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Review

A Comprehensive Review of IoT Networking Technologies for Smart Home Automation Applications

Vasilios A. Orfanos, Stavros D. Kaminaris, Panagiotis Papageorgas, Dimitrios Piromalis and Dionisis Kandris *

Department of Electrical and Electronic Engineering, University of West Attica, Thivon Avenue 250, GR-12244 Athens, Greece
* Correspondence: dkandris@uniwa.gr

Abstract: The expediential increase in Internet communication technologies leads to its expansion to interests beyond computer networks. MEMS (Micro Electro Mechanical Systems) can now be smaller with higher performance, leading to tiny sensors and actuators with enhanced capabilities. WSN (Wireless Sensor Networks) and IoT (Internet of Things) have become a way for devices to communicate, share their data, and control them remotely. Machine-to-Machine (M2M) scenarios can be easily implemented as the cost of the components needed in that network is now affordable. Some of these solutions seem to be more affordable but lack important features, while other ones provide them but at a higher cost. Furthermore, there are ones that can cover great distances and surpass the limits of a Smart Home, while others are more specialized for operation in small areas. As there is a variety of choices available, a more consolidated view of their characteristics is needed to figure out the pros and cons of each of these technologies. As there are a great number of technologies examined in this paper, they are presented regarding their connectivity: Wired, Wireless, and Dual mode (Wired and Wireless). Their oddities are examined with metrics based on user interaction, technical characteristics, data integrity, and cost factor. In the last part of this article, a comparison of these technologies is presented as an effort to assist home automation users, administrators, or installers in making the right choice among them.

Keywords: Wireless Sensor Networks (WSN); Internet of Things (IoT); home automation; smart home; LPWAN; home networks; networking technologies

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1. Introduction

The continuous advances performed regarding Integrated Circuits (ICs) technology enabled the introduction of Micro Electro Mechanical Systems (MEMS) [1]. MEMS include microsensors, microactuators, micro-electronics, and other microstructures within tiny dimensions (Figure 1).

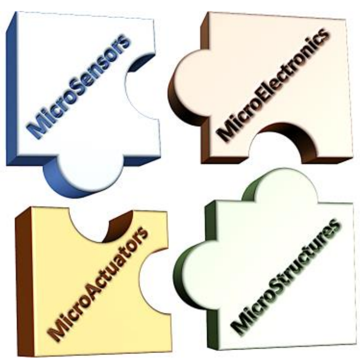

Figure 1. Graphical representation of the typical architecture of an MEMS.

The next goal was to wirelessly interconnect sensing MEMS. In this way, WSNs (Wireless Sensor Networks) were introduced [2]. WSNs consist of MEMS-based devices, called sensing nodes that, despite their small size, have enhanced capabilities. Specifically, sensing nodes cannot only monitor ambient conditions in wide areas of interest but also process and transmit sensed data [3]. This makes WSNs ideal for supporting a practically endless range of applications [4–10], although their operation is obstructed mainly due to their limited energy sustainability [11–13], but also because of other problems such as congestion, vulnerable security, connectivity loss, insufficient coverage, and deteriorated Quality of Service (QoS) [14–20].

The interconnection of the sensing nodes through Internet technologies led to the birth of IoT [21–23]. With IoT technology, all Things (devices) can be managed and configured remotely, such as Cyber-Physical Systems (CPS) that interconnect the physical and cyber worlds with telecommunications.

The application of IoT in Home Automation (H.A.) systems led to the development of the so-called Smart Home sector [24–26]. In Smart Homes, systems controlled manually, such as heating, cooling, lighting, and other appliances, can be monitored and controlled remotely. A cyber-physical system, as depicted in Figure 2, takes measurements concerning temperature, humidity, and energy consumption, which can be displayed to a remote user, giving them the capability to initiate actions through appropriate actuators and modify them to a desirable level in a closed-loop feedback control scheme where communications are vital [27]. The most common example, regarding home comfort, is for a user to control their HVAC (Heating, Ventilation, and Air Conditioning) through a smartphone, tablet, or PC. The home temperature can be adjusted from a remote location to the appropriate one for its residents.

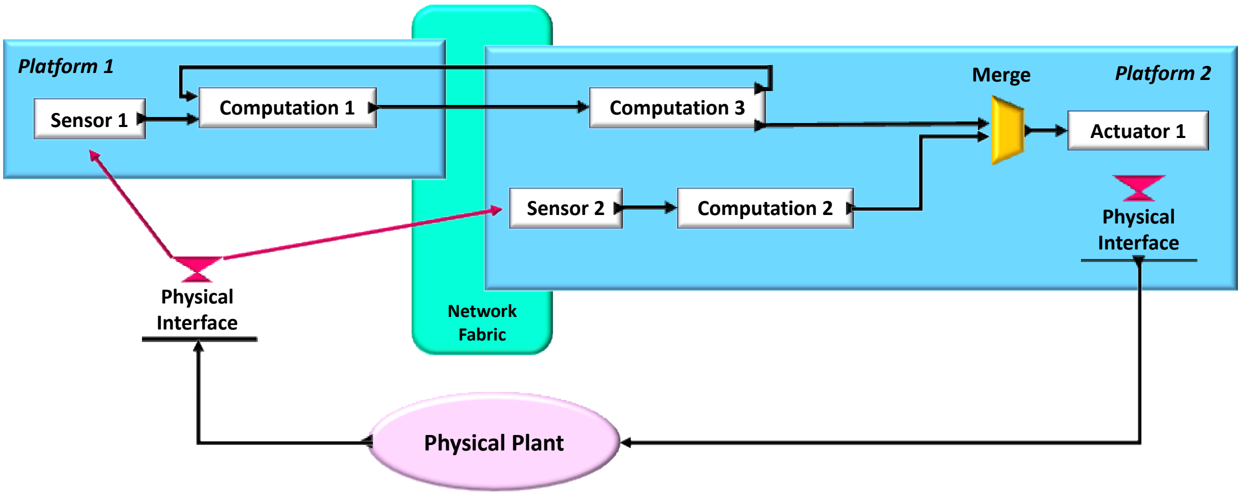

Figure 2. Cyber-physical system example structure.

As the growth of IoT began, many companies developed sensors, actuators, and control systems that are IoT compatible [28]. The need for interconnecting them with sensors realized by other vendors has led to the development and growth of many standard communication technologies. BACnet [29], Dupline [30], Ethernet, and KNX [31] were the first to be used that focus on Home Automation and the establishment of the so-called Smart Home domain. Later on, new technologies, i.e., Bluetooth [32], Wi-Fi [33], Zigbee [34], and Z-Wave [35], were introduced. There are also ones used to offer more capabilities and innovative features, such as 6LowPAN [36], EnOcean [37], Insteon [38], mioty, and Thread [39]. Technologies such as LoRA, mioty, Sigfox, LTE (5G), and NB-IoT are also used but aim to cover larger distances. In the past years, an effort was made by large companies, e.g., Apple (HomeKit) [40], Google (Alexa), and Samsung (SmartThings) [41], with the introduction of consumer products targeting smart homes and unifying them with one application regardless of the short-range communication technology used (BLE, Wi-Fi, ZigBee).

The plethora of choices available for consumers confuses the optimal selection according to the target application. There is a plethora of articles dealing with this issue [42]. This review article aims to present a thorough comparative study among existing technologies of this kind. Specifically, in what follows, in the first section of this article, IoT-enabled communication technologies suitable for Sensor Networks as well as for Smart Home applications are presented. In Section 3, these technologies are comparatively examined in regard to appropriate metrics and criteria. These criteria are divided into four major categories: user perspective, technical characteristics, security/quality, and energy/cost. The first one represents the popularity of these technologies, the platforms that are used, their primary markets, and whether they are open-sourced or proprietary. The second category issues the technical characteristics of these technologies, such as their coverage-supported data rates and the maximum number of concurrent connections. In the next one, the data integrity of the data exchanged, as well as the security mechanisms provided, are examined. The last category is dedicated to the energy factor, which includes consumption, efficiency, and overall cost [43,44]. In Section 4, concluding remarks are drawn. At the end of this article, readers will be able to have a better understanding of the technologies presented, and the conclusion will be clear.

2. IoT-Based Technologies for Smart Home Automation

IoT-based technologies for home automation are now available for every home. There are ones that can be applied using the existing wired infrastructure (powerline cables or Ethernet), connecting sensors, controllers, and other devices, while others are using wireless technologies. In what follows in this section, the most widely used technologies of this kind are presented in three major categories: wired, wireless, and dual-mode (i.e., both wired and wireless).

2.1. Wired Communication Technologies

Wired technologies are the eldest ones, as the first smart home implementations were based on the existing home infrastructure (Power Lines). They provide more secure communications with limited interference.

2.1.1. BACnet

This technology is well-known and used in the US. As presented in "Smart Home Automation in the IoT Era: A Communication Technologies Review" [45], it is a specification based on three major characteristics. It can provide connectivity with the use of various wired communication technologies and is wireless with the collaboration of EnOcean technology [43,44,46–49].

2.1.2. Dupline

Dupline is a wired home automation technology mostly known in the EU. It uses powerlines or twisted pairs for exchanging information. The maximum number of devices that can be connected in this system is 128, whilst its packet size is very small (14 Bytes), achieving data rates up to 9.6 Kbps [30,45,50,51].

2.1.3. Ethernet

Ethernet is one of the most well-known technologies introduced by Bob Metcalfe and his team [52], who allied. It is known for interconnecting network devices such as computers and PLCs through its RS586 port. It is a proprietary technology, standardized with backward compatibility. It uses twisted pair or fiber optics as a data exchange medium while achieving very high data rates [45,53–59].

2.2. Dual-Mode Communication Technologies

These technologies take advantage of both wired and wireless technologies in home automation through communication redundancy and provide high availability.

2.2.1. KNX

KNX (aka KONNEX) is a very popular worldwide open standard technology. It supports powerline and ethernet cabling for wired communications and provides wireless connectivity as well. Furthermore, it can collaborate with other known wireless technologies such as EnOcean, WiFi, and Zigbee. According to the medium used, it can provide data rates from 9.6 Kbps up to 100 Gbps with a packet size of 16 Bytes [31,45,53,60–63].

2.2.2. LonWorks

This technology was presented by the Echelon Corporation Company in 1991. It first originated as BACnet's competitor; therefore, compatibility is provided between them. LonWork is an abbreviation of "Local Operating NetWORK". Its' innovation is that each device has an embedded Neuron Chip, along with transceivers and electronics for application. In detail, it has an SoC (System on a chip) implementation containing many microprocessors, ROM (Read Only Memory), RAM (Read Access Memory) modules, and I/O (Input/Output) interface ports. Moreover, an electronic module is provided for physical interface connections with other devices.

It is a multi-medium technology, as it can provide connections through:

- Twisted pair;
- Ethernet;
- Fiber Optics;
- RF;
- BACnet.

The message size is 228 Bytes, while the data rates provided can reach up to 1.25 Mbps. Regarding coverage, it can reach distances up to 2700 m in wired connections.

Devices or systems can be separated into smaller groups of intelligent elements, called nodes, creating a smart network [64–66].

2.2.3. X10

It is one of the oldest home automation systems, as it was introduced in 1975. This technology is open-sourced and used for remotely controlling X-10's compliance transmitters and receivers. It has two modes for connections:

- Wired: powerlines already pre-installed in every home;
- Wireless: RF.

Short messages (commands) are used and broadcasted by transmitters to the receiving unit and processed by a unique ID. Receivers read this information and compare it with the receiving ID to determine if it matches their own. If the condition is met, then the whole message is downloaded and processed.

Due to the nature of this technology, data rates of 60 bps are provided, covering distances up to 30 m. Therefore, it is mostly used in automation networks such as lightning, home appliance, and security sensors [43,67].

2.2.4. Insteon

This technology is X10's successor; it provides backward compatibility with all existing devices supporting the technology (operating in 132 KHz) despite the commands not being similar. Its network consists of both wired and wireless connections providing MESH connections between them and ensuring connection redundancy [38,43,44,64,66].

2.3. Wireless Communication Technologies

These technologies are introduced to solve the need for interfacing with the existing home infrastructure and to provide a low-cost, high-efficiency solution for device communication. They can be divided into two major categories, according to the distance they cover.

2.3.1. Short Range

Short-range technologies can be used primarily on small buildings and homes, providing high-speed and high-availability connections between devices.

6LowPAN

IPv6 over low-power wireless personal area networks is used for home automation systems and is characterized by its simplicity and low cost. It provides wireless connectivity where serious power constraints are needed. It makes use of IEEE 802.15.4 standard in the lowest OSI-7 layers [53] and IPv6 (IP version six) protocol for communications.

This technology is characterized as WPAN (Wireless Personal Area Network), exchanging data packets of 100 bit, while achieving data rates up to 250 Kbps and covering distances up to 200 m. It also provides mesh capabilities, but with a device making multiple wireless concurrent connections with more than one neighboring device. If its primary connectivity is lost, communication can still be established through another connection in the same network.

6LowPAN has compatibility with devices using the same standard (802.15.4) and can also communicate to a computer network through Wi-Fi using a gateway [36,68–73].

Bluetooth

Bluetooth is a very popular short-range networking technology mostly used in computers, smartphones, and peripheral interconnections. In 2015, the Bluetooth 4.0 standard was introduced [74]. Described as BLE (Bluetooth Low Energy), it has unlocked its potential to ensure proper communications to the devices in the network whilst improving battery life and data rates [32,69,74–84].

EnOcean

This technology is a wide-spreading technology, as it provides energy harvesting capabilities in wireless IoT and in-home automation. Every device in this WPAN (Wireless Personal Area Network) does not require any external energy source or battery [45].

The characteristics of this technology are:

- It can cover distances up to 300 m (outdoors);
- Network speeds up to 125 Kbps;
- 50 μW is required for signal transmission;
- Low band radio, which operates at 868 MHz and 315 MHz radio bands;
- Short telegrams (messages of 4 Bytes) are exchanged between devices;
- It can have heterogeneous connections with other technologies, such as:
    - Ethernet gateway;
    - Wi-Fi gateway;
    - BACnet;
    - LonWorks;
    - BLE;
    - Zigbee.

Furthermore, mesh connectivity is supported while providing quality mechanisms QoS (8-bit CRC) and encryption with the use of VAES (Variable AES) [37,44,47,60,77,78,85–89].

Thread

Thread is a technology that is also based on the 802.15.4 standard, originated by seven companies (ARM (Softbank), Big Ass Fans, Freescale (NXP), Nest Labs (Google), Samsung, Silicon Labs, Yale Locks), which formed the Thread Group Inc. in 2015 [45,90]. It is an open standard technology incorporating many known standards. Therefore, it provides compatibility with other ones like the Nest thermostat and several Zigbee devices [39,75,78,86,90–97].

Wi-Fi

This network technology is very popular, as it is known for the interconnection of various everyday devices. The 802.11ac standard (released in 2013) operates at the frequency bands of 2.4 GHz and 5 GHz, achieving data rates from 600 Mbps to 6.93 Gbps. With the introduction of 802.11ax in 2016 (Wi-Fi 6) and the use of M.I.M.O. (Multiple Input, Multiple Output) techniques, the technology can handle multiple connected devices, while providing data rates of 866.6 Mbps, 15 Gbps, 3466 Gbps of up to 9.6 Gbps. The protocol suite used for communications is the TCP/IP (v.4 and v.6), providing mechanisms for QoS (Quality of Service) with 32-bit CRC and security with encryption of AES128.

As a well-known and used technology for end-user devices, connections with almost all known home automation technologies are provided by vendors.

In 2014, the standard 802.11af of Wi-Fi enhanced its capabilities by improving energy management and efficiency. With the use of the existing WLAN topology, TV White Space frequencies (54 MHz–97 MHz band), and four channels for communications, the area covered remains 100 m, while the data rates can reach or surpass 400 Mbps.

802.11ah (WiFi HaLow) standard, newly introduced by IEEE and released in 2017, is an evolution of the 203.11af and is aimed at IoT devices. It provides many power-constrained stations, up to 100 m of area coverage, using frequencies of 900 MHz and network speeds of 4 Mbps. This technology also supports channels of 1 MHz/2 MHz for use in IoT, which can be increased up to 16 MHz to achieve greater data rates [33,56,75,98–100].

Z-Wave

Z-Wave is a proprietary technology used by many vendors for home automation and IoT. It is characterized as low-cost, providing low-power transmissions. As described in Paetz (2013) [101], this technology has static routing and is implemented with a centralized routing table. Routing calculations are embedded into the messages so their forwarding behavior can be indicated (Fuller) [102].

OpenZwave is a variation of Z-Wave, which is open-source [103]. It is used in PCs as a USB transceiver dongle, but still, its routing logic is not accessible. It is encrypted in the firmware of the device [35,44,75,78,81,86,96,102,104–106].

Zigbee

This technology is quite popular in wireless home automation systems and is one of the base competitors of Z-Wave. Due to the delay in the definition of the Bluetooth standard, several companies started the development of a new WPAN technology, named ZigBee, introduced in 2004 [44,61,75,77–80,86,88,94,98,105,107–111].

2.3.2. Long Range

Long-range connections are mostly used for connections in larger buildings or architecture, providing availability without the use of repeaters.

DASH7

Industry-standard DASH7 Alliance Protocol (D7AP) is a standard based on the ISO/IEC 18000-7 and applied in wireless sensors and actuators. As its primary function design, it is based on the BLAST (Bursty, Light Data, Asynchronous Transitive) concept [80]. It operates on unlicensed low wireless frequencies 433 MHz, 868 MHz (EU), and 916 MHz

(US), making the technology capable of reaching distances of 10 Km. Its message length is 256 Byte and provides data rates up to 200 Kbps achieving low latency when connected with moving network-capable objects [80]. Communication is done instantly (bursty) without containing any heavy data, such as audio or video [112], making it capable of light data payloads used in conventional applications.

Due to its command–response communication method, DASH7 provides asynchronous communication. This is achieved as it requires a periodic "hand-shake" for its network and its' upload-centric nature in addition to the download-centric other technologies that follow [68,80,99,112–121].

LoRa (Long Range)

LoRa (Long Range), as the acronym displays, was first introduced in 2015 by Cycleo [122] and promoted to consumers by Semtech [123], is an open standard, used mostly for wireless systems separated by great distances with the use of unlicensed RF bands.

It is described as LPWAN (Low Power Wide Area Network) or WWAN (Wireless Wide Area Network) and is used for long-range data transmissions, more than 10 km (up to 20 km), while consuming very low energy. This is achieved due to the low frequencies used, its' message protocol (LoRaWAN) of 255 Bytes, and the low data rates supported (0.3–50 Kbps). As can be seen, it is suitable for applications exchanging a low set of data for long ranges without having to replace batteries for many years (more than 10 years) [124]. Mainly, it is used in agriculture, but there are also applications developed for H.A.

This technology provides a connection to existing computing networks, such as ethernet and Wi-Fi, through its gateway, providing an administration mechanism. Despite its low data nature, LoRa offers data encryption (AES) but no QoS mechanism [70,81,98,99,108,113,122,125–135].

LTE (5G/NB-IoT)

LTE (Long Term Evolution) is a very popular networking technology, well known for mobile phone communications used worldwide. It was introduced by 3GPP in 2008 and is based on the already existing networks GSM/EDGE and UMTS/HSPA, having as its primary objective faster data rates for mobile networking devices. To achieve that, new techniques of digital signal processing were introduced.

First, 2G was provided to 90% of the world's population, but its' main aim and target was mostly for voice [136]. Therefore, 3G has been introduced, providing more services than voice for a great amount of data. Emerging new technologies such as smartphones and tablets increased the need for higher data rates and led to its evolution in 2012 (4G).

Further, 5G was built on the foundations of its successors, providing even higher data rates of 10 Gbps, reliability (32-bit CRC), and encryption (AES256). For IoT and smart home implementations, special modes of this technology are used, LTE CAT-0, LTE CAT-M, and NB-IoT. These are optimized for IoT and smart buildings, reducing the complexity while covering the same range of the same infrastructure.

With the introduction of 3GPP release 12, a new category for UE (User Equipment) is supported. This evolution in Cat 0 (Category 0) devices resulted in a significant increase in their battery life. The most notable changes are:

- The throughput for Uplink and Downlink is reduced to 1 Mbps;
- The number of antennas is now decreased from 2 to 1;
- The UE receiver bandwidth is reduced to 1.4 MHz, which can allow the reduction of substantial complexity;
- UE can still operate in existing LTE system bandwidths up to 20 MHz;
- A UE with a lower power class allows the integration of a power amplifier in a system provided in a single chip.

Table 1 displays the UE categories from the 3GPP Specification number 36.306.

Table 1. UE Categories of the 3GPP specification number 36.306.

	Rel-8 Cat-4	Rel-8 Cat-1	Rel-12 Cat-0	Rel-13
Downlink peak rate	150 Mbps	10 Mbps	1 Mbps	~200 Kbps
Uplink peak rate	50 Mbps	5 Mbps	1 Mbps	~200 Kbps
Max number of downlink spatial layers	2	1	1	1
Number of UE RF receiver chains	2	2	1	1
Duplex Mode	Full	Full	Half	Half
UE receive bandwidth	20 MHz	20 MHz	20 MHz	1.4 MHz
Maximum UE transmit power	23 dBm	23 dBm	23 dBm	~20 dBm
Modern complexity relative to Cat-1	125%	100%	50%	25%

The 3GPP releases 13 and 14 are widely known as NB-IoT, and it is mostly used for IoT implementations [137]. Huawei Technologies Co. Ltd. was one of the major companies focusing on this technology, providing enhanced, long-range coverage with the support of a substantial number of low-throughput devices [138]. Devices in this network are characterized by enhanced network architecture, low response time, low delay sensitivity, very low cost, and low energy consumption. The main advantage of this technology is the ability, when deployed in authorized frequency bands, to make use again of its core network.

As IoT devices do not require high data rates, the size of the message varies according to the network deployment, and transmission speed can be up to 204.8 Kbps and 234.7 Kbps for upload and download, respectively. Messages are encrypted with the AES256 Standard (Advanced Encryption), providing extra security for the information exchanged. Furthermore, this technology provides great data integrity, as it implements SNOW 3G [139] or ATR-128 CMAC (Cipher-based Message Authentication Code) with 4 Byte MIC (Message Integrity Code) QoS mechanism. Due to its origin, LTE, is supported by many developers creating applications for remote management of systems such as traffic control and home automation [81,99,129,132,134,137,138,140–143].

Mioty

This is a brand-new, open technology created and developed by Fraunhofer Institute in 2016 according to the ETSI telegram splitting ultra-narrow band (TS-UNB) technical specification for low-throughput networks (TS 103 357) and provided to the public through the Canadian company BehrTech. It is a long-range platform (WWAN) covering distances up to 15 km (without obstacles), with data rates of 512 bps. It provides low consumption and long battery life; therefore, it is characterized as LPWAN.The innovation in mioty is the way that messages are transmitted. They are formatted as short telegrams of packets sizing 10–192 Bytes, but they are not sent simultaneously. Using TSMA (Telegram Spread Multiple Access), a random MAC is used, dividing its' message transmission into several shorter packages (fragments). Then, these are distributed randomly on different channels and timeslots. This technique, according to its developers, can tolerate packet loss of up to 50%. In Figure 3, the mioty telegram splitting technique is depicted.

As Mioty is a new technology, there is not so much information available and open-source developments concerning the design of Gateways and wireless nodes, and therefore it is difficult to analyze in-depth the performance of the technology compared with other LPWAN technologies [113,128,134,144,145].

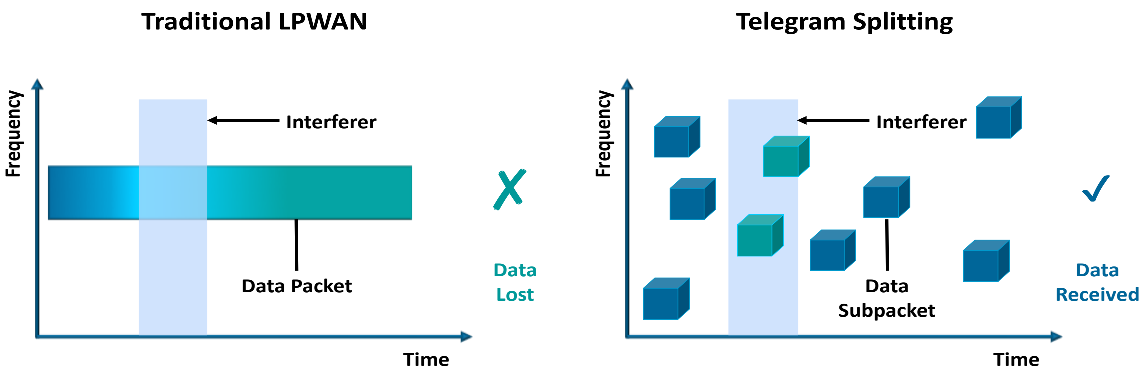

Figure 3. Mioty telegram splitting.

Sigfox

It is a long-range communications technology created and developed in 2010 in Toulouse, France [129]. It is defined by the ETSI ERM TG28 standard and characterized as LTN (Low-Throughput Network).

Sigfox uses the free, unlicensed bands of:

- 868 MHz (Europe);
- 902 MHz (US);
- 430 MHz globally;
- 2.4 GHz globally.

The distances covered are greater than 10 km, achieving data rates up to 100 bps for uploading and 600 bps for downloading. Its' message length is 8–12 Bytes and provides heterogeneity as modules are developed, providing a connection of its gateway to BLE and Wi-Fi. Unfortunately, due to its' slow data rate, QoS is not provided but provides encryption to the packets exchanged.

One characteristic that can be pointed out is a feature called spatial diversity. As its terminal is not attached to a single base station, like most mobile cellular systems, when following the right deployment, a message sent by a terminal can be received by many base stations [70,81,99,129,133,134,146].

3. Technologies' Comparison and Discussion

In this section, a detailed comparison of the technologies studied in this review will be presented.

These will be presented in four separate groups to reduce information overloading. The key groups are wired, wireless (short range), wireless (medium–long range), and dual mode (using both wired and wireless communications). The separation of wireless protocols into short-range and medium–long range is done due to the multiple technologies available.

Wireless technologies can be classified according to the distance they cover (Figure 4). These are:

- Contact, also described as Proximity, is used for communications with distances up to 10 m.
- Short, also known as WPAN (Wireless Personal Area Networks), covers areas from 10 m to 100 m.
- Short/Medium networks are characterized as WLAN (Wireless Local Area Networks) and are used for areas from 100 m to 1000 m.
- Medium (1–10 km), also described as WNAN (Wireless Neighborhood Area Networks), covers areas from 1 km to 10 km.
- Long-range (10–100 km), also known as WWAN (Wireless Wide Area Networks), is used for greater distances of coverage from 10 km to 100 km.

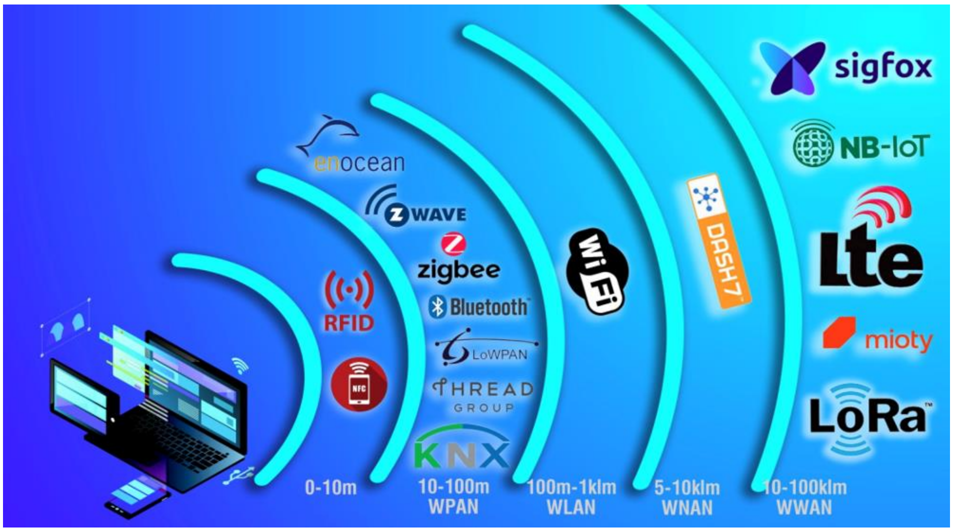

Figure 4. Illustration of existing technologies for wireless networking regarding connectivity range.

Figure 4 illustrates all the technologies according to the distance they can cover. Another classification of these technologies' characteristics is:

- User interaction;
- Technical characteristics;
- Data integrity;
- Energy/Cost.

3.1. User Interaction

According to the information provided in Tables 2–5, technologies, mostly wired, have been provided to consumers for over 20 years. These are BACnet, Bluetooth, Dupline, Ethernet, KNX, LonWorks, Wi-Fi, and X10. Three of them are known for computer and mobile device networking. These are the most popular ones in building automation. In Europe, the most known technologies in the market are Dupline and KNX, while in the US, they are BACnet, X10, and its successor, Insteon. Among the most recent technologies, are Zigbee and Z-Wave the most known ones.

Table 2. Wired home automation technology user interaction.

Home Automation Technologies	BACnet	Dupline	ethernet alliance
Released	1995	2003	1980
Primary Markets	Home Automation	Home Automation	Computer networks, Home automation
Adoption	Medium	Medium	Extremely High
Commercial devices	Medium	Medium	Extremely High
Open source	YES	Proprietary	NO
APIs available	YES	YES	YES
Platforms	Windows/MAC/Linux /IOS/Android	Windows	Windows/MAC/Linux IOS/Android
Connection type	Wired	Wired	Wired
Standard	ASHRAE/ANSI Standard 135, ISO 16484-5:2003	Proprietary	802.3
Multimedia apps	NO	NO	YES

Table 3. WPAN and WLAN home automation technology user interaction.

Home Automation Technologies	6LoWPAN	Bluetooth	enocean	THREAD	WiFi	ZWAVE	zigbee
Released	2007	2002	2008	2014	1997	2001	2004
Primary Markets	H. A.	H. A.	Building Automation	H. A.	H. A.	H. A.	H. A.
Adoption	Medium	Extremely High	Medium	Medium	Extremely High	Widely adopted	Widely adopted
Commercial devices	Medium	Extremely High	Medium	Medium	Extremely High	High	Very High
Open source	YES	YES	Licensed	Licensed, OpenThread	YES	Licensed	YES
APIs available	YES	YES	YES	YES	YES	YES	YES
Platforms	Windows/MAC/ IOS/Android	Windows/MAC/ Linux/IOS/Android	Windows/MAC/ Linux/IOS/Android	Windows/MAC	Windows/MAC/ Linux/IOS/Android	Windows/MAC/ IOS/Android	Windows/MAC/ IOS/Android
Connection type	Wireless	Wireless	Wireless	Wireless	Wireless	Wireless	Wireless
Standard	802.15.4	802.15.1	ISO/IEC 14543-3-1	802.15.4	802.11a/b/g/n/ac/ah	Proprietary	802.15.4
Multimedia apps	NO	YES	NO	NO	YES	NO	NO

Table 4. WNAN and WWAN home automation technology user interaction.

Home Automation Technologies	DASH7	LoRa	Lte 5G	NB-IoT	mioty	sigfox
Released	2011	2015	2012 (5G)	2014	2016	2009
Primary Markets	Sensors H. A.	Building Automation, and Security, Agriculture	Communications, Multimedia	Smart cities, Smart buildings Agriculture Smart metering	Agriculture, Smart metering	Building Automation, and Security, Agriculture
Adoption	Medium	High	Widely adopted	High	Low	Medium
Commercial devices	Medium	Medium	Very High	High	Low	Low
Open source	YES	YES	Proprietary	YES	Proprietary	Proprietary
APIs available	YES	YES	YES	YES	YES	YES
Platforms	Windows/MAC/ Linux	Windows/MAC Linux/IOS/Android	Windows/MAC Linux/IOS/Android	Windows/MAC Linux/IOS/Android	Windows/Linux	Windows/MAC Linux/IOS/Android
Connection type	Wireless	Wireless	Wireless	Wireless	Wireless	Wireless
Standard	ISO/IEC 18000-7	Proprietary	3GPP-R14	3GPP-R13	ETSI TS 103 357	ETSI EN 300 220-1, EN 300 220-2
Multimedia apps	NO	NO	YES	NO	NO	NO

Table 5. Dual-mode home automation technology user interaction.

Home Automation Technologies	KNX	LonWorks	X10	INSTEON
Released	1990	1991	1975	2005
Primary Markets	Home Automation	Home Automation	Home Automation	Home Automation
Adoption	Widely Adopted	High	Low	High
Commercial devices	Very High	High in US	Low	High US
Open source	Proprietary	Proprietary	YES	Proprietary
APIs available	YES	YES	YES	YES
Platforms	Windows/MAC/ Linux/IOS/Android	Widows/MAC/ Linux/IOS/Android	Widows/MAC/ Linux/IOS/Android	Windows/MAC/Linux
Connection type	Wired/Wireless	Wired/Wireless	Wired/Wireless	Wired/Wireless
Standard	ISO/IEC 1454-3	ISO/IEC 14908	Open	Proprietary
Multimedia apps	YES	NO	NO	NO

The demands for wireless communications with better energy efficiency have led to the old ones being improved, as well as the appearance of new ones. Many of them are based on IEEE 802.15.4, as can be seen in Table 3, a standard for low cost and energy with high efficiency. Other technologies use their proprietary solutions.

While there are many solutions regarding home automation in the market, many of them are extending their capabilities by providing support for security systems, remote metering, and medical appliances. Most of them offer an API (Application Programming Interface) to developers for them to include their technology in their products.

Figure 5 is a schematic representation of the technologies' popularity according to the literature findings displayed in the aforementioned tables.

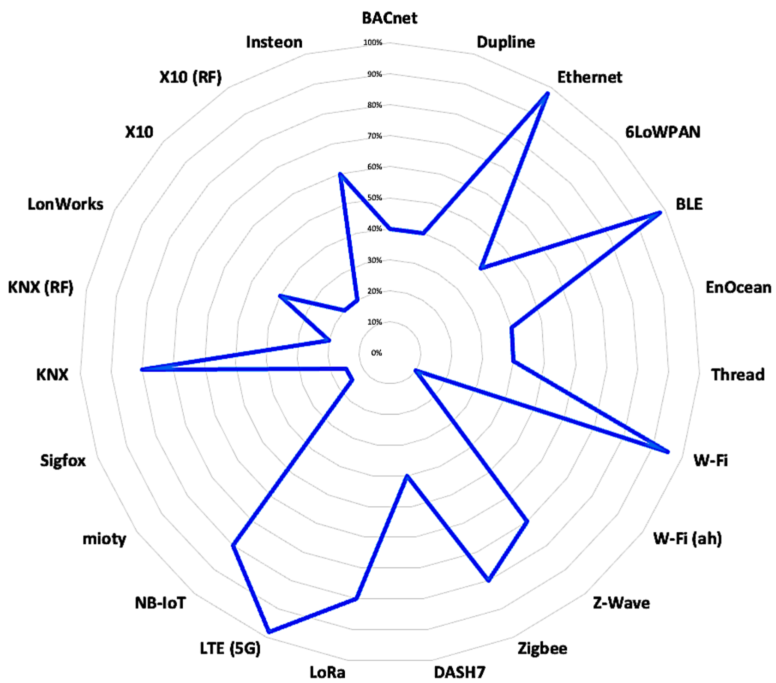

Figure 5. The popularity of home automation technologies.

3.2. Technical Characteristics

Technical characteristics are an important category to examine the technologies' capabilities in more detail. According to "Trends in Home Automation Systems and Protocols" [53], all of them follow the OSI-7 reference model. According to its specification, it has seven layers named from the bottom up: physical, data link, network, transport, session, presentation, and application. These technologies either have the same structure or many of them merge two or more layers into one, described then as OSI-5 of OSI-4. Tables 6–9 display these characteristics.

An important technical characteristic has to do with data rates. While in building automation and IoT, high data rates are not required; since the required data to be exchanged are low, it is considered an advantage for handling future network speed demands. This feature can be seen in technologies where Ethernet or fiber optics media are used. Apart from the Ethernet, which natively uses these mediums, technologies that also use this kind of medium include BACnet (Ethernet medium), KNX (Ethernet medium), and LonWorks (fiber optics). For wireless communications, Wi-Fi, also used for computer networks and multimedia applications, is the fastest one. Other wired and many wireless technologies can provide low data rates, capable of managing the traffic issued by IoT devices. There are also wireless, long-range ones that offer even lower data rates due to the low frequency used for transmission. Figure 6 is a representation of the data rate used in each technology, while Figure 7 illustrates the data rates according to the packet size used in each one.

Table 6. Wired home automation technology technical characteristics.

Home Automation Technologies	BACnet	Dupline	ethernet alliance
Network Size	65,534	128	unlimited
Range (m)	1000	10,000	100–40,000
Connection Medium	T.P, PL	P, PL	T.P, Optical Fiber
Message type	Telegram, TCP/IP, LonTalk	Telegram	TCP/IP
Packet length (Bytes)	Ethernet: 1515, ARCNET: 501 MS/TP: 501 LonTank:228	1.5	1522
Data Rate	Ethernet: 10–1000 Mbps, ARCNET: 0.156–19 Mbps MS/TP: 9.6–78.4 Kbps LonTalk: 4.8–1250 Kbps	9.6 Kbps	~100 Gbps (TP), ~1.6 Tbps (FO)
Gateway	YES	YES	YES
Topology	Star/P2P	Star/P2P	Star/P2P/mesh *
Mesh Enrollment	-	-	YES *
Heterogeneity	Ethernet, LonWorks, EnOcean	Ethernet, LonWorks, LTE	With almost all wired and wireless protocols
SoC Solution	YES	YES	YES
CPU architecture	32-bit	N/A	32-bit–64-bit

* It can be achieved with extra hardware implementation.

Table 7. WPAN and WLAN home automation technologies technical characteristics.

Home Automation-Technologies	6LoWPAN	Bluetooth	enocean	THREAD	WiFi	ZWAVE	zigbee
Network Size	64,000	9	64,000	250	50/8191 (ah)	232	64,000
Range (m)	10–100	100	30 (in)/ 300 (out)	100	100, 2000–4000 (1 Mbps)	30 (in)/ 100 (out)	100–100
Frequency (MHz)	868 (EU), 915 (US), 2400	2400	868	868 (EU), 915 (US), 2400	900 (ah), 2400 5000 6000	868 (EU), 908 (US), 2400	868 (EU), 915 (US) 2400
RF Channels	16 (2.4 GHz), 10 (915 MHz), 1 (868 MHz)	40	1	16 (2.4 GHz), 10 (915 MHz), 1 (868 MHz)	14 (2.4 GHz), 8 (5 GHz), 4 (900 MHz)	2	16 (2.4 GHz), 10 (915 MHz), 1 (868 MHz)
Modulation	BPSK/BPSK, O-QPSK	GFSK	ASK	BPSK/BPSK, O-QPSK	B/QPSK, COFDM, QAM	FSK/GFSK	BPSK/BPSK, O-QPSK
Spreading	DSSS	FHSS	No	DSSS	DSSS, CCK, OFDM	No	DSSS
Message type	MQTT, TCP/IP	Frames, TCP/IP, CoAP	Telegrams	MQTT, D.V.R., TCP/IP	MQTT, TCP/IP	Network identifiers	Frames
Packet length (Bytes)	100	8–47	4	100	2304/100 (ah)	32	100
Data Rate	20/40/250 Kbps	1 Mbps	125 Kbps	20/40/250 Kbps	1 Gbps/1 Mbps (ah)	9.6/40/200 Kbps	20/40/250 Kbps
Gateway	NO	YES	YES	YES	NO	YES	YES
Topology	Star/P2P/mesh	Star/P2P/Mesh	Star/P2P/Mesh	Star/P2P/mesh	Star/P2P/Mesh	Star/P2P/mesh	Star/P2P/mesh
Mesh Enrollment	Procedural	Procedural	Procedural	Procedural	Procedural	Procedural	Procedural
Heterogeneity	Bluetooth, Thread, Wi-Fi, Zigbee	Wi-FI, 6LoWPAN EnOcean Sigfox	BACnet, BLE, Ethernet, KNX, Wi-Fi, Zigbee	Wi-Fi Zigbee	Most technologies	Wi-Fi	EnOcean, Ethernet, Wi-Fi, Thread
SoC Solution	YES	YES	YES	YES	YES	YES	YES
CPU architecture	32 bit–64 bit	32 bit–64 bit	32 bit–64 bit	32 bit–64 bit	32 bit–64 bit	32 bit–64 bit	32 bit–64 bit

Table 8. WNAN and WWAN home automation technologies technical characteristics.

Home Automation Technologies	DASH7	LoRa	Lte 5G	NB-IoT	mioty	sigfox
Network Size	Unlimited	>10,000	50,000–100,000	>50,000	10,000	>10,000
Range (m)	2000	20,000	5000	5000–15,000	5000–15,000	15,000
Frequency (MHz)	433, 868 (EU), 916 (US)	169, 433, 868 (EU), 915 (US)	700–900, 1700–1900, 2000–4000, 24,000–40,000	450–3500	433, 868 (EU), 916 (US)	868 (EU), 902z (US)
RF Channels	8	8 (915 MHz), 10 (868 MHz),	6 (2U + 3D)	6 (2U + 4D)	N/A	360 + 40 reserved
Modulation	FSK/GFSK	CSS	GFSK/BPSK	QPSK/BPSK	GMSK (UNB)	DBPSK (U) GFSK (DL)
Spreading	CSMA/CA	FHSS	OFDMA/SC-FDMA	OFDM, SC-FDMA	TSMA	DSSS
Message type	OpenTag, TCP/IP	LoraWAN	TCP/IP	Frames	Telegrams	Frames
Packet length (Bytes)	256	255	Network Deployment Driven	Network Deployment Driven	10–192	U: 12 D: 8
Data Rate	200 kbps	0.3–50 kbps	1 Mbps (CAT-M), 10 Gbps (CAT-0)	U: 204.8 kbps D: 234.7 kbps	512 kbps	U: 100 bps D: 600 bps
Gateway	YES	YES	YES	YES	YES	YES
Topology	Star/P2P/mesh	Star/mesh *	Star	Star	Star	Star
Mesh Enrollment	Procedural	-	-	-	-	-
Heterogeneity	Wi-Fi	Ethernet, Wi-Fi	NB-IoT, Wi-Fi	LTE	Ethernet	Wi-Fi, BLE
SoC Solution	YES	YES	YES	YES	YES	YES
CPU architecture	32 bit–64 bit	32 bit–64 bit	32 bit–64 bit	32 bit–64 bit	32 bit–64 bit	8-bit

* It can be achieved unofficially [147].

Table 9. Dual-mode home automation technologies technical characteristics.

Home Automation Technologies	KNX	LonWorks	X10	INSTEON
Network Size	32,768	4096	256	Unlimited
Range (m)	350 wired, 100 wireless	2700 wired	30 wired	120 wired 45 wireless
Connection Medium	Twisted pair, Powerline	Twisted pair, Powerline, Fiber optics	Power Line	Powerline
Frequency	868 MHz	120 KHz (PL) 432 MHz	132 KHz (pl) 310 MHz (US), 433.92 (EU)	132 KHz (pl), 869.5 (EU), 915 MHz (US), 921 (AU)
RF Channels	5	1	1	34
Modulation	2-FSK	N/A	NO	FSK
Spreading	OFDMA/SC-FDMA	NO	NO	NO
Message type	Telegrams, TCP/IP	LonTalk, Telegrams	Frames	Frames
Packet length (Bytes)	16	228	4	10–24
Data Rate Wired	9.6 Kbps (pl) 100 Gbps (ethernet)	1.25 Mbps	60 bps	13,165 bps
Data Rate Wireless	38.4 Kbps	N/A	N/A	38.4 Kbps
Gateway	YES	YES	YES	YES
Topology	Star/P2P/mesh *	Star/P2P	Star/P2P	P2P/mesh
Mesh Enrollment	YES *	-	-	Automatic
Heterogeneity	Ethernet, Wi-Fi, Zigbee, EnOcean	BACnet, Ethernet, KNX	No	X10, Ethernet
SoC Solution	YES	YES	YES	YES
CPU architecture	16 bit, 32 bit	8-bit, 16-bi, 48 bit	8-bit	8-bit

* It can be achieved via the collaboration with protocols such as Zigbee or EnOcean.

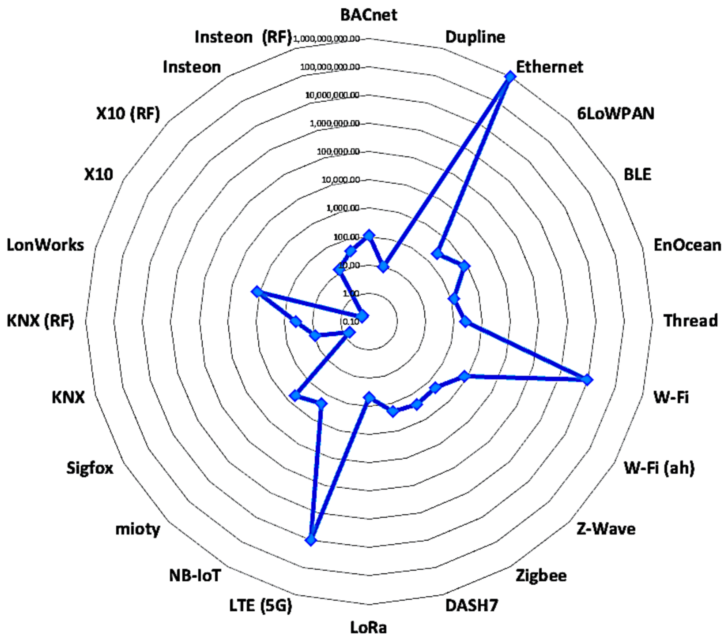

Figure 6. Data rates of home automation technologies (Kbps).

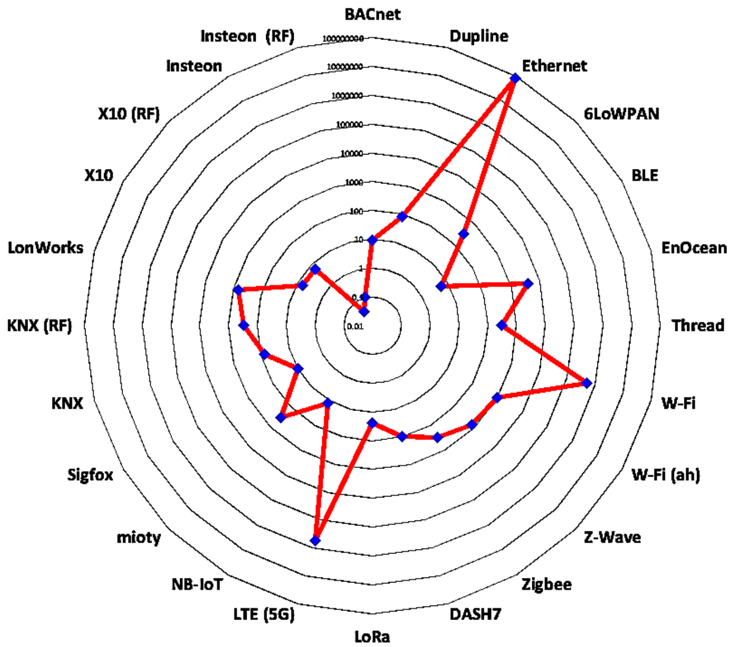

Figure 7. Data rates to packet sizes ratio (minimum to maximum).

Of course, the most devices that can be supported by network technology, the more versatile this technology is. Technologies based on the 802.15.4 standard (apart from Thread) can have a significant number of devices in their network, 64,000. Some, such as Bluetooth, Dupline, Z-Wave, and X10, offer a small number of connected devices, while others are capable of a very high number of devices, such as Ethernet, Insteon, Wi-Fi (v.6), LTE, NB-IoT, DASH7, mioty.

Mesh capability is offered by many networking technologies. It can be provided in two ways, in the first, a device has its data (routing) table with its neighborhood ones in the network it belongs to. If a connection is lost (dropped) to one element of the network, it can still be connected to the WPAN/WLAN using multi-hop mesh networking through their neighbor devices. All of the technologies (6LowPAN, Thread, Zigbee) based on the 802.15.4

standard for the PHY layer offer this feature, as well as BLE, DASH7, EnOcean, and Z-Wave. The second way is for each device to be connected to the same network, both wired and wirelessly. Insteon is the only technology supporting this feature. Mesh, though, can be achieved with the collaboration of wired and wireless technologies. Ethernet technology follows the same OSI model as Wi-Fi and also uses the TCP/IP protocol. Therefore, like a PC or a laptop, an IoT device can have both wired and wireless connections to the same network, and therefore mesh can be achieved. KNX can offer this feature by implementing its wired connection in collaboration with its wireless features or with the use of other technologies such as Zigbee or EnOcean. If one of these connections fails, connectivity to the network is provided by the other medium. A graphical representation of mesh technology in comparison with other known ones is shown in Figure 8 as indicated in [45].

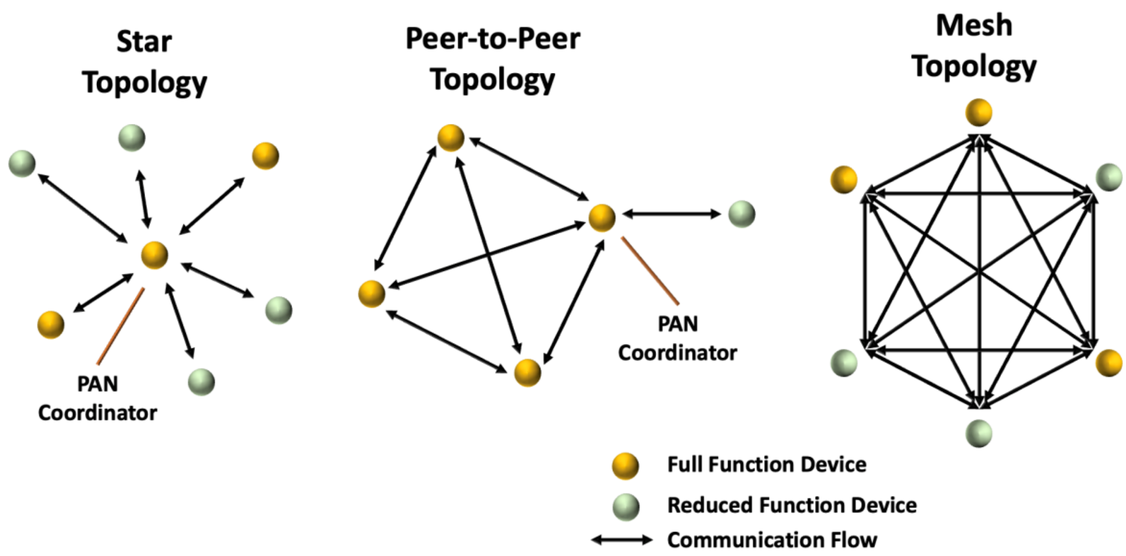

Figure 8. Illustration of various network topology types [45].

Another important feature examined has to do with the communication protocols used for their communications. TCP/IP, also used in computer networks, is supported by most of the technologies presented. This is important for data exchanged from one technology to another. Other technologies exchange a very small amount of data; therefore, small frames or telegrams are used.

In each technology, variations can be seen regarding the distance covered and the data rates they achieve. Low-frequency wireless transmission data can be transmitted over large distances and consume a small amount of energy, but the network speeds are not so fast. These are 802.15.4-based technologies (6LowPAN, Thread, and Zigbee), Dash7, EnOcean, LoRa, NB-IoT, mioty, Sigfox, Wi-Fi (802.11ah), and Z-Wave. Technologies that use higher frequencies can only cover small distances, as the attenuation is significant while consuming significant energy, but in addition, they provide great data rates. In this category, LTE and Wi-Fi (802.11a/b/n/ac/ax) can cover large distances, and the energy used is significant. Bluetooth operates at a high frequency and can cover small distances, but with the introduction of BLE, the amount of energy used is low.

In wired mediums, technologies based on Ethernet can be used in large areas, but they consume a significant amount of energy. Other technologies, such as Dupline, can cover great distances with small energy usage, but with the impact of low data rates.

Heterogeneity and the ability of each technology to co-exist and cooperate with other technologies is a future study in this paper. As can be seen in Figure 9, many technologies, such as Ethernet and Wi-Fi, are provided through the gateways of other technologies to be configured and controlled by a computer or smart device.

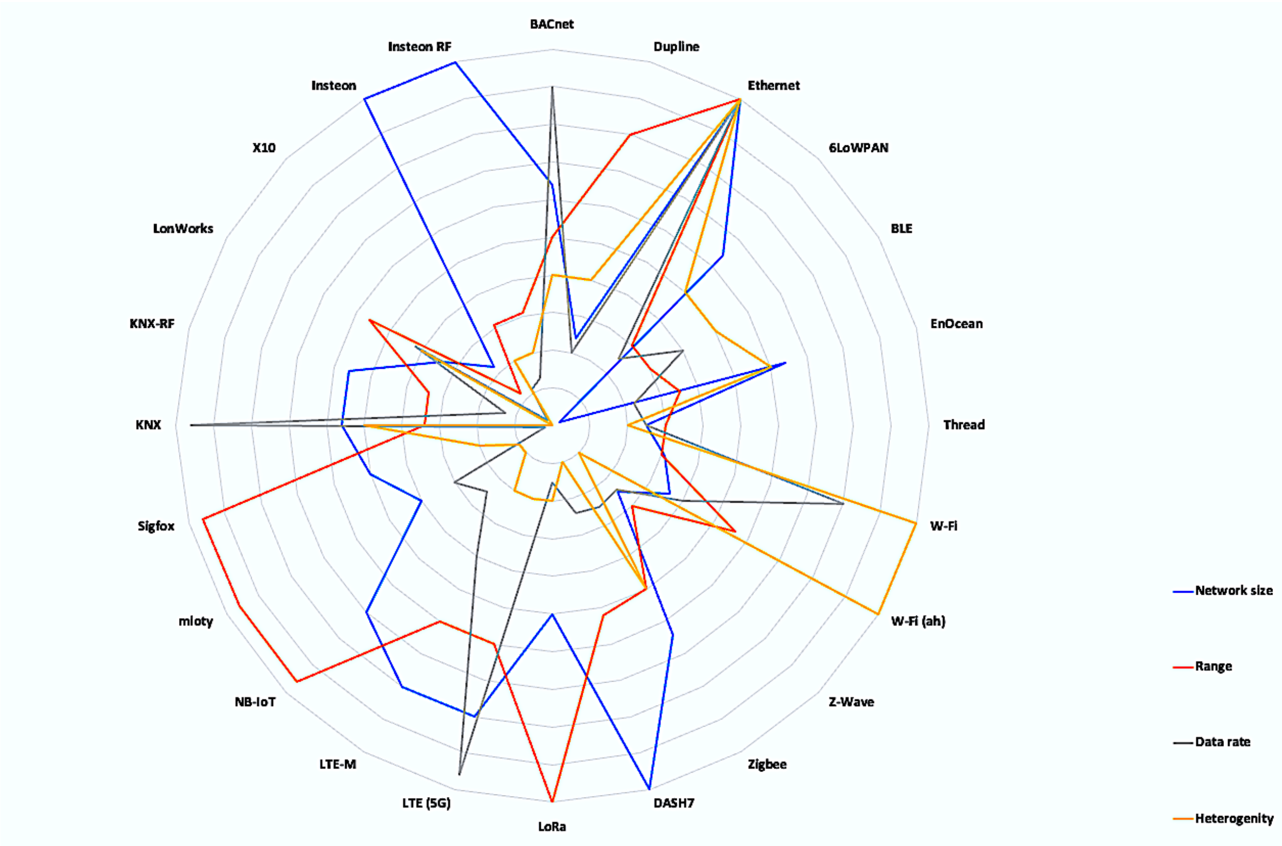

Figure 9. Graphical comparison of existing networking technologies regarding network characteristics (minimum to maximum).

3.3. Security/Quality

Security is a significant factor for each technology, and the assurance of the information exchanged through these technologies is necessary. Either at a basic level or enhanced, a form of security is provided by almost all of the technologies examined. Old technologies, e.g., Dupline and X10, are the only ones in this review that do not provide this feature. For wired mediums, BACnet provides encryption to the transport layer with the use of TLS (Transport Layer Security), which is a 256-bit frame used with the rest of the data payload exchanged to provide encryption. Ethernet technology, according to its' 802.11AE definition, uses MACsec (Medium Access Control Security) and S-ARP (Secure Address Resolution Protocol) for data transfer security [148], applied in the Data link layer. In addition, in the network layer, with the use of TCP/IP protocol, IPSec encryption is provided, as well as TLS. In KNX, EIBsec is provided, making the technology's communications safe. In Tables 10–13, the main security and quality features are displayed.

Table 10. Wired home automation technology security/quality characteristics.

Home Automation Technologies	BACnet	Dupline	ethernet alliance
Encryption	TLS128, TLS256	-	MACsec, S-ARP, IPSec, TLS
QoS (Error handling)	CRC16, CRC32	-	CRC32

Table 11. WPAN and WLAN home automation technology Security/Quality characteristics.

Home Automation Technologies	6LoWPAN	Bluetooth	enocean	THREAD	WiFi	Z-WAVE	zigbee
Encryption	AES128	E0 Stream, AES-128	ARC4, VAES	AES128	RC4 Stream, AES Block (128), WPA, IPSec, TLS	AES-128	AES-128
QoS	16 bit CRC, ACK, CSMA-CA	16 bit CRC	8 bit CRC	16 bit CRC, ACK, CSMA-CA	32 bit CRC	8 bit CRC, ACK, CSMA-CA	16 bit CRC, ACK, CSMA-CA
Interference Avoidance	CSMA-CA [94]	AFH (Adaptive Frequency-hopping) [75]	315 MHz	CSMA-CA	CSMA-CA	CSMA-CA	CSMA-CA

Table 12. WNAN and WWAN home automation technology Security/Quality characteristics.

Home Automation Technologies	DASH7	LoRa	Lte 5G	NB-IoT	mioty	sigfox
Encryption	AES-128	AES CCM 128	AES 256	NSA, AES 256	AES-128	Key Generation, Message Encryption, MAC verification, Sequence
QoS (Error handling)	16 bit CRC	-	32 bit CRC	SNOW 3G/ ATR-128 CMAC with 4 BYTE MIC	TSMA	-
Interference Avoidance	CSMA-CA [149]	Channel hopping, asynchronous nature, and high bandwidth	OFDMA, SC-FDMA	OFDMA, SC-FDMA	TSMA	proprietary frequency hopping and frame repetition pattern

Table 13. Dual-mode home automation technologies Security/Quality characteristics.

Home Automation Technologies	KNX	LonWorks	X10	INSTEON
Encryption	EIBsec, AES CCM128	NO	None	UID/AES 256
QoS (Error handling)	CRC8 CRC32	CRC16	-	CRC16
Interference Avoidance	N/A	N/A	Unique frequency	Unique frequency

Technologies using wireless transmission provide encryption to lower OSI layers and physical and data links. The most common method used is 128-bit size AES used by following the 802.15.4 standard. There are also long-range ones, such as Dash7, LoRa, and mioty, which use the same method. Bluetooth, Insteon, LTE, NB-IoT, and WiFi provide enhanced encryption with 256 bit. EnOcean provides a different method of encryption as it uses VAES (Variable AES) for providing extra security. Sigfox, as a low data rate technology, uses as a security mechanism for Key Generation and MAC verification sequence.

Apart from data security, integrity is an important feature of home automation technologies. Most of them use CRC (Cyclic Redundancy Check) to provide QoS (Quality of Service). This feature is provided by a set of bits, usually at the end of the message, as a verification of the data being transmitted or received. If this information is confirmed by the counted data, then the information has been exchanged successfully. There are variations of the bits used for this feature, KNX (with the use of TCP/IP protocol), EnOcean, and Z-Wave provide 8. Technologies with more data exchanged, such as6LoWPAN, BACnet, Bluetooth, Insteon, Thread, and Zigbee, use 16 bit. There are also ones proving an even larger number of bits (32), e.g., BACnet, Ethernet, KNX, and WiFi. Low-data transmission technologies, e.g., Dupline, LoRa, Sigfox, and X10, do not provide integrity mechanisms.

NB-IoT varies in this category as it uses one of the algorithms (SNOW 3G or ATR-128 CMAC) with 4 Byte MIC. The first one is used by 3GPP to provide confidentiality of data based on UMTS (Universal Mobile Telecommunications Service) mobile networks [138]. It consists of two modules interacting with each other, using 32-bit registers [139]. ATR-128 is a proprietary algorithm performing 128-bit encryption, while CMAC is MAC (Media Access Control) scheme based on block-cipher providing data integrity and authenticity. MIC is a mechanism that ensures, through hash in the messages, that messages have not been altered.

Mioty, with its TSMA technique, provides a QoS mechanism, as it is designed for zero packet loss. If packets are lost, it can tolerate up to 50% of the packets to arrive to decode the information [134]. In Figure 10, the QoS and Encryption characteristics of each technology are presented.

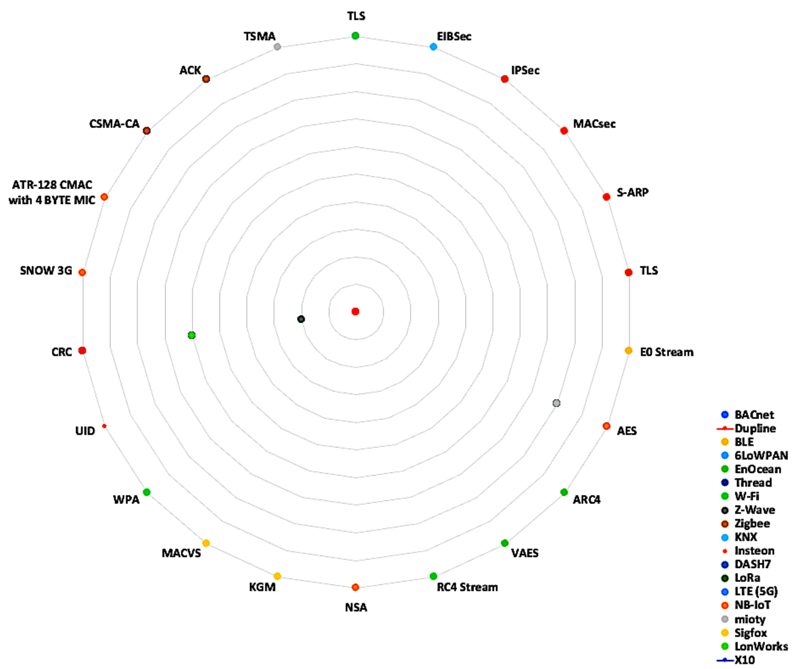

Figure 10. Graphical comparison of existing networking technologies regarding encryption/QoS features, from minimum to maximum in each feature provided.

As depicted in Figure 11, wireless technologies use specific transmission bands. As a result, in a specific frequency, interference can occur, affecting the quality of data exchanged from one technology to a co-existing one. For this phenomenon to be avoided, each technology uses a specific mechanism to ensure data integrity. Most of them (6LoWPAN, Dash7, Thread, WiFi, Z-Wave, Zigbee) use CSMA/CA (Carrier Sense Multiple Access—Collision Avoidance). It is applied in the Data Link OSI layer and performs a specific procedure to ensure the data is transmitted without collisions [97]. Another technique used for interference avoidance is frequency hopping. If the data exchanged use the same band, the transmitted channel (frequency) is changed to the next supported/available one [150].

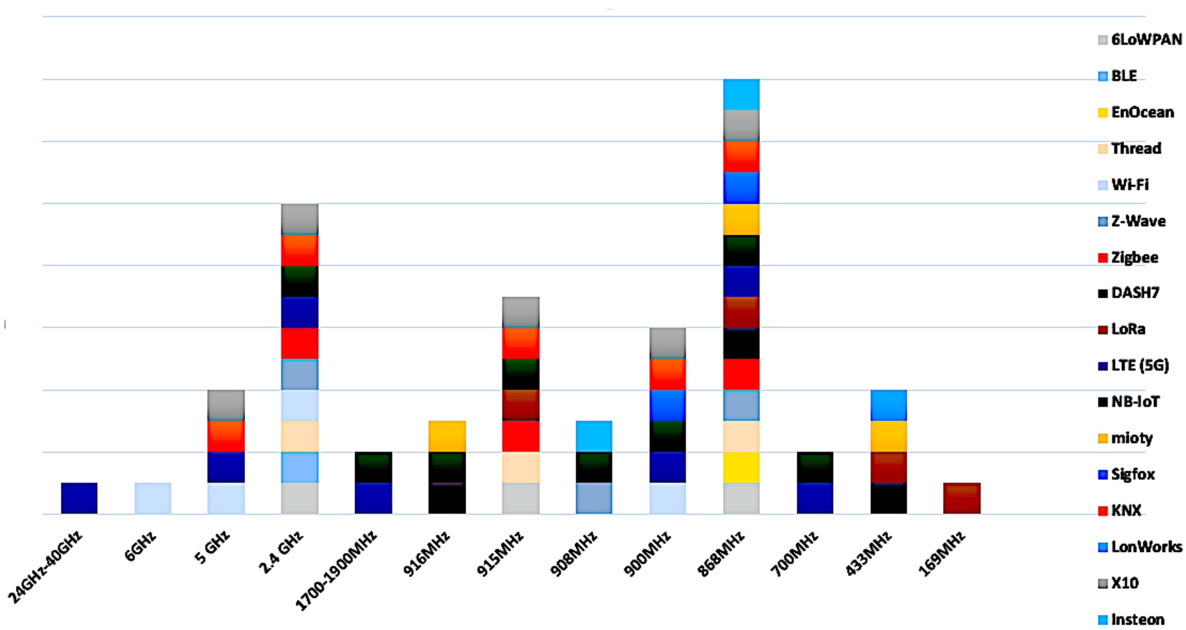

Figure 11. Graphical comparison of networking technologies regarding frequency co-existence.

3.4. Energy/Cost

Energy consumption constitutes one of IoT and home automation's major goals. Every improvement presented for this technology aims for this characteristic. This feature is most needed for wireless-based technologies, where a component can be in an area without a stable power supply; therefore, batteries must be used. Therefore, there is a need for them to consume a small amount of energy for their operation and to have better efficiency (power loss). All wireless technologies provide this feature except Wi-Fi (802.11 a/b/n/ac/ax) and LTE, as they are mainly used for high data rates (multimedia applications), and therefore more energy is needed. Transmission power is very low in technologies that use short-range (0–100 mW) features that vary according to the obstacles in between transceivers causing interference.

Wired medium technologies, as they are constantly connected to a power supply, are not so focused on low energy consumption. As in wireless, apart from the ones used for high data rates, energy consumption is small.

The best technology regarding power consumption and efficiency is EnOcean. As an energy harvesting technology, the power needed for its operation is produced by it; therefore, the overall number is zero. Its' transmission power (TX-power) is still the lowest at about 50 μW. Most of the short-range wireless technologies also have this factor in very low numbers from 0–100 according to the distance and the obstacles blocking their transmission. Two factors have an impact on the power transmitted and increase its value: the frequency used (the greater, the more power is needed) and the distance they cover. Therefore, long-range technologies such as DASH7, Sigfox, LTE, NB-IoT, LoRa, and mioty values greater than 10 mW boost the signal to cover the distance, with the first two being the most efficient while the following two (due to the high data transmission and their design) consume the most (200 mW). In contrast to the TX-power, NB-IoT, LoRa, and mioty provide very low consumption, while Sigfox has high energy consumption, and DASH7 is low. In Tables 14–17, energy and cost features are displayed.

Table 14. Wired home automation technologies energy/cost characteristics.

Home Automation Technologies	BACnet	Dupline	ethernet alliance
Energy consumption	High	High	High
Energy Efficiency	None	Low	None
Cost	High	High	High

Table 15. WPAN and WLAN home automation technology energy/cost characteristics.

Home Automation Technologies	6LoWPAN	Bluetooth	enocean	THREAD	WiFi	Z-WAVE	zigbee
TX-power (mW)	0–100	0–10	0.05	0–100	>1, >10 (ah)	1	0–100
Energy consumption	Low	Low	None	Low	High	High	Medium
Energy Efficiency	High	High	Unlimited	High	Medium	High	High
Cost	Low	Low	Low	Low	Medium	Low	Low

Table 16. WNAN and WWAN home automation technology energy/cost characteristics.

Home Automation Technologies	DASH7	LoRa	Lte 5G	NB-IoT	mioty	sigfox
TX-power (mW)	10 (433 MHz), 501.19 (868/915 MHz)	EU 20, US 100	200	200	EU: 25 US: 40	10–100
Energy consumption	Low	Very Low	Medium	Very Low	Very Low	High
Energy Efficiency	High	High	High	High	High	High
Cost	High	Low	Medium	Low	High	Low

Table 17. Dual-mode home automation technology energy/cost characteristics.

Home Automation Technologies	KNX	LonWorks	X10	INSTEON
TX-power (mW)	25	N/A	N/A	N/A
interference Avoidance	N/A	N/A	Unique frequency	Unique frequency
Energy Efficiency	Low	High	Low	N/A
Cost	High	High	Low	Medium

A very important characteristic examined is cost. Almost all of the technologies based on the 802.15.4 standard are open-sourced; therefore, there is no need to buy licenses or extra fees in developing/operating them, so they can be available to everyone. Z-Wave is a proprietary technology, requiring device certification, which adds extra cost to the total value of a product. EnOcean devices are manufactured by a limited number of contractors, as it is not very popular yet. As a result, their value is a little higher than their competition. Wi-Fi and Bluetooth (in many cases) technologies are available in almost every end-user device in the market and can be used without the extra cost of acquiring an extra device or gateway. As a result, there are many solutions available at very low prices. Technologies using BLE standard to better manage their connected devices, require a gateway, adding a small additional cost. Wired technologies, which need a legitimate medium (hardware), are more expensive than wireless ones, which can be further increased with better quality cabling. As technologies become more popular, there are new solutions of devices introduced that can serve as a gateway (multi-mode gateway) in more than one smart home technology, decreasing the cost of acquiring one for each of them. In Figure 12, a schematic representation of the technology behavior regarding energy and cost is given.

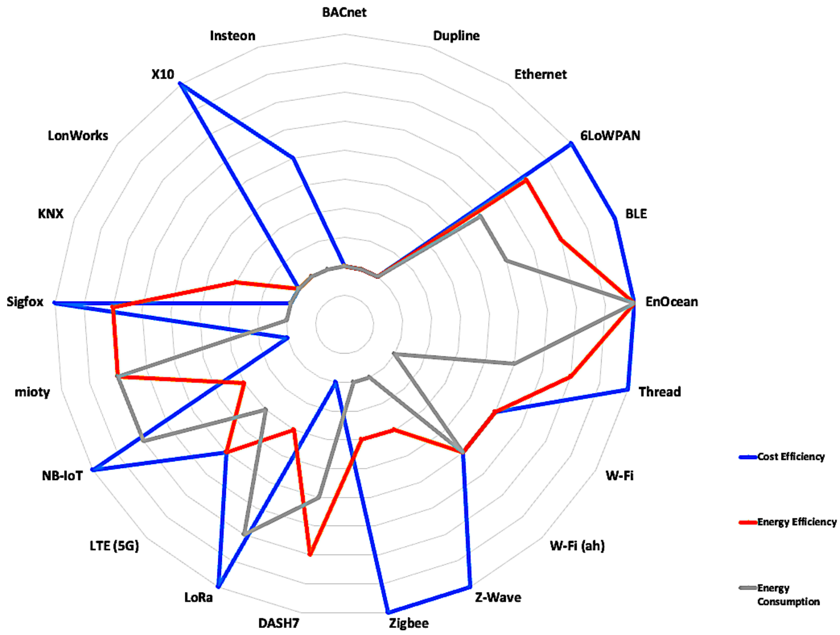

Figure 12. Graphical comparison of existing networking technologies regarding energy/cost, from minimum to maximum gain.

4. Discussion

There are many technologies offering a variety of capabilities in various applications.

This review is focused on covering a more detailed and extensive coverage of the most known and used technologies available in WSN and home automation. This article is based on reviews focusing on statistical usage of home automation or IoT, on a number of technologies, or even some technical characteristics. This article is an attempt to gather most of the information available regarding popularity, technical characteristics, QoS, and even a small approach regarding energy/cost. It is an effort to compare many technologies at once.

The advantages of each technology vary. There are ones that focus on energy consumption, aimed at Green Energy, a term very popular nowadays. Some technologies combine this characteristic and also provide greater coverage. There are others providing higher data rates but with greater energy costs. Mesh propagation is another useful feature provided by technologies, ensuring connectivity, even if one network link is not working.

Security and quality are important factors for intercommunication between devices and ever for the end user. Proper data exchange is provided by most of the technologies covered in this review. There are also very important issues that need to be examined, such as security and more cyber-attacks. There is a lot of research available in this area, but this article does not provide much information as it would be expanding exponentially.

5. Conclusions

This review provides a detailed comparison of all technologies used in IoT-based networking for home automation. It is an effort to support end-users as well as installers and administrators to determine which one of these technologies is the most suitable, according to specific metrics. This survey, according to the knowledge of its authors, is the most complete when compared to other similar reviews. Specifically, various criteria have been taken into consideration, such as popularity (adoption) and technical characteristics such as network size and network speed, quality, and cost. Another factor examined is heterogeneity and the ability of wireless technologies to avoid collisions when using the same frequency as other ones.

The most known technologies in IoT-based networking for home automation were examined from the older ones to the newly introduced ones. Some of them are open-sourced, while others require a license to be purchased. Technologies such as KNX, Ethernet, WiFi, BLE, and Zigbee are quite popular with consumers, while LoRa, EnOcean, and mioty are rapidly increasing their popularity. Most focus on providing low-cost solutions and cover wide ranges providing low data rates. In addition, almost all of them provide a quality mechanism to ensure proper data exchange and security features for end-to-end information transmission. Regarding energy efficiency, technologies such as EnOcean and mioty provide high availability, but if cost is taken into account, LoRa is a more affordable choice. It can provide high efficiency, low budget, and satisfactory data rates.

Whilst there is a variety of solutions provided, and new ones are introduced every year, there is a need for these technologies to have a common interface for ensuring communication among them. This can be achieved with a method or a universal interface for managing each of them. This task is not simple, and an approach needs to be made focusing on the common characteristics these technologies have, such as the medium used (power line, Ethernet, frequency), the OSI layers [53] approach they use, and the protocol for exchanging their data. An approach using the TCP/IP v.6 protocol is a solution to be examined with the use of simulation tools and lab tests.

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