A Case Study of Wireless Communication Technologies Used in Smart Buildings

Mahir Dursun
[1]Electrical and Electronics Engineering
Faculty of Technology
Gazi University Ankara, Türkiye
[2]Azerbaijan University of Architecture and Construction Baku, Azerbaijan
ORCID: 0000-0003-0649-2627

Ahmet Aksöz
Electrical and Electronics Engineering
Faculty of Engineering, Architecture and Design
Kayseri University
Kayseri, Türkiye
ORCID: 0000-0002-2563-1218

Alper Görgün
Vocational Collage
Nevşehir Hacı Bektaş Veli University
Nevşehir, Türkiye
ORCID: 0000-0002-2858-9158

***Abstract*— The increasing world population and rapidly developing technologies are causing the rapid depletion of fossil fuels. This rapid decrease in fossil-based primary energy sources also brings with it environmental problems that are very difficult to reverse. When evaluated as a whole, the decrease in non-renewable reserves in energy sources and the deep feeling of the effects of climate change have made it necessary to take energy efficiency and sustainability into consideration more in the construction sector. Wireless communication technologies can be quickly adapted to almost every area of our daily lives thanks to the mobility, flexibility and accessibility features they provide. Today, smart building technologies stand out with the effective and flexible solutions they offer by using wireless communication infrastructures in both sustainability and energy management areas. Smart building technologies, which reduce carbon emissions by providing maximum adaptation to the environment, are one of the most basic components of sustainable urbanization by optimizing energy consumption. With the wireless communication technologies used in smart buildings, effective control can be achieved by providing a reliable and efficient communication environment between energy production, energy management, energy storage and energy consumption. In this study, the application areas and comparative analyses of wireless communication technologies used in smart buildings were conducted and a case study was conducted on a smart building modeled in the city center.**

Keywords—smart building, wireless sensor network, renewable energy

I. INTRODUCTION

Long-term, permanent and extremely difficult or impossible to reverse processes in the Earth's climate system are called climate change and its global effects. According to the United Nations Framework Convention on Climate Change, climate change is fundamentally caused by uncontrolled and excessive human activities. As a result of human activities, it brings about many negative effects such as increasing global temperature, melting glaciers, rising sea levels, acidification of oceans, increasing frequency and severity of extreme weather events, decreasing biodiversity, increasing diseases, decreasing food supply and water security. In addition to all these, there are serious economic losses caused by the actions taken to slow down, stop or delay the devastating effects of these negative processes. It is assessed that the risks will continue to increase if the current emission rates are not reduced[1].

The causes of climate change are based on both natural processes and human activities. However, the main reason for the rapid change occurring today is human-induced factors. The methods and energy sources that people use to carry out their economic and social activities cause large amounts of greenhouse gas emissions in the atmosphere, strengthening the natural greenhouse effect and triggering global warming. With the increase in industrialization, the use of fossil fuels has increased. The intensive use of fossil fuels such as coal, oil and natural gas in energy production, transportation and industrial processes are the main factors that cause large amounts of carbon dioxide (CO_2) to be released into the atmosphere[2].

The concept of climate change is often confused with the term "global warming". However, there is an important distinction between these two terms. Global warming is a narrower phenomenon that describes the current increase in the average temperature of the Earth. This warming is only one aspect, one cause, of climate change. Greenhouse gases are the carbon dioxide (CO_2), methane (CH_4), and nitrogen oxide (N_2O) gases released into nature from the industrial, transportation, and energy sectors, which trap heat in the atmosphere and increase global warming. The average temperature of the Earth has increased by approximately 1.1°C in the last 150 years. In addition, the rapid increase in fossil fuel consumption, the decrease in forests, and the increase in animal husbandry and agricultural activities increase greenhouse gas emissions and global warming[1, 3].

Today, the rapid increase in urbanization has brought energy efficiency, security and comfort requirements to the forefront. In this context, smart building technologies stand out as integrated systems developed to increase the quality of life of building users, reduce operating costs and ensure environmental sustainability. Reducing the impact of greenhouse gases in order to eliminate the effects of climate change has become a global goal in the world. In the Kyoto Final Declaration signed in 1997, many countries declared that they would increase their energy efficiency and in the Copenhagen Final Declaration signed in 2009, member countries set themselves big goals in this regard. The main theme targeted with these protocols is to halve carbon dioxide emissions, as it is thought that energy needs will double by 2030 as a result of the calculations made [4–6]. Clean electrical energy production and energy efficiency play an important role in the environmental equation regarding climate change [7, 8]. Smart building solutions provided by the electrical, electronics and communication industry with a multidisciplinary approach have the capacity to overcome these challenges.

Communication protocol is a set of globally accepted rules that two or more devices or systems must follow when exchanging data. In other words, the common language that two devices can understand each other is called a communication protocol. These rules determine how data will be sent, how it will be received, how it will be verified, and how errors will be handled. There are different types of protocols used in system communications[9].

Wireless communication is defined as the transfer of data, sound or images from one point to another without using a cable line. In this process, information is transmitted via electromagnetic waves. These waves can operate in different spectrum ranges such as radio frequencies and infrared. Figure 1 shows the transmission of data to the control center via the sensor network.

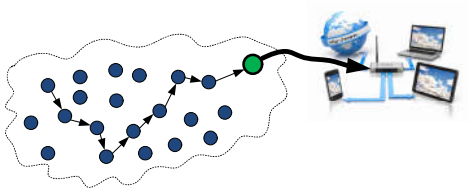

Figure 1 Transmission of data over the sensor network

Modulation and demodulation processes are vital for the efficient transmission of information signals over long distances. Modulation is the process of superimposing low-frequency information signals, such as sound or images, onto a high-frequency carrier signal. This process allows information to be carried over long distances and also prevents different broadcasts from interfering with each other, allowing antenna sizes to remain at practical levels. Modulation is accomplished by changing various properties of the carrier signal, such as amplitude, frequency, or phase, depending on the characteristics of the information signal. The resulting new signal is called a modulated signal, and the circuits that perform this process are called modulators. Types of modulation include analog methods such as Amplitude Modulation (AM), Frequency Modulation (FM), Phase Modulation (PM), and digital pulse modulation types such as Pulse Width Modulation (PWM), Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), Pulse Amplitude Modulation (PAM), Pulse Code Modulation (PCM), and Delta Modulation (DM). Demodulation is the process of separating the information signal from the carrier signal when the modulated signal sent by the transmitter reaches the receiver. The circuits that perform this process are called demodulators. These modulation and demodulation processes form the basis of modern communication systems[10–13].

Since the radio frequency spectrum is a limited resource, various multiple access and multiplexing methods are used to allow multiple users to transmit simultaneously. Frequency Division Multiple Access (FDMA) divides the spectrum into non-overlapping frequency sections; Time Division Multiple Access (TDMA) divides the spectrum into time slots, allowing users to access sequentially. Code Division Multiple Access (CDMA) allows multiple calls to occur simultaneously in the same spectrum block by using a unique spreading code for each call. For two-way transmission, Frequency Division Two-Way Access (FDD) and Time Division Two-Way Access (TDD) methods are available[14].

With the rapid increase in developments in semiconductor technology, there has been a significant increase in the size and processing speed of electronic circuits. In addition, with the increase in bandwidth, there has been a significant decrease in costs. The ability to monitor and manage these applications, which are rapidly spreading in almost every area of daily life, with remote access outside of a fixed center has become possible with the spread and cheapening of communication infrastructures. The active combination of small-sized electronic circuits and communication infrastructures has paved the way for the development of many applications that provide us with great convenience in the daily flow of life and that we use frequently. The necessity of working within the framework of certain rules of communication infrastructures, which are developing every passing day, has led to the diversification of protocols and technologies[15, 16].

Wireless communication technologies have become one of the most fundamental and important building blocks of the modern world today. The fact that wireless communication technologies go beyond traditional wired systems and transfer data, voice and images without using a physical cable line is the most important factor in the spread of these technologies. The air layer in the atmosphere serves as a transmission medium in the wireless communication process. The use of air as a transmission medium for data has led to a radical transformation in the concept of communication. Wireless communication technologies can provide solutions to the problem of "ubiquitous access" and "mobile access" because they eliminate the dependency on a direct connection between the receiver and the transmitter via a physical infrastructure[17].

Wireless communication technologies provide significant advantages over traditional wired systems in terms of ease of application and cost in areas where access is remote and difficult. In addition, wireless communication systems offer freedom of movement to users and devices used in data communication. Thanks to mobile devices that we frequently use in our daily lives such as smartphones, tablets, and laptops, it is possible to perform remote monitoring and control operations flexibly. In a ddition, sensors and sensor networks that read environmental and system data and transfer it to the central control unit can work flexibly over a wireless infrastructure. In addition, when the number of sensors and users of wireless networks is variable, it is much easier to expand, relocate, and develop their infrastructures compared to wired structures. New sensors and users can be easily added to the network without additional cabling and infrastructure changes. In addition, it eliminates the cable mess in the design area and the environment, allowing for more organized and more aesthetic environments. Since wireless communication networks completely eliminate the need for cabling, installation processes are shorter and less costly. If the system design is made in an existing area that has been previously designed or in an environment that requires temporary installation, cabling costs and labor costs will be minimized[17, 18].

In areas with infrastructure deficiencies in cities, wireless solutions play an important role in providing and maintaining communication. With the use and spread of wireless technologies, many innovations such as the internet of things, smart grids, smart cities, smart home systems, etc. have become applicable and have paved the way for many innovations thanks to data transfer between devices and remote control possibilities.

II. Smart Buildings and Wireless Communication Technologies Used In Smart Buildings

A. Smart Buildings

Smart buildings provide centralized and automated management of various systems such as energy, water, security, ventilation and lighting through technologies such as sensors, control systems, automation software and the Internet of Things (IoT). These systems collect real-time data, analyze user habits and optimize resource use. For example, according to data from the US Department of Energy (DOE), smart building automation systems can save up to 30% of energy consumption[19]. In addition, security systems are of great importance in smart buildings. While the level of security is increased with tools such as cameras, motion sensors and biometric entry systems, automatic responses have also been developed for emergency scenarios. Smart fire detection and evacuation systems play critical roles in protecting human life inside the building. In terms of sustainability, smart buildings are important in terms of reducing carbon footprint and encouraging environmentally friendly structures. The use of smart building technologies in environmental certification systems such as LEED (Leadership in Energy and Environmental Design) ensures high scores[20].

Smart buildings outperform traditional buildings in terms of energy efficiency and user satisfaction. In addition, these technologies are seen as one of the basic building blocks of the smart city concept[21].Traditional building design and management approaches are not sufficiently responsive to today's complex urban, environmental and social needs. At this point, smart building technologies have become one of the cornerstones of contemporary building design, offering multidimensional advantages such as not only energy efficiency but also sustainability, quality of life, resource management, urban security and digital integration[22].

Smart building systems work in an integrated manner with technologies such as building automation systems (BAS), energy management, lighting automation, heating-cooling-ventilation systems (HVAC), security and monitoring systems, smart meters and user interfaces[23, 24]. These systems monitor user behaviors, optimize environmental conditions and make automatic decisions with sensor data and artificial intelligence-supported analysis. For example, indoor temperature can be kept under control with sun-sensitive shutter systems in a building and energy consumption can be optimized by reducing the load on HVAC systems[25].

B. Wireless Communication Technologies Used In Smart Buildings

Wi-Fi (IEEE 802.11), ZigBee (IEEE 802.15.4), LoRa/LoRaWAN, LTE/5G, RF, NB-IoT (Narrowband IoT) and Bluetooth Low Energy (BLE) technologies are frequently preferred in wireless communication applications in smart buildings.[26, 27].

Wi-Fi technology is derived from the combination of the words Wireless Fidelity and is translated as wireless connection. Wi-Fi infrastructure operates at 2.4 GHz, 5 GHz and 6 GHz frequencies. This technology, defined by IEEE 802.11 standards, is used in internet connection, home-work network and communication between multiple devices. Devices working with Wi-Fi technology have two basic operating modes. These operating modes are; Infrastructure mode and Ad-Hoc, which is a direct communication mode between multiple devices. Infrastructure mode has two different operating states called Client and Station (Access Point) modes. Personal computers, mobile phones and smart devices can be given as examples of devices working in client mode. Modems and routers can be given as examples of devices working in station mode. In addition, it is possible to use some devices in both client and station modes. For example, by activating the wireless access mode of smart phones, we can remove the Wi-Fi module from client mode and operate it in station mode. Devices operating in Ad-Hoc mode operate in both client and station modes while communicating with each other. The most preferred IEEE 802.11 standards are 802.11/b/g/n and ac standards. The comparison of these standards is given in Table I [28–30].

TABLE I. IEEE 802.11 WI-FI STANDARTS

Wi-Fi Standarts	***Frequency Band***	***Max.Speed***	***Prevalence***
802.11 b/g/n	2.4 GHz	72 – 600 Mbps	High
802.11 a/n/ac	5 GHz	433 Mbps – 1.3 Gbps+	High
802.11 ax (Wi-Fi 6/6E)	2.4 / 5 / 6 GHz	600 Mbps – 9.6 Gbps	Increasing

Zigbee technology is a short-distance network infrastructure based on the IEEE 802.15.4 standard. Zigbee modules using the 2.4 GHz frequency band can reach a data transmission speed of 250 Kbps over ten channels. Zigbee modules can transfer data between 20 meters and 45 kilometers when high-gain antennas are used in open areas[31]. In addition, each Zigbee module in the network can work as both a receiver and a transmitter. Thanks to these features, Zigbee modules can be used as access points for long-distance data transmission. ZigBee modules allow wireless communication channels to be searched automatically and multiple wireless networks to coexist. Zigbee modules characteristically have low energy consumption. Since Zigbee modules have a sleep mode feature, they provide significant energy savings by going to sleep when they are not in use. For example, a Zigbee module that detects a rare fault condition and reports the process to the control unit can operate for approximately 5 years with standard AA batteries [16, 32, 33]. Versions and communication speeds of ZigBee technology are given in Table 2.

TABLE II. IEEE 802.15.4 ZIGBEE VERSIONS AND COMMUNICATION SPEEDS

ZigBee Versions	***Max.Speed***	***Frequency Band***
ZigBee (2004)	250 kbps	2.4 GHz
ZigBee (2006)	250 kbps	2.4 GHz, 868/915 MHz
ZigBee PRO (2007)	250 kbps	2.4 GHz
ZigBee RF4CE (2009)	250 kbps	2.4 GHz
ZigBee 3.0 (2015-)	250 kbps	2.4 GHz (generally)

LoRa is a new technology that enables communication over long distances using radio frequencies. It has a wide area of use, especially in the field of the Internet of Things (IoT). LoRa is derived from the word Long Range, meaning long distance. Although LoRa has a low communication speed, it is a wireless modulation technique that stands out with its long range and low power consumption[34]. LoRaWAN, which uses unlicensed ISM radio bands, consumes 50 mA current during data communication. With this power consumption, approximately 10 years of operation is provided with a single battery[35]. LoRaWAN operates in the 863-870 MHz frequency band. The range it can transfer data varies depending on the modules used, obstacles such as buildings in the area, and environmental conditions, but it reaches 2-4 km in the city and 15 km outside the city. LoRaWAN topologies are generally used in wide area networks designed to be low power. LoRaWAN, which uses the Symmetric Key Encryption system AES 128, is configured with a star topology like ZigBee[36]. In the physical layer of LoRaWAN technology, a modulation technique called Chirp Spread Spectrum (CSS) is used. This protocol works with the LoRa modulation method. LoRaWAN technology is basically composed of three main layers. At the bottom of the design is LoRa, which forms the physical layer. The task of the middle layer is determined as providing connection. The top layer includes applications[37]. Frequency ranges and maximum data transmission speeds of LoRaWAN technology according to usage areas are given in Table 3. The variable specified as Spreading Factor represents the data transmission speed that changes with increasing distance.

TABLE III. LORAWAN FREQUENCY AND DATA RATE BY REGION

Region	***Frequency Band***	***Max.Speed***	***SF (Spreading Factor)***
EU 868 MHz	863–870 MHz	0.3 kbps – 50 kbps	SF7 – SF12
US 915 MHz	902–928 MHz	0.98 kbps – 21.9 kbps	SF7 – SF10
AS 923 MHz	915–928 MHz (Asia)	0.3 kbps – 21.9 kbps	SF7 – SF12

GSM (Global System for Mobile Communications) technology is a network that uses 2G, 3G, 4G and 5G infrastructures and was initially designed for voice communication. After 2G technology,

which used TDMA (Time-division multiple Access) infrastructure to access the GSM network, GPRS, or "General Packet Radio Service", was developed, designed for the transfer of packetized data. After GPRS technology, EDGE, 3GPP, 3G, 4G and 5G technologies were introduced. With these technologies, good voice quality and high-speed packetized data transfer as well as internet access were made available. 4G and 5G LTE technology was designed to increase speed and data transmission capacity and is a very suitable option for remote reading, remote monitoring and control of systems[26, 38].

RF communication technology is the name given to data transmission between a receiver and a transmitter device via Radio Frequency. RF Modems used in RF communication infrastructure are classified as Licensed Band RF Modems and Free Frequency RF Modems according to the frequency ranges they broadcast. Permission is required for the use of RF modems that transmit data in the licensed band range[39].

NB-IoT is an LPWAN (Low Power Wide Area Network) technology designed to work on cellular networks. It was developed especially for IoT devices that need low bandwidth, communicate infrequently and require long battery life. It works with the 3GPP Release 13 standard defined in LTE-A Pro. The operating frequency is the same as the LTE bands between 700-2100 MHz. The bandwidth is 180 KHz and the data rate is ~66 kbps in uplink mode and ~26 kbps in downlink mode. The coverage area is up to 20 km and the data delay is between 1.5 and 10 seconds depending on the distance. Battery life varies depending on usage, but is stated as approximately 10+ years in the factory data[40, 41].

Bluetooth technology was developed by Ericsson in 1994 to provide data transfer over short distances. It is within the scope of the IEEE 802.15.1 standard. The IEEE 802.15.1 standard has not been updated after 2005. Newer versions of Bluetooth technology (2.0 and later) were created by the Bluetooth SIG (Special Interest Group), not by IEEE. Bluetooth is a short-range wireless communication protocol operating in the 2.4 GHz ISM (Industrial, Scientific and Medical) band. The Bluetooth protocol is frequently used in mobile applications for audio and file transfer[42]. Bluetooth technology versions and communication speeds are given in Table 4.

TABLE IV. IEEE 802.15.1 AND BLUETOOTH SIG (SPECIAL INTEREST GROUP) BLUETOOTH STANDARTS

Bluetooth Versions	***Max.Speed***	***Explanation***
Bluetooth 1.2	1 Mbps	Noise reduction with AFH (Adaptive Frequency Hopping) support.
Bluetooth 2.0 + EDR	3 Mbps	Speed increase with EDR (Enhanced Data Rate).
Bluetooth 3.0 + HS	24 Mbps	HS = High Speed (Transfer is done via Wi-Fi).
Bluetooth 4.0	1 Mbps (Low Energy)	Low power consumption with BLE (Bluetooth Low Energy).
Bluetooth 4.2	1 Mbps	Improved security and IPv6 support.
Bluetooth 5.0	2 Mbps (BLE)	Longer range (up to 120m) and double speed.
Bluetooth 5.1 / 5.2	2 Mbps (BLE)	Position determination (Angle of Arrival / Departure), LE Audio (LC3 codec) support.
Bluetooth 5.3 (2021)	2 Mbps (BLE)	Energy efficiency and more advanced connection management.

III. SMART BUILDING CASE STUDY

Today, the rapid increase in urbanization necessitates the efficient use of energy resources and environmental sustainability. In this context, smart building technologies offer important solutions in line with goals such as energy efficiency, user comfort and reduction of carbon emissions. In this section of the study, a case study of a 25-storey commercial office building named "Green Plaza" located in Ankara and developed with the aim of sustainability will be carried out. The project is equipped with smart building technologies in order to increase energy efficiency, reduce carbon footprint, maximize user comfort and reduce operating costs. The smart building technologies applied in the building are given in Table 5.

TABLE V. COMPARATIVE ANALYSIS

Technology	***Usage Details***
Building Management System (BMS)	It manages all HVAC (heating, ventilation, air conditioning), lighting and security systems from a single center.
Smart Lighting	Light intensity is automatically adjusted according to the environment with daylight sensors. Lights in empty areas are turned off with motion sensors.
Smart Heating-Cooling	Automatically adjusts according to user density and outside weather conditions. Regional control is provided for energy efficiency.
Energy Monitoring System	Instantaneous energy consumption is monitored. Inefficient systems are detected and intervened.
Solar Panels	The panels placed on the roof of the building meet 15% of the building's electricity needs.
Wind Turbine	In addition to the parking area, it meets 10% of the building's electricity needs.
Rainwater Recycling	The collected water is used in garden irrigation and reservoir systems.
Smart Elevators	Elevators are directed according to floor usage density, reducing waiting times.
Battery Center	The battery system, which transfers data to the cloud database via LTE, carries out the processes of storing and selling energy.
Electric Vehicle Charging Station	The energy required to charge electric vehicles is provided from renewable sources.

There is a charging unit for electric vehicles in front of the plaza. Instant consumption data can be sent to the control center from the smart meters in the businesses. In addition, devices operating in the building can be controlled by communicating with each other and the building management module. The inverter in the solar power plant sends instant production data to the control center. The wind turbine, located next to the parking area 1 km away from the building center, transmits production and operating data to the control center at certain periods. The battery storage system with cloud connection sends data to the energy management software. The central control unit processes all incoming data and ensures system operation, continuity and stability.

The success of smart building technologies depends not only on the use of energy-efficient devices, but also on the effective and secure communication of these devices with each other. Wireless communication technologies enable this communication by providing maximum control and flexibility with minimum physical wiring in the building infrastructure. In this section, the main wireless technologies used within the scope of the Green Plaza project are presented with their application areas.

ZigBee sensors are used in lighting automation, temperature/motion sensors, window/door detection systems, etc. Since ZigBee sensors support intensive sensor use, they provide a safe and wide range of use in mesh topology. In addition, the low energy consumption of ZigBee sensors is among the important advantages. Due to its high data transmission speed and easy

integration with the existing internet infrastructure, Wifi technology is used in monitoring IP cameras, user devices, and control panels. LoRa technology is used in remote meter reading, environmental monitoring systems such as air quality, water level, etc., open area sensors, smart lighting, and smart heating-cooling technologies due to its very low energy consumption and long range advantage. Bluetooth Low Energy (BLE) technology is used in user recognition, indoor positioning, and mobile application control applications due to its ability to communicate directly with mobile devices in short-range areas. Nb-IoT is used in the transmission of critical data with low data density, such as meter reading, fire and emergency systems, and access control systems.The communication structure between the solar power plant and the control center is presented in Figure 2.

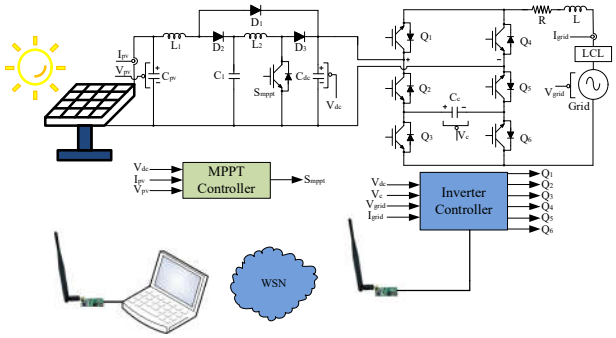

Figure 2 Communication of PV Power Plant with the Control Center

The block diagram of the proposed system is presented in Figure 3.

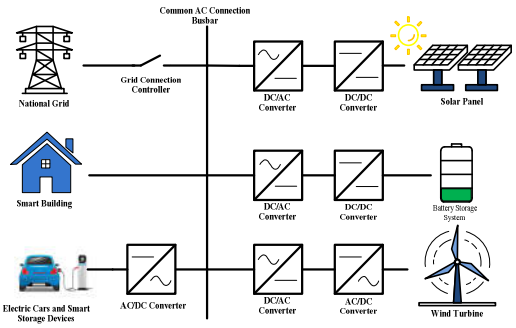

Figure 3 Block Diagram of the proposed system

A comparative analysis of the wireless technologies that can be used in this system designed within the framework of smart building principles is given in Table 6.

TABLE VI. COMPARATIVE ANALYSIS OF WIRELESS TECHNOLOGIES

Technology	***Range***	***Power Consumption***	***Data Speed***	***Usage Area***
Wi-Fi	Middle	Middle	High	Building and inside
ZigBee	Short	Low	Low	Sensor Network, Management
LoRa	Long	Very Low	Very Low	Remote monitoring
LTE/5G	Long	High	Very High	Real-time management
NB-IoT	Long	Low	Low	Electricity Meter data transfer
BLE	Very Short	Very Low	Low	Portable devices

IV. CONCLUSION

In this study, wireless communication systems used at various levels in smart buildings and the technical features of these systems are comparatively examined. Smart building technologies are not only an architectural innovation, but also a systematic transformation process directly related to energy policy, sustainability goals, user life quality and smart city visions. This transformation plays a critical role in achieving sustainable development goals with a holistic approach that requires interdisciplinary collaboration and covers many areas such as engineering, architecture, urban planning, environmental sciences and information technologies. In the designed model, a strategy based solely on technical performance was not followed, but an approach based on human, space and object interaction was adopted. The adaptability of parameters such as heat, humidity and lighting according to user preferences increases comfort, health and productivity in spaces. In the later stages of the study, inclusive architectural solutions can be provided thanks to the accessibility technologies developed for the elderly and the disabled. The development of the study within this framework is also very valuable in terms of social sustainability. Smart buildings are one of the basic modules of the smart city infrastructure. They contribute to a holistic urban ecosystem by exchanging real-time data with elements such as transportation systems, healthcare services, public safety and environmental monitoring. Despite their high potential and profitability, there are obstacles to the spread of smart building technologies such as high costs, lack of technical expertise and data security concerns. However, it is anticipated that these technologies will become more accessible and secure with the integration of artificial intelligence, machine learning, 5G communication technologies and blockchain.

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