high diversity of heterogeneous devices that collect personal health and medical data. Therefore, healthcare systems must incorporate enhanced methods to provide data security and privacy but must also ensure high-performance metrics. Interoperability and scalability play a major role in healthcare systems' performance. Furthermore, these systems need to continually improve and increase the performance of healthcare services and meet relevant pervasive and ubiquitous requirements. Scalability signifies the capability to insert new systems and functionality keeping or increasing the QoS as it is extremely important to develop large-scale healthcare systems. In medical environments that assume a huge diversity of hardware platforms and communication protocols, scalability assumes an interesting challenge to develop healthcare systems. Interoperability is a relevant challenge investigated by academia and industry. The industry approach to address interoperability issues has been conducted through standardization [114]. Several methods have been designed to provide interoperability between IoT devices, services, platforms, and data structures. Interoperability plays a major role in IoT development and is particularly relevant in the healthcare domain. Healthcare systems incorporate heterogeneous IoT devices, which generate high amounts of data in heterogeneous formats [115]. Therefore, extracting data from different healthcare systems is a complex challenge and interoperability must be ensured to enable heterogeneous systems' interaction and is a relevant requirement to solve data heterogeneity issues [116]. Thus, interoperability should be considered by IoT developers and constructors to develop healthcare systems. PHDs and IoT systems use different standard communication protocols for healthcare applications. Several IoT systems use the oneM2M communication protocol as an international standard for IoT systems while the PHDs use the ISO/IEEE 11073 protocol. Consequently, communication protocol conversion methods are needed to provide interoperability for healthcare services in ubiquitous environments. Regarding the great number of PHDs used in IoT environments designed using oneM2M protocol, a protocol conversion process between ISO/IEEE 11073 protocol and oneM2M protocol is required. Thus, some protocol conversion studies are presented in the literature. An IoT approach for a remote monitoring system for patients at home which incorporates a protocol conversion scheme between ISO/IEEE 11073 protocol and oneM2M protocol and a Multiclass Q-learning scheduling algorithm based on the urgency of biomedical data delivery to medical staff was proposed by [117]. Protocol conversion between ISO/IEEE 11073 protocol messages and oneM2M protocol messages performed in gateways located between PHDs and the healthcare management server was constructed, and evaluated in various experiments by [109].

Healthcare systems are an appropriate method to deal with medical service frameworks, in light of new research that allows characterization of new propelled strategies for the treatment of numerous sicknesses, e.g., by checking chronic infections to help the medical team to decide the best medications [118]. Regardless of the capability of the IoT view and innovations for medicinal services, there are many difficulties to be settled as shown before, in spite of the fact that IoT presents an enormous effect on the economy and it is not yet certain if there are limitations to the early and pervasive adoption of IoT frameworks [119].

Security is also an incredible challenge for IoT applications for healthcare environments that are extremely sensible. Healthcare systems based in IoT architecture must be studied on the effect of packet fragmentation and DoS (denial of service) attacks [120]. The development of healthcare systems should address technical problems, planning, infrastructure, management, and security problems. At the network layer, medical service frameworks should join encryption and avert DoS attacks. IoT has specialized issues as well as arranging, foundation, administration, and security issues [121]. In 2008, the ISO/IEC 29192 standards were made so as to contribute light-weight cryptography to devices with reduced specifications, including block and stream cyphers and asymmetric mechanisms. Lightweight cryptography adds to the security of smart devices due to its efficiency and smaller footprint and should be used in healthcare systems that incorporate smart objects with limited processing capabilities [122]. Healthcare systems attacks can be defined as physical, side channel, cryptanalysis, software, and network attacks [123] (Figure 6). Physical attacks consist of attacking physical hardware and are the most difficult to achieve. Side channel attacks consist of using data information in order to find the key that the target device is using. Cryptanalysis attacks are based on the ciphertext with the objective of breaking the encryption. Software attacks search for vulnerabilities in system software through its own communication interface. Network communications are exposed against network security attacks because of the broadcast nature of the transmission medium. Most medical IoT-based frameworks combine a few wireless technology enhancements and are susceptible to numerous security challenges, for example, attacks on secrecy and authentication, silent attacks on service integrity, and attacks on network availability. Network availability attacks can be classified as DoS attacks that appear at multiple layers, such as physical layer, data-link layer, network layer, transport layer, and application layer [124].

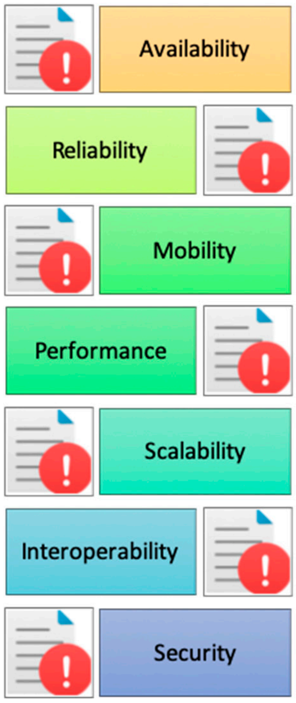

Figure 5. Healthcare systems' open issues.

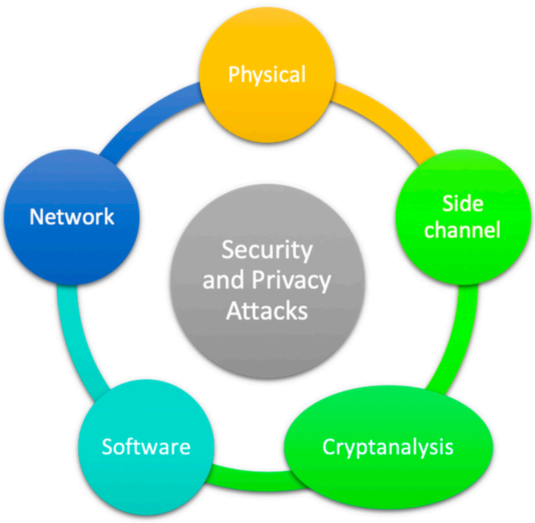

Figure 6. Security and privacy attacks.

Despite all the concentrated efforts done by numerous researchers on IoT, in particular for healthcare systems, several open issues continue to persist. Cryptographic mechanisms, network protocols, data and identity management, user privacy, self-management, and trusted architectures represent important examples [125]. However, there are also many studies that demonstrate the concern in solving these problems that are presented in the literature [126–132].

5. Discussion and Future Directions

IoT must be assumed as an important and feasible architecture for enhanced healthcare systems. However, several challenges still exist, and research efforts should be made to address usability and user interface; ubiquitous design and ergonomics; data access and data structure; social and ethical issues; and security, privacy, and QoS for enhanced pervasive and personalized healthcare systems.

Currently, IoT is responsible for an enormous quantity of personal data that is transferred across the Internet without the guarantee of data privacy. Therefore, several ethical and social questions can be raised about transparency at the expense of our privacy. This is an important challenge to be analyzed particularly on healthcare systems in order to provide protection against observation from non-authorized sources [133]. Pervasive monitoring deals with ultra-sensible data about patient well-being and daily routine, therefore the healthcare systems should incorporate strong security methods to guarantee the reliability of the data. Important legislation and regulations should be made in order to guarantee the user's rights, particularly in the development of healthcare systems. The design of the referred systems should consider ethics as a major factor by adopting policies to ensure that different developers use safe and trustable infrastructures [134]. The healthcare systems data should be protected and implemented in encryption schemes, key management, appropriate cryptographic, and security measures to avoid privacy leakages. Moreover, IoT devices in the healthcare context must be regularly verified to not expose vulnerabilities to security attacks [135].

The proliferation of healthcare services has led to an increase in the amount of data generated, which causes design issues on data access and data structure. Therefore, an extra effort must be made to address the complexity and diversity of the data generated by healthcare systems. Furthermore, the diversity of data sources requires a uniform standard of heterogeneous data management; the diversity of data content requires a unified programming interface for multiple data analysis modules, and the diversity of service objects require a uniform standard service platform interface as was proposed by [136].

The QoS also play a major role in healthcare systems. Efficient and effective cooperation between the physical and digital domains must be guaranteed in order to provide reliable healthcare systems. The state-of-the art technologies, such as 5G, offer several opportunities for the IoT, in general, and to healthcare systems, in particular, especially in real-time applications that involve video on demand [137].

The main application of the enhanced healthcare systems is to develop intelligent and ubiquitous systems for several purposes, such as patient health and well-being monitoring, activity and emotion recognition, anomaly detection in daily routine behavior, and specific diseases supervision for ELEs and to improve occupational health. Additionally, these systems aim to be used on a large scale, which leads to a proliferation of application domains, including the development of platforms on healthcare data sharing, visualization, and analytics.

The development of enhanced healthcare sensors is closely related to the design and configuration setting of several sensing technologies for efficient and effective data acquisition. Particularly, wearable sensors, such as EGG, ECG, accelerometers, and heart rate sensors, are a common trend in the design of enhanced healthcare systems. These sensors are commonly positioned on the wrist, belt, hand, and/or chest in order to provide ubiquitous sensing. Mobile devices, such as smartphones, tablets, and smartwatches, are simultaneously used for data collection using built-in sensors, such as GPS, camera, and microphone, but also as a bridge to interface external medical devices. Moreover, the mobile devices have also been used as processing units to transform the collected data into knowledge. Furthermore, assistive robots are also used combined with ambient sensors for activity recognition and monitoring.

The connectivity is extremely relevant as it is responsible to provide data transmission and sharing among the sensing devices and the rest of the equipment in the framework. The majority of healthcare systems are based in wireless communications technologies [138]. The Bluetooth and Zigbee protocols are usually used for device-to-device communication, as well as Wi-Fi and mobile networks technologies, such as 3G/4G, have been used recurrently to provide Internet access [139].

The access to monitored data is provided using several approaches. On the one hand, the majority of the healthcare systems provides mobile access to data collected using a web interface. On the other hand, some healthcare systems do not provide remote data access. However, there is a clear tendency to develop systems that can be ubiquitously accessed anywhere, anytime [140,141].

The results of the research on healthcare is promising as it provides real-time patient monitoring solutions as well as it often incorporates off-the-shelf mobile devices as sensing and processing units. It also offers activity and anomaly behavior recognition, real-time notifications, and alerts to the medical team and caregivers and a relevant acceptation rate by the users. Particularly, the IAQ monitoring solutions can provide a relevant dataset of the occupant's environmental quality and be correlated with their health status and living environment to support medical diagnostics. Moreover, real-time monitoring data can be used to generate alerts to advise the occupants to act in a useful time to promote health and well-being. Therefore, there is a relevant need to design and develop cost-effective IAQ solutions based on open-source technologies for ELEs and occupational health. However, there are also several limitations, such as energy consumption, validation and calibration in real scenarios, modularity and scalability, and more effective and ubiquitous notifications to act in useful time for ELE and well-being [142,143].

6. Conclusions

IoT offers new methods, architectures, and solutions for enhanced healthcare systems and can be faced with an opportunity to improve medical treatments for personalized healthcare. Open-source platforms and operating systems could improve the quality, security, and availability of healthcare systems. Moreover, existing open-source solutions may improve the evolution and efficiency of healthcare systems by also enabling devices, applications, and systems to securely expose APIs to external systems. Thus, this will improve interoperability and thus decrease the cost of management and governance of heterogeneous device networks. Currently, there is a large set of very diverse open-source tools that provide secure and cost-effective platforms to develop and prototype new healthcare systems. These can be based in IoT and should provide smartphone and smartwatch compatibility, as these devices are seen today as an essential part of daily life and are perceived as extremely important and effective instruments to provide notifications and active coaching in order to improve their users' health and consequently, public health. Today, mobile devices incorporate a diversity of sensors that can be used to provide real-time monitoring solutions and data collection to support medical treatments.

Despite all the advantages of healthcare systems, several open issues continue to exist, such as availability, reliability, mobility, performance, scalability, and interoperability, among others, and as the evolution of the society will not stop, these will be ongoing open issues because the use case scenarios will not remain static. It is extremely important to note that this kind of healthcare systems should exist to support medical treatments and as an important complement of medical supervision.

This paper has presented relevant aspects of IoT for healthcare systems, such as open-source platforms, operating systems, and open issues. It is hoped that a thematic overview has been provided, to introduce not only health and IT professionals but also engineers and students to a paradigm that is essential for the near future in healthcare.

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