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Review

Smart Home Communication Technologies and Applications: Wireless Protocol Assessment for Home Area Network Resources

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Abstract: The paper discusses Home Area Networks (HAN) communication technologies for smart home and domestic application integration. The work is initiated by identifying the application areas that can benefit from this integration. A broad and inclusive home communication interface is analysed utilizing as a key piece a Gateway based on machine-to-machine (M2M) communications that interacts with the surrounding environment. Then, the main wireless networks are thoroughly assessed, and later, their suitability to the requirements of HAN considering the application area is analysed. Finally, a qualitative analysis is portrayed.

Keywords: smart home; HAN; M2M; wireless home communication protocols

1. Introduction

The advancement of the human race has been driven to a great extent by the innovation, expansion, and diffusion of new technologies, which play a central role in modern societies by enhancing social welfare and defining new ways for humans to interact with their environment. In the last century, humans achieved unprecedented levels of comfort and wellbeing. Naturally, this progress was due to the large scale introduction of technologies in all aspects of human existence.

However, the exploitation of our resources is not sustainable, and if we continue the consumption of energy at the current levels, then it may cause the end or at least a pause in the prosperity cycle we have been accustomed to since the beginning of the last century. Besides, our society faces serious challenges which jeopardize our model of economic and social development. As a consequence, mankind has to find a way to rationalize existing resources. The change in our habits is inevitable.

Society is gradually getting older; we are witnessing the growth of an aging population and a significant reduction in the birth rate. Given this scenario, within medium- and long-term horizons, states will not be able to afford the expenses since this is going to place a huge burden on the health care systems, and the pressure and demands on the health care providers will increase. Therefore, medical care for the elderly has become a major health and ethical issue and a critical part of government policy [1]. On the one hand, we have an unsustainable pattern of energy consumption and, on the other hand, we have an aging society.

An emerging idea to overcome such challenges is to transfer part of these responsibilities to common citizens, to enable them to play an active role in the collective effort of rationalization.

In recent years, a new paradigm that allows people to manage consciously home energy resources and to improve their behaviour in order to reduce energy consumption is the smart home. This concept, which could be the answer to the challenges stated above, has gained importance due to four factors [2]: (a) the fast progress and miniaturization observed in semiconductor technology resulting in a proliferation of computing and electronic devices in our everyday lives; (b) the exponential growth of microcontrollers unit (MCU's) processing power; (c) the integration of advanced signal conditioning in very small sensor nodes that can measure and store data using complex processing techniques; and (d) the rapid development and progress of wireless technologies, essentially short range and low power applications. All four factors are generating remarkable possibilities.

As life expectancy has risen significantly over the last century, and people enjoy more satisfying lives, they desire as much independence as possible. However, autonomous lifestyles bring new demands and challenges. One is a constantly aging population and the other is the unsustainable habit of energy consumption; both require new ways to manage this apparently impossible problem.

The smart home concept is based on the interaction between services and features. This idea results from a convergence of several areas: entertainment, security, energy management and health care.

The smart home paradigm can be the answer to such demands since the residence is equipped with technology that observes the inhabitants and provides proactive services that can deliver comfort, security and safety, energy saving and sustainability, and home care.

In this work, we intend to survey the characteristics of wireless protocols, in order to determine the strengths and weaknesses of each of the communication protocols. With the knowledge of these characteristics, it is possible to integrate the communication and collaboration capabilities of the various systems and devices within their habitat to reach a common goal.

2. Smart Homes

2.1. Introductory Definition

Smart home definition and its functionality goals have evolved continuously due to the fast evolution of diverse technologies, emerging from the research activity in home automation related technologies and from home networking developments.

There is a low level of scientific consensus on the subject of "Smart Home" definition. Thus, several authors disagree on what is characterized by this term and what is or not part of it. A smart home is described by L.C.D. Silva *et al.* [3] as a "home-like environment that possesses ambient intelligence and automatic control" capable of reaction to the behaviour of residents and to offer various accommodations and is further divided into four types of smart homes: healthcare based, multimedia and entertainment based, security based and energy efficiency based smart homes—a definition which is supported by D. Zhang *et al.* [4], and M.A.A. Pedrasa [5] among others.

Following the line developed by the authors above, Smart Home is the backbone which will enable the management and the control of different areas of a residence binding four pillars of human livelihood inside a house: comfort and welfare, physical integrity and facilities' safety, rational management of domestic equipment's energy and the possibility to provide healthcare services to its inhabitants. The critical aspect for this backbone to work is to possess a cheap, reliable and easy designed structure of communication. Therefore, Smart Home can be defined as a concentrator and disseminator of information and services that intends to cover the totality of a home's functional areas, this function being operational not only for the particular elements that are in the house in order to improve the levels of comfort and quality but also to provide a gateway or interface to the exterior by the means of an interaction with other paradigms such as a smart grid [6–8] and smart city [9] which will originate the ability to share all the managed information with external elements.

Smart homes will radically alter the way people interact with each other and how they manage their private lives. As a result, people will start to play an important part in this effort by adding technology to domestic management, which in turn will support them to limit energy waste and also to receive health services that are, at present, centralized and provided by hospitals.

2.2. Home Application Areas

The smart home has been of interest to researchers over the last 30 years. Several studied this topic which has branched out into a wide variety of applications. According to the literature, the smart home will enable the management and control of different areas of a residence [3]. Four distinctive general functional areas of service can be classified, which are [10–13]: (a) Energy Efficiency and Management; (b) Health Care; (c) Entertainment; and (d) Security.

2.2.1. Energy Management

Households use one of the major parts of the world's energy and more than half of the energy consumption in homes comes from electricity [14].

The central task of energy management is to reduce costs for the provision of energy in households and residential building facilities without compromising the user's wellbeing. The functions of the home energy management are: controlling activation/deactivation of home appliances, collecting real-time energy consumption from smart meter and power consumption data from various household appliances, generating and monitoring a dashboard to provide feedback about power usage, providing control menus to control appliances and providing a universal link to the broadband Internet. The overall improvement of a house's energy efficiency is urgent. A need to increase energy efficiency of appliances was identified by many researchers and—amidst numerous approaches to do so—a smart home was deemed as a serious answer to this challenge.

Emerging trends, developments and paradigms in smart environments such as Smart Homes are frequently based on smart devices and equipment, such as Smart Meters which can manage and monitor through a network the home energy consumption. The aim of an energy efficiency driven Smart Home is to allow the network elements to dynamically work together and make their resources available, with the intention of reaching a common goal, *i.e.*, the energy saving of a house. A few key features that apply to various energy efficiency driven Smart Homes are [15]:

(i) The available node energy, which is frequently limited, *i.e.*, a battery supplied nodes, which work with limited amounts of energy.
(ii) Smart devices and equipment, which are able to offer the opportunity to monitor and to remotely control key features within homes.
(iii) Decision-support tools designed to assist users in making smarter decisions and based on getting the most out of the benefits gained by the end users when they use energy saving services. It becomes then necessary that at the same time with the energy management challenge, a proper communication protocol between smart devices would regularly improve the system performance.

The proposed energy efficiency driven Smart Home systems by the literature are based on task assignment, integration of various physical sensing information and control of various devices. However, they do not concentrate on finding the best communication protocol between devices that would translate to an improvement of the overall system performance [15].

Authors researching this specific topic have diverse views about how improvement of household's energy efficiency can be done, what resources to use and what system architecture to implement. Some make a reference to Smart Home Energy Management Systems (SHEMS)—capable of reducing the total electricity bill for consumers and to simultaneously flatten demand peaks [16] while others call it Home Energy Management System (HEMS) [17]. M. Peruzzini *et al*. propose a methodology to improve smart home information management by promoting device interoperability, and network collaboration for energy efficiency aims to overcome the main issues of existing Smart Homes by mapping the devices' functions and data, correlating the devices' functions with the smart home actions, and defining what information to send/receive to propose energy-control services [18]. However, since the accidents in power security occur frequently, S. Ma *et al*., proposed to ensure the security of household electricity appliances, designing a power security system based on stream data mining [19].

D.-M. Han and J.-H. Lim present a smart home energy management system using Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 and ZigBee by integrating diversified physical sensing information and control of various consumer home devices, with the support of active sensor networks having both sensor and actuator components [20,21]. Q. Hu and F. Li present a hardware design SHEMS with the applications of communication, sensing technology, and machine learning algorithm so consumers can easily achieve a real-time, price-responsive control strategy for residential home loads such as electrical water heater (EWH), heating, ventilation, and air conditioning (HVAC), electrical vehicle (EV), dishwasher, washing machine, and dryer [16]. R. Cherchi *et al*. proposed a framework through M-Bus communication system that aims to manage the energy consumption of controllable appliances in groups of Smart Homes belonging to the same neighbourhood [15]. They also propose a lightweight algorithm with the purpose to share the available alternative power between the houses.

2.2.2. Renewable Energy Management Driven Smart Home

The universal concept of an energy management driven smart home could include the use of solar, wind and/or other renewable energy sources with an intelligent power consumption mechanism for the electric appliances placed inside the house and a collaborative smart grid to ensure the interconnections between them [22].

With the use of advanced metering and display technologies in an established smart home, the user or the system itself is capable of lowering the energy consumption or postponing the energy demanding operations concerning the present electricity price by managing the household electrical features and under the condition of ensuring a positive comfort level [23].

J.A. Nazabal *et al.*, present a paper where they propose an Energy Management System that includes renewable energy sources for the efficient use of the power created by a Smart Home and the power consumed by the electric appliances of the house with an overall system description, from software protocol to employed hardware is presented [22]. A. Tascikaraoglu *et al.* investigate an experimental smart home with several renewable energy sources and storage systems in terms of various aspects such as appliances control, in-home energy management and power flow. Additionally, the study embodies one of the very first challenges to assess the contribution of power forecasting of renewable energy sources on the performance of smart home concepts [23]. A.R. Al-Ali *et al.* present the design, implementation and testing of an embedded system that integrates solar and storage energy resources to a smart home. It was made by utilizing a controlled load bank to simulate scaled random real house consumption behaviour [24].

2.2.3. Health Care Systems

Having advanced technology in our homes will lead to various opportunities in the near future in this area. One of the most important is the monitoring of a person's cognitive and physical health and, as a consequence of an aging population, an area of critical need is eldercare. The Health Smart Home concept, which can meet this challenge, has been extensively researched by many authors [25].

Suggestive kinds of smart healthcare technologies contain simple devices (blood glucometers, oximeters, blood pressure monitors, *etc.*) which deliver standardized outputs for specific physiological conditions, smart applications or software able to analyse and process body signals, sensor integrated smart devices (gaming devices, smartphones and pads), wearable sensors (e.g., wrist straps, T-Shirts) and additional devices entirely manufactured for the purpose of body signal monitoring/processing (e.g., mainframe computers, tablets). The proposed solutions can be applied to several healthcare technological solutions, including smart homes [26]. Each of these categories poses different challenges when their designers try to comply with the Health Care Smart Home requirements.

The patients utilize components (e.g., sensors), which may be invisible and transparent to the user. Their constantly increasing storage and communication capabilities coupled with their small size enable collection, processing, and potential disclosure of personal health information. Whether at home, work or traditional settings (physician's office, hospital), healthcare IT infrastructures transfer sensitive patient health information and, as such, this issue faces several constraints and information security threats. Security safeguards and controls and data quality and integrity are classified as top priority, mostly because they arise by different fields of information security, but protecting the patient's location and purpose specification, remain the least addressed requirements [26].

N.K. Suryadevara and S.C. Mukhopadhyay reported a mechanism for the estimation of elderly well-being condition based on usage of household appliances [27]. D. Brulin *et al.* proposed a computer vision-based posture recognition method for home monitoring of the elderly [28], while J. Wang *et al.* implemented an enhanced fall detection system based on on-body smart sensors that successfully detect accidental falls in a consumer home application [29]. S. Junnila *et al.* proposed a general purpose home area sensor network and monitoring platform intended for e-Health applications [30].

The outdated devices commonly used to monitor body parameters like heart beat rate or exertion level are not fit for real-time measurements [31]. Nonetheless, a continuous monitoring [13] of such parameters as diabetes, hypertension, and cardiac diseases could allow for constant control of elderly people's physical conditions and provide valuable information since these chronic diseases are more common among this age group.

2.2.4. Advanced Multimedia Services

Media consumption within the home has been growing over the years and new forms of domestic entertainment are very popular, forever changing how we act and relate. Such a category of smart home shows the enormous development potential.

A main promoter for the evolution of future Home Area Media Networks (HAMNs) is the emergence of beyond High Definition (HD) media formats. These formats oblige far greater demands on networks for low latency, high-capacity and rigorous Quality-of-Service (QoS) in comparison to other existing formats. Furthermore, their data-intensiveness will require real-time interconnection of multiple, probably distributed, high performance media processing and storage resources. In order to be able to satisfy this, novel networked architectures are required [32].

Ultra-High-Definition (UHD) embodies the next generation of digital media *i.e.*, past High Definition (HD) as 4 K and 8 K have four (4096 × 2160) and sixteen (7680 × 4320) times the spatial resolution of HD respectively [32].

As a result, large-scale networked circulation of UHD content demands high bandwidth interconnections normally found in optical networks. UHD formats are also data intensive and, as such, it results in a direct correlation with the quantity of processing capacity that it is necessary. Consequently, high performance media processing resources and high capacity networked storage are also required for large-scale UHD HAMNs. Additionally, there is a paradigm shift headed for user-centric HAMNs.

The purpose of this paradigm is to set up flexible customizable network-based media communication platforms that support distinct media users and tools. In addition, it allows the creation and generation of new media content and services on-the-fly, and supports the transmission of content across several media and network environments [32,33].

T. Li *et al.* developed a framework for resource allocation in a Cognitive Digital Home (CDH) with a multiplicity of radio access technologies (RAT) such as cognitive radios and legacy radio devices supporting heterogeneous applications [11]. T.-H. Yu and S.-C. Lo designed and implemented an integrated architecture that supports the outdoor remote control to home devices and the sharing of digital media among indoor and outdoor devices [34]. Y.-C. Yu *et al.* proposed a smart furniture prototype for the smart home, a magic mirror table that has a camera to capture the viewer's facial expression. The system is able to determine the emotion of the viewer and then act accordingly to alleviate his/her emotion [35].

2.2.5. Surveillance and Security

The implementation of communication technologies for essential surveillance and home automation leads to a wide range of opportunities as well as technical challenges.

Surveillance and Security System require a robust configuration in order to collect meaningful, reliable, and accurate data. As a result, they do have a need for adequate support for the QoS required by the delay-sensitive and bandwidth-intensive multimedia data that they currently do not display. These restrictions do not significantly impact delay-insensitive data acquisition but can have considerable consequences for the real-time surveillance or monitoring applications as they often lead to insufficient or improper measurements and erroneous event detection [36].

Real-time multiuser multimedia applications like monitoring or surveillance using multiple cameras have recently begun to be proliferated over flexible and low-cost multi-hop wireless networks. In these types of multimedia systems, several sources share the limited network resources and together transmit the captured video streams to a remote central monitor [36].

There are many recent studies dealing with security issues in a smart home infrastructure. N. Komninos *et al.* classified the main risks of interaction between entities in a smart home and smart grid environments and proposed promising security countermeasures given the specific security goals [37]. Kim *et al.* proposed a smart system using both face recognition and sound localization techniques to identify foreign faces through a door phone [38]. K.-Y. Lian *et al.* proposed a smart home safety handwriting recognition technology to confirm user identity and to manage door security using a recurrent neural network with associative memory [39]. T. Li *et al.* considered the architecture and design of a secure access gateway for Home Area Networks (HAN), so that real-time secure monitoring and control of the devices could be achieved through a smart phone [12].

3. Home Area Network

3.1. Home Communication General Architecture

A smart home can function to a certain extent in an interactive and independent way. These additional capabilities can then be used to improve the quality of life within the household in various respects, such as automation of routine tasks, provision of health services, rationalization of energy consumption, improved individual efficiency, and enhanced home security, as well as to revolutionize what we define as entertainment.

Since smart home interconnection specifications and communication technologies are relatively new and under development, most available communication protocols were developed prior to the advent of the smart home vision. Consequently, evaluation studies are critical to determine whether these protocols are suitable for smart home communication requirements. Thus, intense research has been devoted to this field [40].

In this context, local networks for small home areas are gaining more presence and relevance as advanced automation and energy management functionalities are added to household devices. Essentially, the HAN-enabled smart home is a fundamental step to enable the exchange of information and interoperability among several smart domestic appliances connected to other devices or networks through many protocols, such as Bluetooth, ZigBee, WiFi, Z-Wave, *etc.* inside or within the close neighbourhood of a house.

The modern home local wireless networking approach is based on standards such as Local Area Network (LAN) and Body Area Network (BAN) or Personal Area Network (PAN), which are used to describe a network of a smaller scale ranging from 12 to 100 meters. Commonly, they target local network applications based on low cost wireless technologies [41]. PAN and BAN communication infrastructures are largely employed in domestic applications allowing the user to be on the move, and do not require high expertise to manage the network operation, such as adding or removing components.

Although some services like the monitoring of a certain feature related to health issues and performed by smart homes can be included in the BAN range of communication, a wider area of action is required for the whole infrastructure to function. On the other hand, such a network configuration can be sufficient since it is capable of staying fully operational for a long time and its energy is cost effective. PAN can fulfill more requirements since it consists of wearable and portable equipment capable of interacting with the immediate neighbourhood and is able to communicate with the wider environment via larger area wireless backbones.

Wireless sensor networks (WSN) are alternative cost effective solutions for connecting sensor nodes in highly meshed networks with very low energy requirements [42]. Integrating sensing, communication, and computation capabilities for monitoring and data processing of variables, such as temperature, pressure, humidity, and light, allows complex data processing based on sensed physical phenomena for smart living purposes [43].

Even though such categories of networks cover a broad range of functionalities, this is insufficient. In addition, there is no interoperability feature that could allow communicating with each other.

Therefore, a wider network (global wireless infrastructure) is required to congregate different levels of communication that have specific complexities such as timing constraints or critical data traffic of high priority.

Figure 1 shows the general framework of the smart home integrating main application areas as identified below, meaning that security, health care, entertainment, energy efficiency, and all related services are connected to a domestic communication infrastructure.

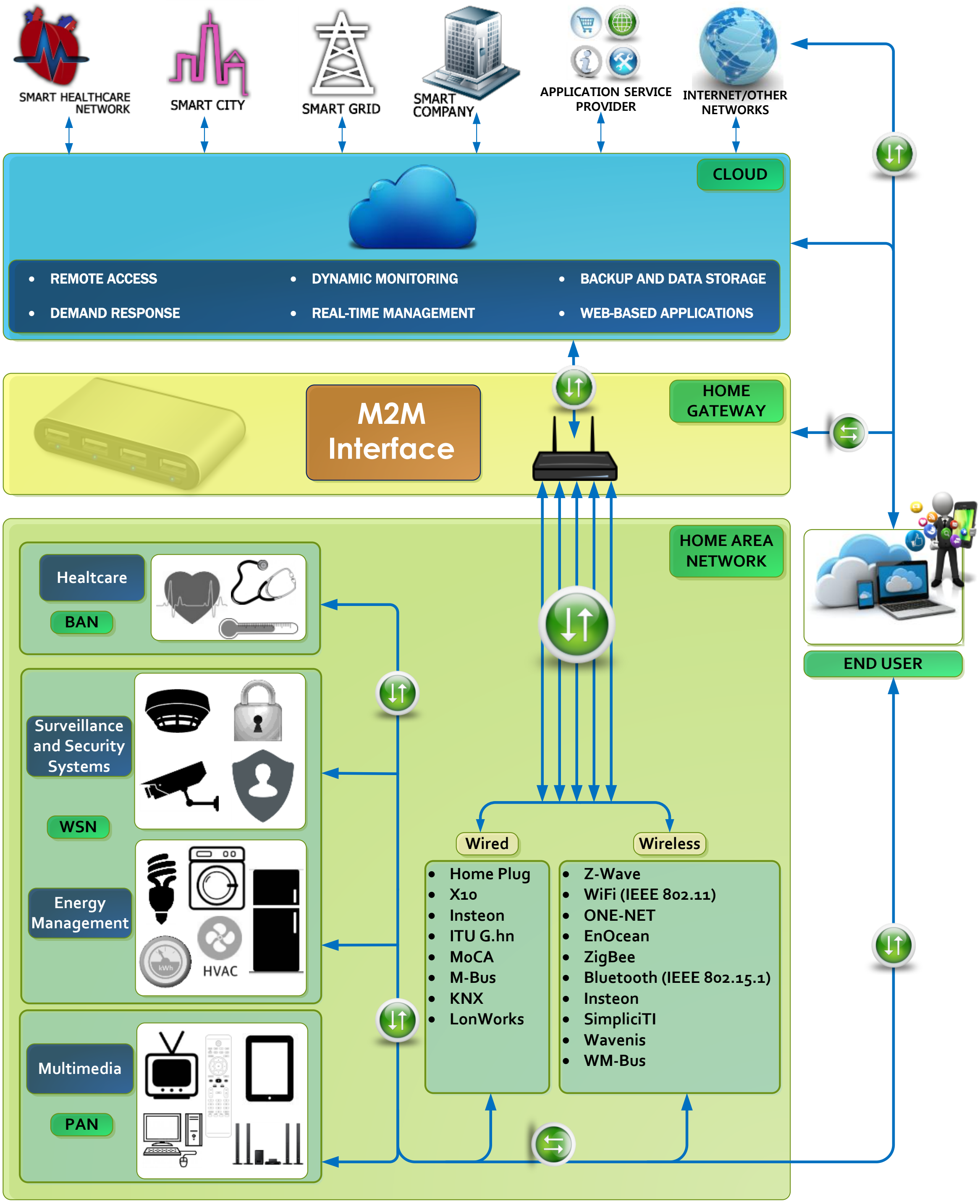

Figure 1. Smart home devices accessed through global network framework.

Taking into account the different purposes of each of these areas, a global network is needed for an integrated higher structure of communication that comprises several dedicated home networks. The interoperability between the different applications relies on a universal multi-purpose home gateway that acts as communication protocol translator. It is actually a data aggregator that processes data traffic coming from different home networks, independent of the means of physical transmission, *i.e.*, wired or wireless. On the other hand, the gateway connects the Smart Home data communication infrastructures with the outside world. The connection can be routed to a mobile network or through a cable based infrastructure. At the upper level, the data is forwarded to a cloud system where it is classified, organized and stored for different purposes and aims. In turn, their access is provided to specific entities such as a smart grid [7], smart city [9], and smart healthcare network, which will make sharing all the managed information with external elements possible.

3.1.1. Home Gateway with M2M Interface as Enabler for Smart Home Services

Machine-to-machine (M2M) refers to technologies that can enable both wireless and wired systems to interact with other devices of the same nature and where one device generates events and the other interprets them. Among a wide range of possible applications at the early development of M2M, smart homes have the highest market potential for the reason that it is closely related to human life [44,45].

Along with the growth of M2M related technologies, wireless networks (WN) are in the process of being applied to smart home systems, therefore, enabling a greater ability for devices and a more reliable and richer function of the smart home system [45,46]. M2M wireless networks can help to increase the production and efficiency of machines and to improve the safety and reliability of complex systems [47].

The main concerning issues in these M2M service networks come from the vertical fragmentation and complexity of M2M markets. This complexity is as a result of the number of connectivity means, embedded devices, and service platforms—particularly of their heterogeneity [48].

3.1.2. HAN Oriented Cloud

Cloud computing has just emerged as a new paradigm of ubiquitous computing and has been one of the utmost significant improvements in computer technologies and industry in recent years. The development of cloud computing expands the capacity of computer calculation and the convenience for the users [40]. Though home automation technologies already are commercially available, they are essentially intended for signal-family smart homes with a high cost, and are alongside the continuous development of digital appliances in smart homes.

There are many benefits of introducing two-way communication of the smart home HAN with a cloud based system. In the first place, information of the house's expected electricity usage comportment is concentrated and made available to a utility, load serving entity or an aggregator. Therefore, these entities are able to execute their optimization processes by ensuring precise information of their consumers. Another significant feature is that the end-user could remotely access with a smartphone, data regarding electricity consumption or even set parameters to the HAN in real-time.

Moreover, the computational resources part of HAN in a domestic environment are systems that might have reduced capacities of storage and computational power and in the case of data being stored in a local database or a Personal Computer (PC), the risk of losing the data or it being corrupted by third parties.

3.1.3. HAN Internet Protocol (IP)-Based Solutions

Regardless of the initial doubt shown by many researchers about the suitability of the Internet architecture for wireless networks, in the present good performing implementations of IPv6 stacks exist already for HAN. In addition, IPv6 presents solutions prepared for network statelessness and auto-configuration, and satisfies the great address space needed for such networks.

At the same time, the Internet Engineering Task Force (IETF) has been developing the standardization of mechanisms in order to encompass the Internet for actuator and sensor networks. In addition, the utilization of IP for such type of devices is being endorsed by the recently created IP for Smart Objects (IPSO) Alliance. Despite the fact that the work prepared by the IETF is at present in progress, IP-based sensor networks are emerging and could radically increase the capillarity of the Internet. In the near future, entirely standardized IP-based solutions for wireless HANs will be possible and accessible [49].

3.2. Smart Home HAN Requirements

The communication requirements related to HAN are defined by the services and applications which run in the household; for example, diverse processes have to be executed among all devices in a smart home network. According to this condition, HAN have to provide reliable communication between application area devices and from the functional area devices to HAN devices for different indoor scenarios. If such is the case, then all HAN devices have to be dependably accessible as well.

Communication can be seen from the general and individual point of view. Therefore, it is important to identify what is needed to ensure an efficient exchange of information in a functional area. However, since we have more than one functional area in the same physical space of a smart home, we are required to find a way for them to coexist in a superior infrastructure of communication inside the same house.

It may not be advantageous and economical to have identical communication requirements for all smart home appliances; for example, a temperature monitoring device needs only low speed communication infrastructure, whereas facial recognition communication infrastructure is greater.

Next, the organization and classification in four sections of main characteristics and requirements for HAN [4,41,50] is made, as shown in Figure 2.

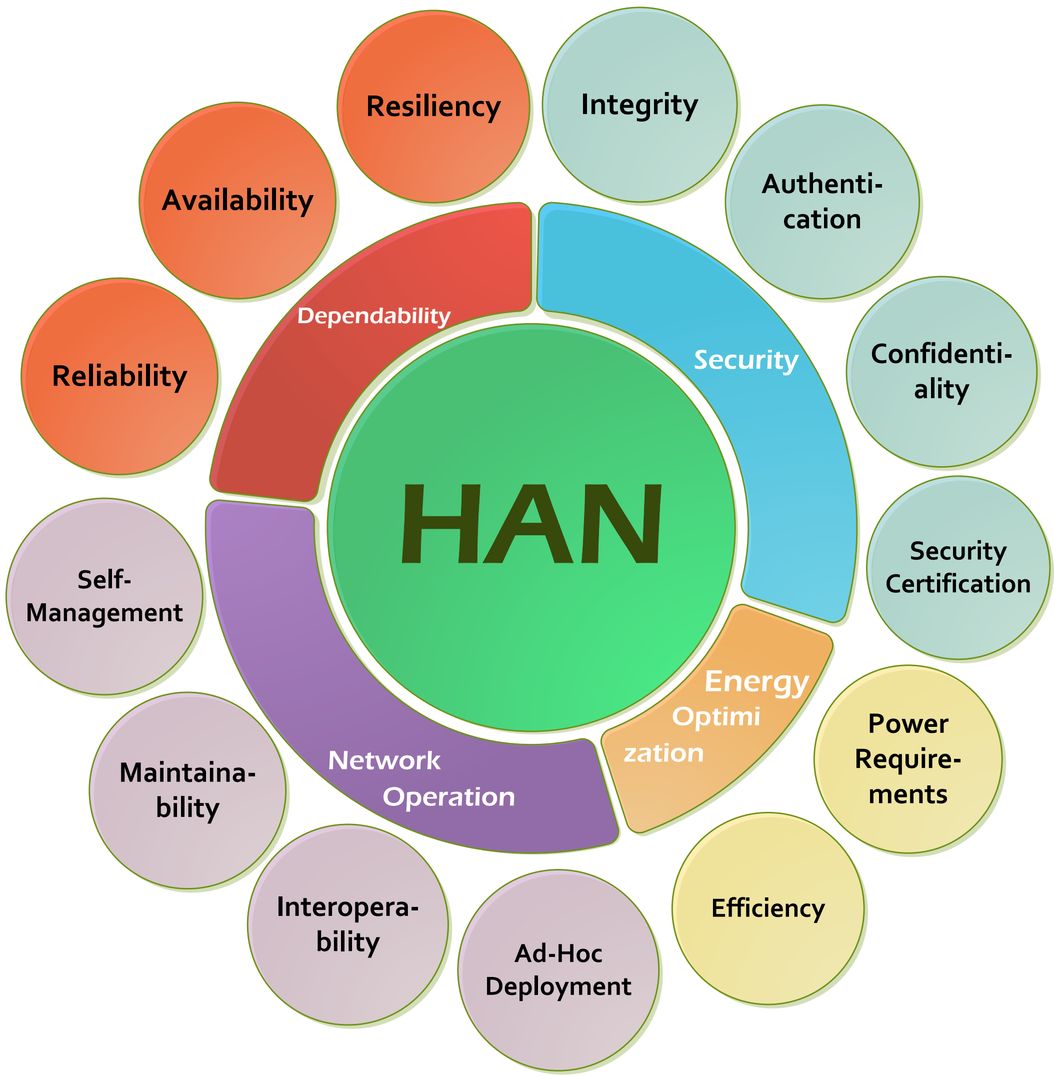

Figure 2. The classification of the main characteristics and requirements for HAN.

3.2.1. Secure Communication

Home data networks are increasingly exposed to external attacks from the internet. At the same time, near local networks inside or outside of the house may be used to get access to sensitive information such as data metering or to change the dose of diabetic medicine endangering the lives of their residents. This means that the HAN has to authenticate all devices, protect data integrity and privacy (e.g., by encryption) and provide protection against replay attacks; such attacks are a particular concern where the HAN is used to support a security related application (people and/or property). HAN connected devices may have very limited resources to achieve low cost and long battery lifetime. This is the case of wireless HAN tailored for portable devices used, for example, to monitor patient health state or for tracking packages with restrictions such as antibiotics. As for networks based on physical cables, Ethernet enabled devices have enough hardware resources for accomplishing the security issue. Despite the physical and energy constraints advanced security services are expected to be provided by the wireless HAN technology and the platform operators. This is to say, higher level software does not need to implement security measures if the same are provided by the communication protocol.

Security is one of the most significant characteristics of any system. Researchers have different perspective regarding security and it can be defined in many ways, for instance, the US department of commerce defines security as a condition that results from the creation and maintenance of protecting measures that guarantee a state of inviolability from hostile acts or influences [51]. In general, security is a concept similar to safety of the system as a whole. Thus, its intention is to defend HAN area of attacks such as: data modification, impersonation attack, eavesdropping and replaying. The security requirements are:

Integrity

It certifies if a message that is being sent reaches the receiver intact. It is important that this is done in an effective and accurate manner. If this does not happen the receiver equipment can be unutilized, damaged or even a message could be sent to the wrong receiver by the source. Falsifying message contents, including the sender's address, has to be detected. The sender of a message must be able to prove that a specific message has been sent and if the receiver has indeed received the message. Nobody can falsify the network operators in terms of usage fees and the network operators can only charge fees for successfully delivered messages.

Authentication

Authentication is known due to its three major aspects. Entity authentication helps to verify the veracity of a claimed or presumed identity of the sender. Data origin authentication verifies the source of the message. Location authentication guarantees the truthfulness of the claimed or presumed location information [52]. This requirement is utilised by one node to identify another node or to verify the source of origin of data in the network. Thus, it is essential for tasks like association, beaconing, parametrization, and sending and/or receiving of critical data for the adequate operation of the involved network's elements.

Confidentiality

Message contents must be kept confidential, which means that only the communication partners may comprehend it. The messages of the sender and/or receiver should be indecipherable for everybody else, and third parties, such as the network operators, should be incapable to perceive their communication. Furthermore, potential communication partners or third parties cannot be capable to locate HAN stations or their users. This can be achieved by generating the information incomprehensible by using cryptographic encryption. As the information travels across the home networks, data must be ensured to prevent non-authorised access from other elements. In this sense, data encryption allows a high level of protection by masking the information whose reading requires a key for that purpose. The communication technology shall provide native mechanics with adequate strength and encryption method, as recommended for example in RFC3565 for AES128.

Security Certification

The HAN operated communication must support device security certification. Each device model must be security-certified by a recognized independent authority.

3.2.2. Network Operation

Interoperability

The interoperability and completeness of the infrastructure strongly affects the effectiveness and efficiency of the overall performance of the system. Smart home elements involve a number of common and interoperable standards for communications purposes. To integrate the various technologies and communications protocols, this kind of capacity is desirable with the aim of mutual recognition and offering continuous data transference. Inefficient and deficient integration and interaction among elements could delay the response time and also damage the global system's throughput and operation.

Ad Hoc Deployment

Since it is important for different network devices to be deployed in a non-structured mode and spread through the house, several wireless HAN applications lack the requirements to predetermined locations of individual stations. Nodes have to perform many setup and configuration steps autonomously. Those steps should incorporate the establishment of communications with near sensor nodes and find out their positions in order to start their sensing responsibilities. The information available directly affects the variability of the mode of the sensor nodes' operation.

Self-Management

Various sensor network applications are programmed to operate with no infrastructure support or the prospect of maintenance and repair. Consequently, in order to configure themselves, operate and collaborate with others, to adapt to failures, changes in the environment or environmental stimuli, it is a requirement of the sensor nodes to be self-managed, which means to be completely independent of human intervention.

Maintainability

Maintainability is a requirement that essentially reflects how durable and reliable the HAN is. The environment can change, which means depleted batteries, failing nodes and new tasks. Thus, HAN units have to monitor their own health and status in order to change operational parameters or to choose different trade-offs, such as providing lower quality when energy resource becomes scarce. In order to repair quickly and cost-effectively the various devices and communication components, the HAN must be designed for the purpose of an easy maintenance.

3.2.3. Dependability

Reliability

Reliability can be defined as the probability that a network functions continuously and properly in a time period interval. A reliable network is a network that is capable to unceasingly deliver an accurate service. Reliability can be categorized into different levels: event reliability, packet reliability, Hop-by-Hop reliability, and End-to-End reliability.

Both packet and event reliability levels operate with the required quantity of information to notify the sender of the occurrence of an event within the network environment. End-to-End and Hop-by-Hop reliability levels are related with the successful recovery of the event information. Still, all of them rely on redundancy and retransmission mechanisms.

Availability

In the traditional definition, a network is considered highly available when its downtime is very limited. The purpose of the availability is to guarantee that the services of network are always available and will still operate either when few failures occur or to operate quick restarts when failures take place.

Resiliency

The resilience defines the recoverability and fault tolerance of a network. Due to some intrinsic features, wireless mesh networks are more vulnerable to possible node and link failures when compared with wired networks. Consequently, the resilience to failures has become a very significant issue recently in the design of wireless mesh networks. It has been also noticed that sensor nodes misbehaviour can origin failures as well and thus have driven new challenging and open problems to the resilient wireless network design and can weaken the performance and even the whole connectivity of the networks [53]. When incidents occur, the degree of resiliency defines how trustworthy the HAN can truly be. It clarifies, mainly from a safety and security perspective, the capability to restore and recover from a range of disruptions or malfunctions through the robust fast-response process, especially the vulnerable digital elements in the house.

3.2.4. Energy Optimization

Power Requirements

This factor in wireless portable devices has always been one of the most important. The main motives for waste of energy embrace overhearing, idle listening, collision and control overhead. Over the last decade, significant developments were achieved in this area; however, an evolution towards more power-efficient elements must continue, especially for monitoring sensors, battery-powered devices, remote control and mobile handheld equipment so as to extend the durability of these devices by saving as much energy as possible.

Efficiency

The use of frequency spectrum can be costly so an effective result with the lowest amount of waste, unnecessary effort, or expense is desirable. With the aim of avoiding needless redundancy in the transmissions such outcome obliges an exhaustive reading of the power consumption data.

4. Wired HAN

At present, there are many traditional and non-traditional transmission infrastructures such as telephone lines, electronic wiring, unshielded twisted pairs, coaxial cables, and optical fibers. A widely adopted power line communications technology named HomePlug uses the already available home electricity wiring infrastructure to communicate; it is mainly used for high-speed wired communication applications (e.g., multi-stream entertainment networking) and has a developed set of standards [54].

Ethernet is a family of computer networking technologies for LANs and metropolitan area networks (MANs). It is a common and widely adopted technology that offers a vast range of data rates (10 Mbps–1 Gbps) or optical fibres (as high as 10 Gbps) [55]. This technology uses a shared interface present in various parts of household equipment, such as printers, laptops, game consoles, servers, and audio-video (AV) equipment. Ethernet might not be the best option for connecting all the equipment and devices in the HAN (especially appliances) as a result of the power requirements and high cost, but perhaps the most important issue is with the need for separate wiring back to a central point.

X10 is an international and open industry standard that utilizes power line cabling for signalling and control of home devices in which the signals include brief radio frequency (RF) bursts of digital information. Yet, it suffers from some issues such as incompatibility with installed wiring and appliances, limited functionality, interference, excessive attenuation of signals between the two live conductors, slow speeds, lack of encryption, and frequent loss of commands [54].

Administered by the KNX Association, KNX is a standardized (EN 50090, EN 50090) OSI-based network communications protocol designed for smart buildings. KNX is the improved replacement and enhanced version of three previous standards: BatiBUS, the European Home Systems Protocol (EHS) and the European Installation Bus (EIB or Instabus). All KNX installation devices are linked together by a dual wire bus—the most usual form of installation, consequently permitting them to exchange data [56]. The individual bus devices function is established by their project planning and can be adapted and modified at any time. KNX allows three bus topologies: line, star and tree, and can be mixed when needed, but it doesn't allow ring topologies. The tree topology has advantages over remaining ones in certain cases when a large network is required [57]. KNX contains a wireless physical layer (PHY) called KNX-RF and along with home automation networks, the basic PHY technology of KNX-RF is also utilized for the transmission of metering information between smart meters in Europe [58]. Other development by KNX Association is KNX IP—the name of the IP protocol when it is utilised as a pure KNX communication medium. Thus, KNX IP devices communicate with each other exclusively via KNX IP [59]. My companies have been involved in development of a system that integrates powerline products with the already-established KNX system configuration. Thus, through powerline gateway it is possible for the system to receive and send information, events and commands to and from the electrical bus [60,61].

Insteon it defines a mesh topology composed of RF and power line links and it addresses X10 limitations while maintaining backward compatibility with X10. Insteon is a solution specifically developed for home automation and its devices can be power-line only or RF-only, or can support both forms of communication. All Insteon devices are peers, signifying that each device can transmit, receive, and repeat any message of the Insteon protocol, without requiring a routing software or master controller [49].

Local Operating Networks (LON, LonWorks) is a sensor/control networking technology that covers a wide range of applications. It has an architectural flexibility since its intelligent devices are projected to acquire data from the surroundings in a sensor network and also to interact with the sensed object in a feedback loop as a control network. LON is one of several solutions in building automation and home networking. It comprises all the fundamental building automation subsystems: heating, air conditioning and ventilating, security, lighting, fire detection, energy monitoring, and access control, fire valve control, gas detection, smoke detection. LON platforms are also utilized in semiconductor manufacturing, pulp and paper equipment, textile machinery, automotive, petrochemical, food and beverage, wastewater treatment and material handling [62]. Most devices in LON-based building automation system are connected by wire, but wireless transmission is also used in cases like building-to-building communication, environmental monitoring of particular areas of the building or of stored materials in a building. With this, technology networked systems can be developed with a peer-to-peer architecture with a large number of nodes that exempts synchronization and generally cover wide distances. LON also utilizes multiple media including wireless communication, supporting battery-powered nodes, usually powered down and only activated for sending a message or receiving it [63].

All the previous described technologies support the IP protocol meaning that those can be easily integrated with IP-based smart grids [54].

A global and non-profit trade group, The HomeGrid Forum, and its members are supporting and contributing to G.hn specification of the International Telecommunication Union's Telecommunication standardization sector (ITU-T). The main objective of G.hn is to merge the connectivity of media devices and digital content by providing a wired home network over coaxial, telephone, and data-grade cable networks, along with residential power line wiring in order to supply data at rates of up to 1 Gb/s. ITU G.hn delivers secure connections between devices supporting IP and provides advantages such as self-installation by the consumer, the capability to connect to any room regardless of wiring type, self-management, built-in diagnostic information, and multiple equipment suppliers. Consequently, it addresses specific concerns and satisfies several requirements of electronic manufacturers, service providers, and consumers alike [64].

The Multimedia over Coax Alliance (MoCA) is an industry standard alliance developing technology for the connected home that runs over the existing in-home coaxial cabling that provides high quality performance and reliability for the home network. There are two versions of the specification currently available, MoCA 1.1 and MoCA 2.0 which are the deployed standards for the majority of service providers in North America. It is also being adopted in other parts of the world. MoCA enables highly robust, low-latency, and secure communication at net throughputs of over 400/800 Mb/s and 1 packet error in 100 million Packet Error Rate. Its primary use is for the distribution of premium content high definition video and content, including applications such as multiroom DVR [33].

The Meter-Bus (M-Bus) interface was developed for remote reading of household energy such as water or gas consumption meters and it can be also useful for security systems, heating or lighting control systems. M-Bus is an important communication technology for remote reading of meters in Europe, and standardized as EN13757-x [65]. M-Bus consists of a controller (master, MUC), a slave unit and a two-wire cable that are physically connected to each-other through twisted pair cables. The M-Bus interface has an exclusive feature that it can remotely supply counters with power, and the counters transmit the gathered data by demand of the master which in turn, the master connects to a mobile network modem or the Internet. To avoid loss of counter pulses in circumstances of power failure, M-Bus opts for power supply batteries as power replacement [46].

5. Wireless HAN

5.1. Based on IEEE Standards

The IEEE Standards comprise a family of networking standards that cover the media access control (MAC) and PHY specifications for implementing wireless networks.

IEEE 802.11 series standardize PHY and MAC layers for wide local area networks (WLAN) by employing frequency radio bands at 2.4 and 5.8 GHz. This range of standards and further evolutions offer the basis for wireless network products using the well-known Wi-Fi brand. WiFi is a popular IP-based wireless technology used in home networks, mobile phones, video games, and other electronic devices.

This set provides mobility, flexibility, and low-cost connection with the wired technology which makes it appropriate at the distribution level where the performance requirements and data rate are less strict and the cost of technology is more significant. Furthermore, advanced security and the QoS can in addition be reached using this technology [66].

The IEEE 802.15.4 is a standard for low-power, low data rate wireless communication between small devices. This standard only defines PHY and medium access control (MAC) layers, is currently the most widely adopted standard for WSN for low power, low data rate (250 kb/s at 2.4 GHz), low complexity, and short range transmission [67].

Above IEEE 802.15.4, there are several standards like ZigBee, MiWi, 6LoWPAN, WirelessHART and ISA100.11a. In addition, these higher layer protocols define the suggested application framework, device profile, network layer, and security services among other functionalities.

Bluetooth is designed for applications that are primarily based on computer peripherals, such as wireless keyboard and mouse. Bluetooth or IEEE 802.15.1 is a standard intended to be a secured and cheap way of connecting and transferring data amongst supported devices, creating a PAN. At present, many versions of Bluetooth are available such as Bluetooth Low Energy (BLE), which is a short-range wireless transmission technology targeting low complexity, low-cost, communication in wireless BAN by utilizing frequency radio bands from 2.4 to 2.485 GHz [68].

Table 1 shows in detail the wireless networking protocols supported on IEEE Standards.

Table 1. Wireless Network Based on IEEE Standards.

Specifications \ Protocols	ZigBee Over IEEE 802.15.4	WirelessHART Over IEEE 802.15.4	MiWi Over IEEE 802.15.4	Isa100.11Over IEEE 802.15.4	Bluetooth (IEEE 802.15.1)	Wi-Fi IEEE 802.11 a/b/g/n/ac/i
ISM Bands	2.4 GHz/915 MHz (USA)/868 MHz (EU)				2.4 GHz	2.4 GHz 5 GHz
Number of RF Channels	16 (2.4 GHz)/10 (915 MHz)/1 (868 MHz)				79 40 (v4.0)	14 (2.4 GHz) 8 (5 GHz)
Network Topology	Star, Peer-to-Peer and Mesh	Star, Peer-to-Peer and Mesh	Star, Peer-to-Peer	Star, Peer-to-Peer and Mesh	Star, Peer-to-Peer	Star, Peer-to-Peer
MAC Scheme	CSMA/CA TDMA + CSMA/CA (Star Topology)	TDMA + CSMA/CA (beacon mode)	CSMA/CA (beaconless mode)	TDMA + CSMA/CA (beacon mode)	TDD	CSMA/CA + PCF
Modulation Scheme	BPSK (868-915 MHz) Q-QPSK (2.4 GHz)	O-QPSK (2.4 GHz)	FSK/OOK	O-QPSK (2.4 GHz)	GFSK/DQPSK 8DPSK (optional)	BPSK, QPSK, COFDM, CCK, M-QAM
Nominal Rate	250 kbps (2.4 GHz) 40 kbps (915 MHz) 20 kbps (868 MHz)				1 Mbps (v1.2/v4.0) 3 Mbps (v2.0) 24 Mbps (v3.0)	11-65-450 (IEEE 802.11 n) Mbps
Power Saving Mechanism	Supported					
Encryption	AES128				AES64 and AES128	CCMP 128
Data Authentication	MIC-32; MIC-64; MIC-128 (Shared key) ENC-MIC-32; ENC-MIC-64; ENC-MIC-128 (Encrypted key)				Challenge response scheme	4-Way handshake
Data Integrity	CRC16	CRC16	CRC32	CRC16	CRC32	CRC32
Autonomy (Days)	100 to 1000+	Depends on Battery Specifications	Depends on Battery Specifications	Depends on Battery Specifications	1 to 10	0.5 to 5
Range (meters)	10–300	100	20–50	100–200	10	10–100
Application Areas	Demand Response, remote control and automation in residential and commercial buildings	Industrial Control, building control the sensory data conveying temperature, pressure or speed	AMR metering, consumer, electronics, home, automotive, industrial, automation, toys business and medical applications	Industrial and control market	Wireless connectivity between personal devices such as headphones, medical, sport & fitness, mobile phones or laptops	Wireless LAN connectivity, broadband Internet access
Advantages	Low Power consumption, several application profiles (home automation, smart energy) and topology flexibility	Communication Security, reliability and Environment with wired HART infrastructure	Flexible, cost-effective platform	Low energy consumption devices, Robustness in the presence of infrastructure, flexible and communication security	Speed and flexibility	Speed and flexibility

5.2. Not Based on IEEE Standards

There are several protocols that are not based on any kind of standardized PHY or MAC layers. These are SimpliciTI, Z-Wave, EnOcean, and Insteon, among others. For comparison purposes, they are shown in detail in Table 2.

Table 2. Wireless Network Standards Not Based on IEEE Standards.

Specifications \ Protocols	SimpliciTI	Z-Wave	Insteon	EnOcean	Wavenis	WM-Bus
ISM Bands	2.4 GHz and Sub 1 GHz	2.4 GHz 908.4 MHz (USA) 868.4 MHz (EU)	915 MHz (USA)	315 MHz (USA) 902.875 (USA) 868 MHz (EU)	433 MHz 868 MHz (EU) 915 MHz (USA) 2.4 GHz	169 MHz 433 MHz 868 MHz
Number of RF Channels	Set by the application	2	34	1	1	12
Network Topology	Star and peer-to-peer	Mesh	Dual-mesh (RF and powerline) Peer to peer and mesh	Star, peer-to-peer and mesh	Star, peer-to-peer and mesh	Star, peer-to-peer
MAC Scheme	LBT (Listen-before-talk)	CSMA/CA	CSMA/CA	CSMA/CA	CSMA/TDMA (synchronized networks) and CSMA/CA (otherwise)	CSMA/CA
Modulation Scheme	MSK	FSK, GSK, narrowband	BPSK, FSK (in ISM Band)	ASK	GFSK	FSK, GFSK, MSK, OOK, and ASK
Nominal Rate	Up to 250 kbps	9.6 kbps (868 MHz) 40 kbps (915 MHz)	38.4 kbps	120 kbps (868.3 MHz)	From 4.8 kbps to 100 kbps. Usually 19.2 kbps	2.4 kbps to 100 kbps
Power Saving Mechanism	Supported	Supported	Supported	Supported	Supported	Supported
Encryption	Depends on the radio MAC	AES128	No	No	3DES AES128	DES AES128
Data Authentication	Depends on the radio MAC	8-bit node I.D 32-bit home I.D	24 bit pre-assigned module I.D	8/32-bit	48-bit MAC addresses	-
Data Integrity	Depends on the radio MAC	Assigned by primary controller	CRC16	CRC8	BCH (32,21)	CRC16
Autonomy (Days)	Depends on Battery Specifications	Depends on Battery Specifications	Depends on Battery Specifications	No batteries (is solar cells, electromagnetic)	Depends on Battery Specifications	Depends on Battery Specifications
Range (meters)	10	30	45 (outdoors)	30	200 (indoors) 1000 (outdoors)	Up to 1000
Application Areas	Distributed alarm and security devices, energy meters and home automation	Remote control lighting and automation, in residential and commercial buildings	Energy measurement, Energy savings, irrigation control, Occupancy sensing, Remote control heating and air conditioning	Building Automation, Smart Homes, Logistics, industry and transportation	Industrial Automation, AMI, AMR, Smart Homes, lighting and access control, cold-chain monitoring, active RFID applications	Smart Meters (Electricity, Gas, Water, and Heat)
Advantages	Small code size and low software complexity	Controllers and slaves network, flexible network configuration	Reliability, low cost, scalability and flexibility	Ultra-low Power, no batteries, Easy to install and time is saved	Ultra-low-power energy consumption, multiple years battery life	Very cost effective

5.2.1. Insteon

It is a registered trademark for a home automation networking technology that enables light switches, lights, thermostats, motion sensors, and other devices to interoperate through power lines, radio frequency (RF) communications, or both [49].

5.2.2. Z-Wave

Z-Wave has so far largely been used for home automation applications: Z-Wave networks can be used to turn lights on or off, change the thermostat, open and close doors, unlock and lock doors, and control security systems (among other things). In addition, Z-Wave networks can handle up to 232 devices. Z-Wave radio frequency (RF) systems operate in the sub-gigahertz frequency range (≈900 MHz) and at a nominal rate of 20 kb/s [69].

5.2.3. SimpliciTI

SimpliciTI is a simple open-source low-power RF network protocol developed by Texas Instruments, Inc and aimed at small RF networks. Such networks typically contain battery operated devices which require long battery life, low data rate and low duty cycle and have a limited number of nodes talking directly to each other or through an access point or range extenders. Access point and range extenders are not required but provide extra functionality such as store and forward messages. With SimpliciTI, the MCU resource requirements are minimal which results in the low system cost [70].

5.2.4. EnOcean

This standard efficiently exploits applied slight mechanical excitation and other potentials from the ambiance (motion, pressure, light, and temperature) using the principles of energy harvesting for networking self-powered wireless sensors, actuators, and transmitters. In order to transform such energy fluctuations into usable electrical energy, electromagnetic, piezo-generators, solar cells, thermocouples, and other energy converters are used. The transmission range is around 30 m inside the building, and this technology allows for wireless gateway connectivity with common automation systems [71].

5.2.5. Wavenis

Developed by Coronis Systems is a wireless protocol stack for control and monitoring applications in several environments, involving both home and building automation. Wavenis is presently being endorsed and managed by the Wavenis Open Standard Alliance (Wavenis-OSA). It delineates the functionality of physical, link, and network layers. The access to Wavenis services can be made from superior layers through an application programming interface (API). Wavenis runs mostly in the 433 MHz, 868 MHz, and 915 MHz bands and some devices also operate in the 2.4 GHz band. The maximum and minimum data rates presented by Wavenis are 100 kb/s and 4.8 kb/s, respectively, but 19.2 kb/s is the most common value.

Wavenis embraces Gaussian frequency-shift keying (GFSK) modulation combined with fast frequency hopping spread spectrum (FHSS) which is utilized over 50 kHz bandwidth channels [49]. It delimits the operations at the PHY, data link and Network (NWK) layers, carried through proprietary APIs [72].

5.2.6. Wireless M-BUS

As continuation of the Metering Bus (M-Bus) standard for cable applications, the Wireless M-Bus (WM-Bus) has been developed, to properly operate with WSN scenarios, as partially done in some home automation context [73]. The absence of modularity is one of the main reasons why standardized routing protocols are not available for Wireless M-Bus at the present.

The M-Bus benefits asymmetric network topologies with data collectors or gateways with higher performance on the one side and low-cost or low-power metering devices on the other side.

Presently, it only supports star network topologies or point-to-point but it does not for mesh or multi-hop topologies those are not yet possible [65]. The Wireless M-Bus (EN 13757-4:2005 and EN 13757-4:2011) has been lately recommended by the Open Metering System group 4 for metering scenarios and proposed for use in smart meters. The energy needs for WM-Bus transceivers are low due to a low-overhead protocol, transmission-only modes and long-range sub-GHz broadcast bands. Whereas the first document EN 13757-4:2005 approved the use of the 468MHz ISM and 868 MHz bands, the following standard version EN 13757-4:2011 added new extra communication modes at 169 MHz with reduced data rates [74]. The lower 169 MHz frequency band allows higher transmission range thanks to the intrinsically lower path losses. In the meantime, lower data rates increase the receiver sensitivity, allowing a decrease of the transmission power at the transmitter or a longer transmission range for an identical transmission power. The established WM-Bus modes are classified as following:

- T form: 100 kb/s data rate from meter to gateway, frequent transmission mode (several times per second or per minute), 868 MHz. In T2 mode, the transmitter requires an acknowledgement (ACK) while T1 does not.
- S form: 32.7 kb/s, stationary mode (several transmissions per day), 868 MHz. In S2 mode, the transmitter requires an ACK while S1 does not.

In both of the communication modes, the meter initiates the transmission to the concentrator, which in turn is always in reception mode. Once the transmission of the first packet is done, the sub-meter activates a reception window, waiting for the concentrator request or command. The transmission session cannot be activated by the concentrator for the reason that the meters mostly remain in sleep mode in order to save the life of the battery, corresponding with what generally happens in low rate communication systems [75].

The WM-Bus protocol defines several specifications for the N mode, as follows:

- Nc form: 2.4 kb/s, 169.431 MHz. N2c needs ACK, N1c does not.
- Na form: 4.8 kb/s, 169.40 MHz. N2a needs ACK, N1a does not.
- Ng form: 38.4 kb/s, 169.437 MHz. Ng always requires ACK.

The WM-Bus can reach longer distance transmissions when compared to IEEE 802.15.4. Sensor nodes equipped with ZigBee/802.15.4 transceivers can only cover a few dozens of meters. If greater distances are required to be covered employing ZigBee/802.15.4 technology, then a multi-hop data transfer strategy can be expected which, in exchange, raises the power requirements for the sensor nodes. WM-Bus not only allows long ranges, but it also offers a relaying method to cover longer distances with multi-hop techniques as defined in EN 13757-5 [73].

5.3. Wireless Networks Suitability to Functional Area Requirements

Smart home distributed applications have their own requisites in terms of bandwidth, auxiliary services such as secure data transmission, data authentication, and so on. A first criterion to consider is to trace data rate requirements as a function of the application as depicted in Figure 3. In addition, bandwidth needs between a minimum and a maximum can be consulted in Table 3.

Table 3. Data rate specifications according to application area.

Functional Area	Application			Data Rate Requirements		Reference
				Minimum	Maximum	
Energy Management	A	Activation and deactivation of home appliances/HVAC Control/Lighting System		2.4 kb/s	250 kb/s	[53,76–82]
	A	Real time energy consumption				
	A	Smart Meters				
Health	B	Low Bandwidth (<250 kb/s)	Pulse Oximeter/ Blood Pressure	12 b/s	15 Mb/s	[83–85]
	B	Medium Bandwidth (250 kb/s-1 Mb/s)	EMG/ Deep Brain Stimulation			
	B	High Bandwidth >1 Mb/s	Capsule Endoscopy			
Surveillance and Security Systems	C	Simple Alarms/Detections Sensors		200 kb/s	54 Mb/s	[76,86,87]
	C	CCTV Surveillance Camera				
	C	HD Video Surveillance				
Multimedia	D	Stereo Audio		250 kb/s	500 Mb/s	[33,34,88]
	D	Standard Definition TV (SDTV)				
	D	Whole Home distribution of HD Video and Content				

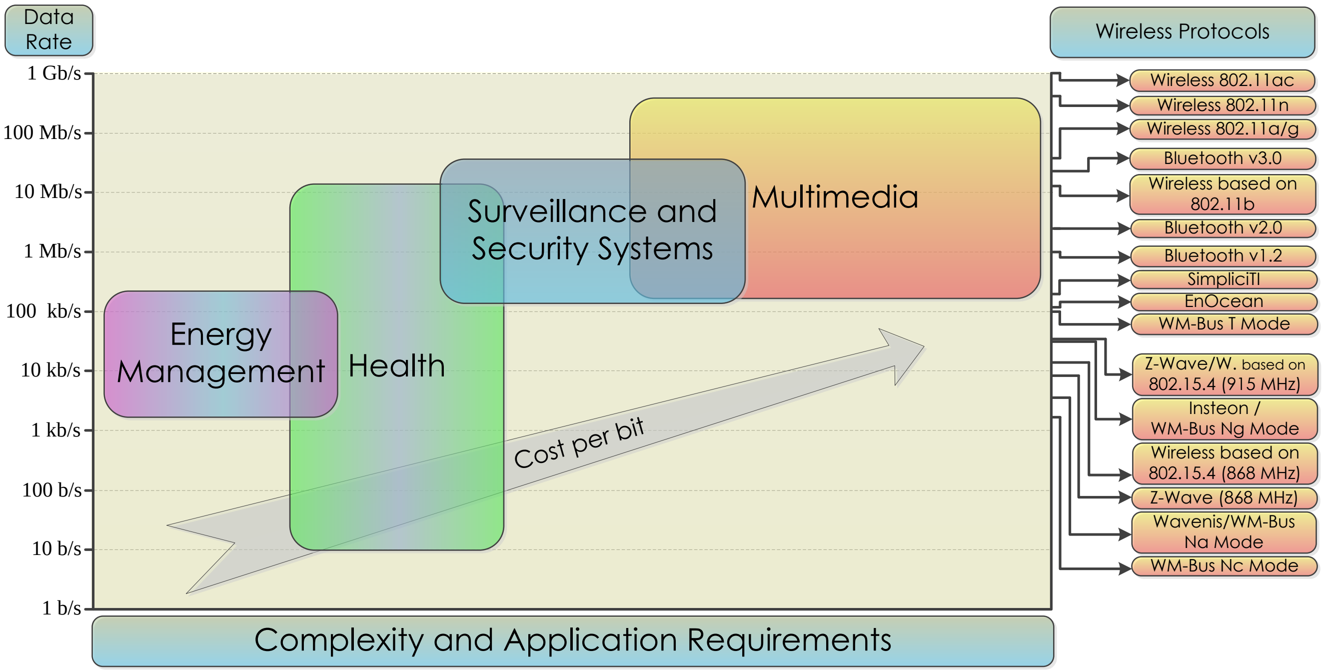

Figure 3. Wireless communication technologies for smart home applications *vs*. data rate.

Home metering data transmission along with energy management services shows the lowest communication bandwidth. Due to its low data requirement, simple low power RF protocol can meet this specification from M-Bus to 802.15.4 based protocols. On the contrary, the number of applications that may be deployed for home health care solutions is, in terms of bandwidth, very wide. In demanding implementations, the data throughput rate can reach 15 Mb/s. Surveillance and Security Systems may require high bandwidth depending on the task to be performed. Intrusion detection and access control are medium intensive data transmission tasks even though events signalization such as alarms activation should be processed by the communication medium with low latency. If the security system includes video capture based surveillance, the number of frames as well the video resolution will have a strong impact on gross bandwidth needs. Among the four Smart Home application areas, the multimedia services demand the highest data rate.

In Table 4, we cross the specific application requirements with the main attributes to characterise a HAN communication infrastructure. In the first hand, the bandwidth necessities are clearly different being this is the first criterion of differentiation between functional areas. On the other hand, it has to be seen if HAN requirements comply with the home application necessities. From the set of analysed functional areas, the healthcare field seems to be the most demanding one, since the integration onto or into the human body of electronic devices for diagnostic, therapeutic, or surgical function have to comply with very restricted technical and biological requirements [84,85]. It is the only functional area that requires high portability medical devices that must be designed with a high-energy optimization concern in a way to maximize the lifetime of power supply (e.g., the battery). Given that the patients need to have a high autonomy, it must be assured that the QoS of transmission cannot be corrupted by electromagnetic interference or by transmission anomalies generated in the patient’s radio. In this case, the network must be prepared in such a way that if the condition of the network deteriorates, it would still be able to safeguard the minimum services of transmission.

Table 4. Functional areas requirements *vs*. home area network (HAN) requirements.

HAN Requirements \ Functional Areas	A	A	A	B	B	B	C	C	C	D	D	D
Bandwidth	L	L	L	L	M	H	L	M	H	M	H	VH
Security	N	I	I	I	I	I	I	I	I	N	N	N
Dependability	N	N	I	I	I	I	N	I	I	N	N	N
Network Operation	N	N	I	I	I	I	N	N	N	N	N	N
Energy Optimization	N	N	N	I	I	I	I	N	N	N	N	N

L -Low; M -Medium; H -High; VH -Very High; N -Not Important; I -Important.

Given that it dealt with sensible information on the patient health status, it was necessary to protect the transmission from data modification, impersonation, eavesdropping and replaying.

Since the majority of multimedia devices are static and transmitted content is not sensible, the security, dependability, network operation and energy optimization are low. When it comes to energy management, the load control has low risk; thus, it is not necessary for the communication infrastructure security to incorporate measures. Consequently, it means that, at this level, the protocol doesn't need to have advanced resources and bandwidth. Likewise, for multimedia services, the majority of home appliances and devices are also static and the transmitted content is not sensible; thus, the dependability, security, network operation and energy optimization are low as well, especially for services such as activation and deactivation of home appliances, HVAC control, illumination systems and real time energy consumption. For people and goods protection, the surveillance and security measures present different performance levels according to their objectives. However, for this functional area, all of the implementations require network security and confidentiality measures since it could mean a security brake with unpredicted consequences. In this context, the sensor networks integrated in the surveillance system have to be designed taking into account the energy optimization of their radio units.

In order to match specific communication requirements with wireless architectures capabilities, a technical and economic trade-off is necessary to minimize the global implementation cost. In this regard, a set of critical features were identified and chosen to qualify wireless standard suitability [1,10–12,31,40,86,87].

Table 5 clearly shows that the different services of a smart home have substantial differences in communication requirements. Therefore, none of the wireless protocols can be an answer to all the requisites.

Table 5. Functional Areas Requirements *vs*. Wireless Protocols.

Wireless Protocols \ Functional Areas	A	A	A	B	B	B	C	C	C	D	D	D
ZigBee Over IEEE 802.15.4	Y	Y	Y	Y	N	N	Y	N	N	N	N	N
MiWi Over IEEE 802.15.4	Y [1]	Y [1]	Y [1]	Y [1]	N	N	Y [1]	N	N	N	N	N
Bluetooth (IEEE 802.15.1)	Y [2]	Y [2]	Y [2]	Y	Y	Y	Y	N	N	Y	Y	N
Z-Wave	Y	N	N	Y [5]	N	N	Y	N	N	N	N	N
Wi-Fi IEEE 802.11	Y [2]	Y [2]	Y [2]	Y [2]	Y [2]	Y [2]	Y [2]	Y [2]	Y [2]	Y	Y	Y [6]
EnOcean	Y	N	N	N	N	N	N	N	N	N	N	N
Insteon	Y	N	N	N	N	N	N	N	N	N	N	N
SimpliciTI	Y	N	N	Y	N	N	N	N	N	N	N	N
Wavenis	Y	Y [4]	Y [4]	Y [4]	N	N	Y	N	N	N	N	N
WM-Bus	Y	Y [4]	Y [4]	Y [4]	N	N	Y	N	N	N	N	N
Isa100.11 Over IEEE 802.15.4	Y	Y [1]	Y [1]	N	N	N	Y	N	N	N	N	N
WirelessHART Over IEEE 802.15.4	Y	Y [1]	Y [1]	N	N	N	Y	N	N	N	N	N

1—Only 2.4 GHz; 2—Minimum requirements over-exceeded; 3—Up to 120 kbps; 4—Up to 100 kbps; 5—Up to 40 kbps; 6—Not Recommended see [88] Y -yes complies N -not complies.

Generally, the analysed protocols can respond to the communication necessities and requirements in home energy management. However, there are exceptions where EnOcean and Insteon do not possess the necessary means to satisfy the requirements of a secure communication. Curiously, Z-Wave does possess requirements of a secure communication but does not have the minimum bandwidth to satisfy the necessities of networks that include smart meters or distributed power measurement units. Given that SimpliciTI is a brand protocol, it is not clear if it activates the security functionalities in radio hardware. From an economic standpoint and since the bandwidth is low, it doesn't make sense to opt for Bluetooth units or Wi-Fi. Besides, IEEE 802.11 is more power-hungry than, for instance, IEEE 802.15.4 in terms of the consumption of energy, that belongs to the low power class of networks.

Contrary to the energy management of the smart home, the healthcare appliances require a far superior bandwidth and are exigent for high security levels of transmission and reception. With the exception of Bluetooth and Wi-Fi, the remaining networks can only satisfy the requirements of low bandwidth application. Insteon and EnOcean do not follow the minimum requirements of network security.

For support services of home surveillance and the introduction of HD video, the bandwidth necessities rise significantly, thus, putting Wi-Fi as the only candidate to fulfil those requirements. Due to the limited range and comparatively lower data rate than Wi-Fi, Bluetooth is not a choice for this functional area.

Finally, the class of applications dedicated to advanced multimedia is by nature very demanding on the data rate without necessarily requiring network security measures. Therefore, Wi-Fi at least for n version could support HD video transmission while the same implementation in Bluetooth can only support video in the conventional format. Although 802.11 n could, in theory, fit for the most exigent multimedia service, a new protocol called Wireless Gigabit Alliance (WiGiG) wireless communications in the 60 GHz band has been developed specifically for this purpose [88].

Despite Isa100.11 and WirelessHART being designed for the industry sector, they were selected merely as a comparison factor, but these networks can also fit for several home automation tasks, alarms, switches, smoke detectors, energy management of appliances such as heater and cooler, oven among others. Insteon and EnOcean have serious limitations in terms of guaranteeing a minimally secure communication; besides, they have a low data rate. The remaining low power data rate networks, when eligible, present similar technical specifications; thus, the selection has to undergo an analysis of development, installation and operational cost. Consequently, it is necessary to study which are the implementation memory, CPU requirements, and the wireless protocol, and analyse the energy profile according to data traffic.

From a market standpoint, several wired and wireless protocols analysed in this study are competing for use in medical applications. Although all of the analysed protocols feature real and tangible benefits such as lower cost, less protocol complexity and overhead, and less traffic to contend with, Wi-Fi is possibly in the better position to capture the wearable medical device market for a number of reasons. The most important reason is that Wi-Fi is widely deployed compared to other protocols. Malls, hotels, restaurants, and other public places are being equipped with free Wi-Fi, which are making them an ideal channel for medical devices that need to communicate directly to the cloud and a medical professional through the public infrastructure.

Nevertheless, the technical limitations resulting from this choice will have to be overcome by strengthening the planning of the network with very careful implementation, which includes adopting extra-level functionalities at the protocol application layer level.

6. Conclusions

Smart Home successful implementation on a large scale may help address some of the major challenges in the twenty first century, such as improving efficiency gains in energy consumption or facilitating the expansion of advanced services for health care in a rapidly aging population worldwide. This paper presented a thorough analysis of wireless protocols for HAN, comparing and discussing their advantages and downsides. In this study, short range wireless architectures have been considered as key for a smart home enabled by wireless HAN. A key element for Smart Home HAN to be a real possibility is to integrate a mixture of wired and wireless networks through an M2M gateway. The analysis has focused on two main families of standards: those built on IEEE PHY/MAC and on solutions that do not comply with IEEE standards. Their adequacy as regards major application area requirements in smart home solutions was investigated. No single wireless protocol analysed appears to satisfy the smart home functional areas' communication requirements on the whole. For energy management in smart homes, most of the low-power and low data protocols are adequate for this kind of function (such as MiWi, ZigBee, Wavenis, among others) with the exception of Insteon and

EnOcean, which do not have enough security services. For medical and surveillance applications, Wi-Fi is better positioned. Finally, UHD multimedia requirements will still be dependent on a wired infrastructure; however, the newer Wi-Fi protocol generations are on the right path to fulfill these requirements.

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Conflicts of Interest

The authors declare no conflict of interest.

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