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# The Integration Among E-Health Applications, Communication Networks and Sustainability: A Review

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**ABSTRACT**

Many types of e-health applications support smart cities in terms of health care. Every application is subject to requirements that must be met to be considered successful. In terms of system performance, the communication networks are responsible for meeting the requirements of e-health applications to transfer the data of applications successfully to their destinations with a focus on reliability, latency and packet loss. In addition, data protection against expected attacks is essential to maintain the data integrity of such applications. The integration of the healthcare system with promising information and communication technologies (ICTs) can lead to effective, personalised and accessible healthcare solutions, thus ultimately improving patient outcomes and the overall healthcare ecosystem. Meanwhile, sustainability has become one of the most vital conditions for any application in a smart city. In this context, this study explores the modern related literature to discover the types and the requirements of e-health applications and the available ICTs that meet these requirements. In addition, this study analyses the cybersecurity requirements related to e-health applications. Furthermore, this work engages the sustainability concept with e-health and ICTs to investigate the expected benefit of this approach. Finally, the work provides as energy consumption analysis for internet of medical things (MIoT) sensors to demonstrate the impact of energy-efficient methods used in e-health systems.

## 1. Introduction

The significant developments in the field of ICTs and the availability of low-cost electronic devices have contributed to creating new fields in medical applications that enable healthcare to shift from a hospital-centric model to a patient-centric one [1-4]. The increase in the population and the Covid-19 pandemic in 2020 have shown the need for healthcare methods that enable the remote collection of physical, psychological or other health data of patients [5-9]. In such cases, patients are monitored remotely (at urban areas or at clinics) using various integrated technologies [10]. Hence, healthcare systems, especially monitoring systems (wearable, portable or fixed) that require two-way communication network, need to be inexpensive, resilient and applicable in real time [11-14]. The communication network should be uninterrupted to achieve availability and reliability. Moreover, patient data should be collected using biosensors and wireless sensor networks (WSNs) [2]. The collected data are transmitted from the sensors to the control and monitoring centres to form large-sized data [9,15,16]. These data are sent continuously for analysis, processing and monitoring [17-19].

Such real-time applications require continuous and uninterrupted energy sources

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(extended life of the network and devices and reduced power consumption), which imposes a strict limitation; given that wireless communications networks consume energy [20, 21], the shortcomings of traditional energy sources, such as the limitations of fossil fuels and environmental pollution, should be compensated [22]. Previous issues have contributed to harming the environment, such as greenhouse gas (GHG) emissions; approximately 60% of healthcare organisations are already using Internet of things (IoT) devices to monitor and collect data; as such, IoT adoption in healthcare is expected to reach 87% of worldwide healthcare organisations by 2025 [23]. Additionally, by 2030, nearly 50 billion IoT devices and products will be in use globally [24]. The Net Zero 2050 project balances the quantity of GHGs removed from the atmosphere with the amount of GHGs emitted; notably, healthcare is accountable for 4% to 5% of these emissions [25] because of the use of traditional energy sources. Therefore, many feasible energy management strategies can be implemented, including the control of energy generation, conservation and storage. These solutions can overcome these issues and enhance sustainability. However, challenges associated with the network performance, such as the trustworthiness of the network, remain [25-29]. Researchers have applied energy management strategies [30] to extend the network's lifetime and reliability. For instance, Murtaza Cicioğlu and Ali Çalhan proposed a wireless body area network (WBAN) architecture based on the software-defined networking (SDN) approach with a new energy-aware routing algorithm for healthcare architecture [31]. This method enhances energy conservation to ensure the efficient use of the provided energy [32]. Selecting the appropriate communication protocols for routing that are the most convenient with the adopted case can also enhance the energy efficiency [33, 34].

However, each e-health application must satisfy its requirements effectively. As such, various methods have been used to enhance the performance of these applications. Researchers have adopted this issue as in [33] and [31]: heterogeneous and complicated network topologies, such as WBANs, can become simple, flexible, manageable and efficient through SDN methods. These approaches use simulation parameters as frequency and bandwidth channel models to analyse network performance using IoT technologies.

IoT technologies have become increasingly used in the current era because of its applicability to e-healthcare systems particularly in enhancing sustainability [27, 29-34]. Through complementary strategies and techniques, IoT can be used to operate healthcare monitoring devices, manage resources efficiently, prevent the spread of infection and improve the delivery of the patient health care; these examples are among the many benefits of this technology to society, the environment and the economy [7,20].

However, meeting the requirements for e-health applications poses challenges and limitations [35], including interoperability, security, privacy, usability, accessibility, evidence-based practices, cost-effectiveness and regulatory compliance, as outlined in Figure 2. Trade off can be achieved [36].

Other challenges related to the adoption of sustainability methods are the cost and size of the adopted renewable energy source [37] and energy harvesters, which must not compromise patient comfort. Additional considerations include data compression methods that should maintain accuracy and reliability, the efficiency constraints of manufacturing low-cost, low-power hardware and the limitations of low-energy communication networks with restricted data rates based on communication protocols [38-40]. Energy harvesting protocols also aim to optimise energy usage. Despite these challenges, achieving balance is possible.

Insufficient research efforts have been made to provide collective insights into issues related to energy efficiency, network performance and application requirements. The current work addresses this gap by conducting a comprehensive review of the integration of all technologies and issues that provide robust e-health applications. Table 1 shows the difference between this review and other existing studies. This work contributes to the literature through the following points:

- Provide a multidisciplinary insight to clarify the role of integrated technologies forming the robust e-healthcare applications.
- Classify e-healthcare applications and services based on different criteria.
- Address the challenges and limitations related to the different applied technologies.
- Explore the most relevant energy efficient methods for e-healthcare applications.
- Examine the energy consumption analysis for e-healthcare applications with multiple sustainable methods applied.

The aim of this review is to include all the relevant e-healthcare technologies that are reinforced their roles and characteristics to create innovative and successful e-healthcare applications. These applications affect the overall healthcare system by improving the healthcare process and patient outcomes. Moreover, this work investigates the integration of e-health applications, ICT and innovative technologies to support sustainability while addressing the quality of service (QoS) requirements of e-health applications and meeting the demands of smart cities. These demands include optimising the use of limited resources. Figure 1 illustrates the integration of e-health applications, ICT and sustainability, resulting in a robust e-healthcare system.

The role of supporting technologies becomes evident through practical examples from e-health applications, such as remote patient monitoring (RPM). This application relies on multiple integrated technologies to create a valuable system. The absence of any key technology renders the e-healthcare system ineffective.

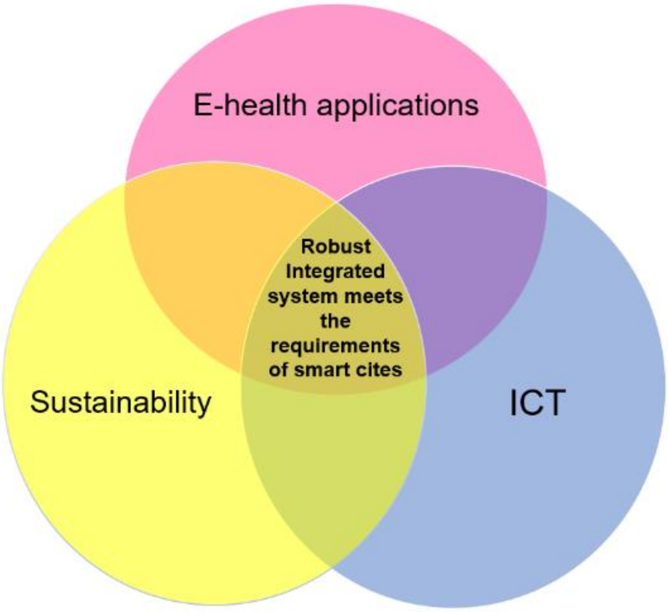


**Figure 1**. Integration among e-health applications, ICT and sustainability

**Table 1:** Comparison between this review and other reviews

| Ref. | E-health | sensors | ICT | | Sustainability (Energy efficiency methods) | Application requirements | QoS |
|---|---|---|---|---|---|---|---|
| | | | Wireless communication networks | At least one type of Information technology | | | |
| [1] | ✓ | ✓ | ✓ | ✓ | | | |
| [4] | ✓ | ✓ | | ✓ | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| [5] | ✓ | ✓ | | | | | |
| [7] | ✓ | | | ✓ | ✓ | | |
| [14] | ✓ | ✓ | ✓ | ✓ | | | |
| [20] | ✓ | ✓ | | | ✓ | | |
| [30] | ✓ | ✓ | ✓ | | ✓ | | |
| [38] | ✓ | | ✓ | ✓ | ✓ | ✓ | |
| [41] | ✓ | ✓ | ✓ | | ✓ | | |
| [42] | ✓ | | ✓ | ✓ | | ✓ | ✓ |
| [43] | ✓ | ✓ | | | ✓ | | |
| [44] | ✓ | | ✓ | | ✓ | ✓ | |
| [45] | ✓ | ✓ | ✓ | | ✓ | | |
| [46] | ✓ | ✓ | | ✓ | | | ✓ |
| [47] | ✓ | ✓ | | ✓ | ✓ | | |
| [48] | ✓ | ✓ | ✓ | ✓ | | ✓ | |
| [49] | ✓ | ✓ | ✓ | ✓ | | ✓ | |
| **This work** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

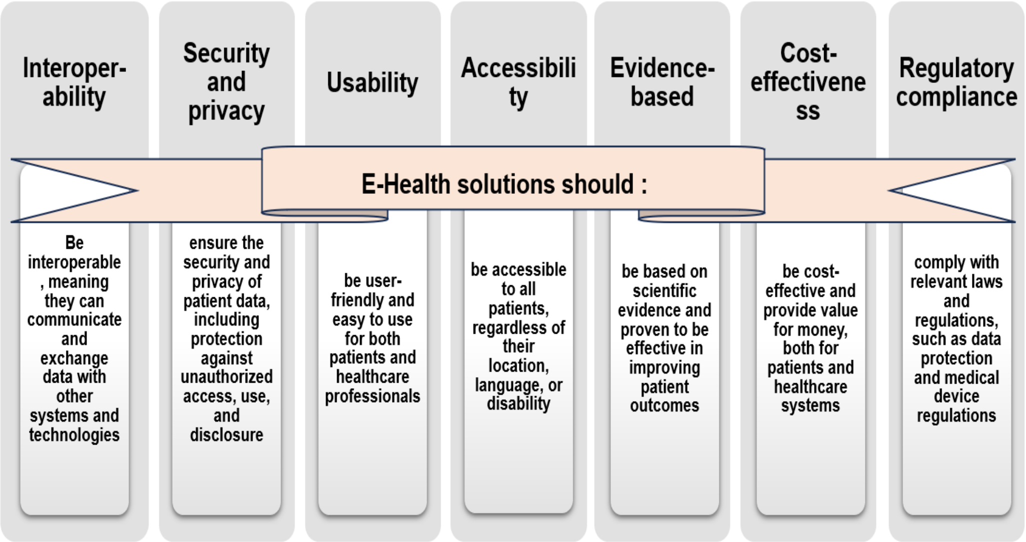


**Figure 2.** Aspects of issues facing the implementation of e-health applications [50]

## 2. Research methodology

This review was conducted to gather and synthesise literature on e-healthcare applications and their technologies. A comprehensive search was performed using three primary databases: ScienceDirect, IEEE and Google Scholar. These databases were selected because of their extensive coverage of peer-reviewed articles in sustainable ICTs in E-healthcare. The search terms included ‘e-health applications’, ‘ICT’ and ‘Sustainability’ along with related terms and synonyms. Boolean operators (AND, OR) were employed to refine the search and capture a wide range of studies. This process reviewed 210 articles that were published between 2019 and 2024 in English and addressed the role of ICT in e-healthcare applications along with sustainable methods. Exclusion criteria involved non-peer-reviewed articles and case studies that were unrelated to the core research question. After the initial search, articles were screened first by title and abstract and then by full-text review. Key data, including author, year of publication, methodology, and key findings, were extracted from each study and synthesised using thematic analysis. Themes, such as application requirements, innovative technologies, and energy efficiency, were identified and explored. Despite efforts to conduct a comprehensive review, the methodology was limited by language restrictions and potential database coverage gaps.

The rest of the paper sections are organised in a structure illustrated in Figure 3.

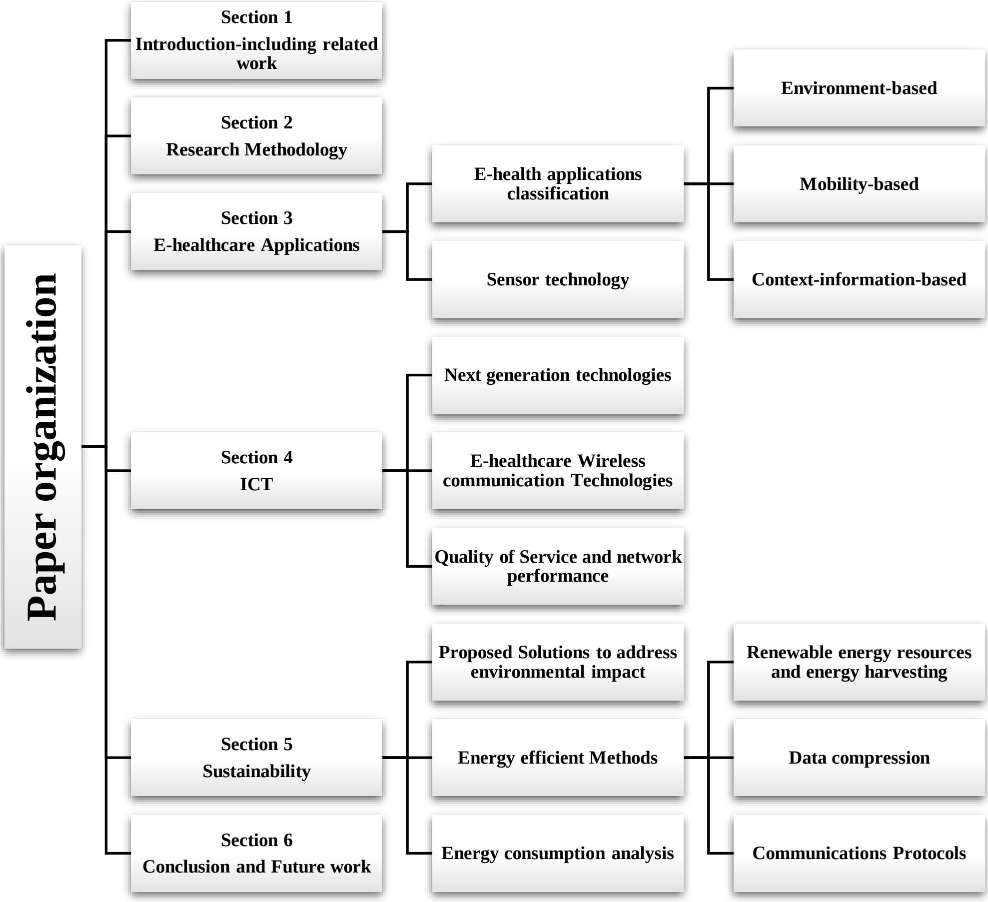


**Figure 3.** Paper organisation

## 3. E-health applications

This section focuses on two major topics: the classifications of e-health applications depending on different strategies and sensor technologies related to e-health applications. E-health is the use of electronic devices that are usually placed or carried next to the patient’s body to collect and transmit data, which can be accessed remotely [4]. It refers to the services and systems rather than the health of people [51]. E-health, or electronic health, refers to the use of digital technology and ICT in healthcare to support and improve the delivery of healthcare services, patient care and health management [28, 51, 52]. In the healthcare ecosystem, different purposes are served by various types of e-health applications [40-44]. These e-health applications generally aim to improve patient outcomes, enhance self-management capacities and support disease prevention and control [44-47]. The many types of e-health applications vary in terms of the service they provide and the requirements they need. The most common types of e-health applications are shown in Table 2.

### *3.1 E-health applications classifications*

E-healthcare application devices that provide services can be classified based on different criteria, which are illustrated in the following three subsections.

#### *3.1.1 E-healthcare applications device classification according to their mobility*

As technology advances, wearable and portable health monitoring systems have become increasingly popular [29]. Individuals can track their well-being in real time through the convenient and continuous monitoring of various health parameters provided by these systems.

Fixed e-health monitoring applications are typically addressed using stationary devices in healthcare facilities or at home, such as electrocardiography (ECG) machines, traditional blood pressure monitors and other specialised medical equipment. Although fixed systems lack wearables’ mobility, they are typically more precise and may provide a wider variety of monitoring capabilities. Conversely, wearable devices, such as fitness trackers and smartwatches, are designed to be worn on the body all day. They frequently monitor signs, such as heart rate, steps taken, sleep patterns and occasionally even complex measurements, including blood oxygen levels or ECG. Wearable technology offers continuous data, which enables users to monitor their fitness and health patterns over time. Devices from Apple, Fitbit and Garmin are well-known examples. Portable devices are compact, lightweight devices that are easy to carry and use on the go. These devices may include blood glucose monitors, pulse oximeters and handheld ECG devices. They are appropriate for people need to track particular health parameters regularly wherever they may be [58]. Furthermore, the advances in textile technology [59] have led to the development of smart clothing embedded with sensors that can monitor various health metrics. Biometric sensors can be integrated into clothing to measure parameters, such as heart rate, body temperature and muscle activity. Thus, this type of clothing can be considered a wearable device. Smart clothing offers a discrete and continuous monitoring solutions [14]. In some cases, devices can be implanted in the body using biodegradable materials to monitor specific health conditions [60]. Implantable devices can be used for long-term monitoring of conditions, such as heart rhythm abnormalities.

**Table 2:** Types of e-health applications

| **E-health application [14, 27, 53, 54, 55, 56, 57, 58]** | **Description** |
|---|---|
| **Electronic Health Records (EHRs)** | • It stores a patient’s medical records digitally.<br>• It contains details about a patient’s medical history.<br>• It enhances the efficiency of healthcare providers in accessing and sharing patient data. |
| **Telemedicine and Telehealth** | • Telemedicine involves providing healthcare services remotely via video calls, phone calls or online chats. |

| | |
|---|---|
| **Mobile Health (mHealth)** | • Telehealth covers a wide range of digital healthcare services, including remote monitoring, virtual consultations and teletherapy.<br>• Smartphones and other mobile devices are compatible with health-related applications.<br>• They include apps for tracking health and fitness, medication reminders and chronic disease management. |
| **Health Information Systems** | • They manage and store health-related data<br>• They assist healthcare organisations in the analysis and sharing of information to enhance patient care, public health and research. |
| **Remote Patient Monitoring** | • Devices and applications allow patients to monitor vital signs, chronic conditions and recovery progress from home.<br>• Healthcare providers can access data to make informed decisions |
| **Healthcare Portals** | • Online platforms that allow patients to access their health records, make appointments scheduling and communicate with healthcare providers; the ability to view test results |
| **Health Information Exchange (HIE)** | • Enable the secure sharing of patient health information among different healthcare organisations and providers<br>• Ensure that care is coordinated and continuous |
| **Clinical Decision Support Systems (CDSS)** | • Healthcare professionals are assisted by CDSSs using data and algorithms to make clinical decisions, such as suggesting treatment options or drug interactions. |
| **Health and Wellness Apps** | • Apps designed to help individuals manage their overall well-being through the provision of information on nutrition, fitness, stress management and mental health. |
| **E-Prescribingn** | • Allows healthcare providers to send prescriptions directly to pharmacies<br>• Reducing errors<br>• Improving medication management. |
| **Health Analytics** | Analytics tools and software:<br>• Used to process and analyse healthcare data<br>• Enabling organisations to identify trends, make predictions and improve healthcare outcomes |
| **Radiology Information Systems (RIS) and Picture Archiving and Communication Systems (PACS)** | • The management and storage of medical images and associated data, such as X-rays, MRIs and CT scans, is handled by these systems |
| **Telepharmacy** | • Remote pharmacy services enable pharmacists to check and dispense medication orders from a distance, especially in rural or underserved areas. |
| **Wearable Health Technology** | • Monitor various health metrics<br>• Can transmit data to healthcare providers or mobile apps. |
| **Personal Health Records (PHRs)** | • PHRs are digital records of an individual’s health and medical history, that are often maintained and controlled by the patient |

Mobility challenges in e-healthcare applications, such as network failures, device compatibility, data privacy issues and battery consumption during real-time health monitoring, must be resolved to guarantee accessibility, usability and dependability. Healthcare services are improved by technologies such as Fifth Generation network

(5G), Mobile Edge Computing (MEC) and data encryption, which increase network dependability, decrease latency and guarantee secure data transfer. For instance, MEC reduces reaction times by processing data close to consumers, while sophisticated security measures safeguard private health data on mobile networks (see Section 4.1). Certain mobility-related challenges must be resolved for e-healthcare applications to provide high-quality treatment while satisfying the expectations of mobile users.

### *3.1.2 E-health monitoring systems environment-based classification*

Monitoring systems are also classified according to their position as indoor and outdoor healthcare environments [14]. IoT technology contributes to the enhancement of patient care and operational efficiency in indoor and outdoor healthcare environments in several ways. Indoor healthcare environments include hospitals where IoT devices can be used to monitor patients, manage medical equipment, track inventory and monitor environmental factors, such as temperature, humidity and air quality. IoT can also be used to track the location of patients and healthcare staff, optimise workflow and enhance emergency response times. Meanwhile, outdoor healthcare environments refer to the integration of smart and IoT-enabled facilities in outdoor healthcare settings. These applications emphasise the role of IoT in enhancing the well-being of individuals in outdoor healthcare environments.

### *3.1.3 E-health services context information-based classification*

Based on the context information [29], e-health services can be classified as follows:

1. Emergency or Patient Critical Services: These services are sensitive to context and are typically performed in emergency situations or involve critical patient data transmission in real time. Examples include telediagnosis and telesurgery [29].
2. Nonemergency or Noncritical Services: These services are not sensitive to context and are performed in nonemergency situations. They may involve the transfer of patient medical data to a remote location for analysis or non-real-time teleconsultation.

However, some important issues may face the implementation of different e-health applications [50], as explained in Figure 2.

Handling these requirements is crucial to ensure the successful implementation of IoT in healthcare, thus providing several benefits, such as improved patient outcomes, early intervention and efficient healthcare delivery [62].

All the aforementioned e-health services in this section utilise ICT to deliver healthcare services. All data that are transmitted and delivered with the help of ICT is collected by sensors (end node or edge of the network). This process is discussed in the succeeding section followed by a section on ICT.

### *3.2 Sensor technologies*

The terms ‘sensing mechanisms’, ‘operating principles’ and ‘technologies’ are frequently used synonymously in the context of healthcare sensors. However, they may refer to several aspects of sensor functionality. Understanding these operating principles helps in designing sensors for specific healthcare applications, thus guaranteeing accuracy, reliability and compatibility with the intended use. Given the diversity of these principles and mechanisms, sensors can be customised for specific applications over a range of industries, including healthcare, consumer electronics, aerospace and automotive [63, 64]. Table 3 lists the most common types of sensors in e-health monitoring applications [26, 55, 56].

In the context of healthcare, researchers have classified MIoT sensors with different criteria [27]. Meanwhile, other researchers have quantified and emphasised the most widely used healthcare sensors [4]. In addition, studies have addressed the applications of IoT in healthcare and discussed the sensors associated with these applications [49]. Sensing techniques have also been classified into non-invasive and invasive techniques; non-invasive sensing technologies are broadly categorised into contactless and contact sensing [63], as shown in Table 4. These technologies have extensively used in healthcare monitoring because that are inexpensive and allow for measurement without harming the subject.

These classifications are not mutually exclusive. Some sensors may fall into multiple categories based on their design and functionality. The choice of sensor technology depends on the specific parameters to be monitored, the requirements of the healthcare application and the environmental conditions in which they will operate.

Healthcare monitoring sensors play a crucial role in collecting data for various healthcare systems to monitor patients' health, track vital signs and provide healthcare professionals with valuable, accurate and timely health information for diagnosis and treatment. Advancements in sensor technology continue to expand the capabilities of remote monitoring and improve patient care in indoor and outdoor settings. Specific devices, such as wearable devices and remote monitoring systems, as well as body area networks, may integrate a variety of sensors to collect data for comprehensive health monitoring. While some overlaps may occur, the specific sensors selected for each application depend on the intended use case and the data needed**.**

**Table 3:** Most common e-health monitoring sensors and their examples

| Healthcare monitoring sensors [26] | Technology examples [64-66] | Examples and services they serve |
|---|---|---|
| **Vital Sign Sensors** | • Optical sensor<br>• Displacement sensor technology<br>• Thermocouples or infrared thermometers<br>• Spirometry and piezoelectric sensor | • Heart rate sensor: A person's pulse and heart rate.<br>• Blood pressure sensors: Systolic and diastolic blood pressure monitoring<br>• Temperature Sensors: Detect body temperature variations in the skin or core.<br>• Respiratory rate sensor: The number of breaths per minute is tracked.<br>• Pulse oximeter: Measure oxygen saturation (SpO2) and heart rate |
| **Glucose Sensors**<br>**(Electrochemical technology)** | • Electrochemical, optical and enzymatic sensors (near-infrared), enzymatic sensors (glucose oxidase) | • Glucose metres: Measure blood glucose levels, commonly used by individuals with diabetes.<br>• Blood glucose monitoring sensors: Monitor blood sugar levels in diabetes management.<br>• Continuous glucose monitors (CGMs): Real-time glucose monitoring |

| | | |
|---|---|---|
| **Cardiovascular (ECG) Sensors** | • Electrode-based bioelectric sensors, capacitive ECG sensors, and textile-based ECG sensors | • Electrocardiogram (ECG or EKG) sensors: Monitor the electrical activity of the heart.<br>• Holter monitors: continuous electrocardiogram monitoring over an extended period.<br>• Blood flow sensors: These measure blood flow or velocity in arteries and veins. |
| **Sleep Monitoring Sensors** | • Actigraphy (accelerometers), EEG (electroencephalography) and respiration sensors | • Polysomnography (PSG) sensors: Measure brain waves, eye movements and muscle activity during sleep.<br>• Actigraphy sensors: These sensors monitor physical activity and rest patterns. |
| **Wearable Health Tracker Sensors** | • Accelerometers, gyroscopes, optical heart rate sensors (PPG) and bioimpedance | • Accelerometers: Measure the motion and activity levels.<br>• GPS sensors: Track location for fitness and health applications.<br>• Smartwatches and fitness trackers: Monitor various health parameters, such as heart rate, steps and sleep.<br>• Wearable electrocardiogram monitors: Provide continuous heart monitoring on wearable devices. |
| **Bioimpedance Sensors** | • Impedance-based sensors | • Measure the resistance and capacitance of body tissues for application to body composition analysis. |
| **Environmental Sensors** | • Gas, particulate, temperature and humidity sensors | • Air quality sensors: These sensors detect pollutants, allergens and environmental factors that affect health. Monitor indoor air quality for respiratory health.<br>• Temperature and humidity sensors: These sensors monitor the |

| | | |
|---|---|---|
| | | environmental conditions in healthcare settings. |
| **Movement and Activity Sensors** | • Electromagnetic sensors | • Accelerometers: Measure the motion and activity levels.<br>• Gyroscope: The gyroscope tracks the orientation and balance to detect sudden falls and sends |
| **Medication Adherence Sensor** | • Ingestible sensors, RFID chips and NFC tags | • Smart pill dispensers or blister packs that record the time of taking of medication.<br>• Remind patients to take medications and track medication compliance. |
| **Biometric Sensors** | • Optical, capacitive and fingerprint sensors | • Measure biometric data for identity verification and access control using fingerprint and facial recognition sensors.<br>• Fingerprint scanner: used for patient identification.<br>• Iris and retina scanners: Ensure secure access to medical records. |
| **Pain and Comfort Sensors** | • Electromyography and electrodermal activity | • Pain-intensity sensors: Assess pain levels.<br>• Comfort sensors: Measure factors, such as room temperature and lighting for patient comfort. |
| **Body Motion and Position Sensors** | • Displacement sensor | Used for monitoring patient activity and positioning in assisted living facilities. |
| **Imaging Sensors** | • CMOS and CCD sensors, ultrasound imaging and magnetic resonance imaging sensors | • X-ray sensors: Internal images are captured for diagnostic purposes.<br>• Ultrasound sensors: These use sound waves for imaging and diagnostic purposes.<br>• MRI sensors: This technique creates detailed images of internal |

| | | |
|---|---|---|
| | | structures using magnetic resonance. |
| **Sensors for Infection Control** | • Ultraviolet (UV) sensors, contactless infrared temperature sensors and chemical sensors | • Hand hygiene sensors: Promote handwashing and monitor compliance.<br>• UV-C disinfection sensors: Ensure proper disinfection of surfaces and equipment. |
| **Foetal Monitoring Sensors** | • Doppler ultrasound, electrocardiogram and non-invasive foetal heart rate sensors | • Foetal heart rate monitors: Record the heart rate of the developing foetus during pregnancy. |

**Table 4:** Non-invasive sensing technique classification

| **Contactless sensing technique** | **Contact sensing technique** |
|---|---|
| Used predominantly for monitoring physical data | Typically, different sensors are integrated based on their functionality, thus allowing for the measurement of physiological and physical data. |
| Generally, more acceptable to subjects | Less acceptable |
| The range of measurements is typically limited because the sensors are usually affixed to the environment. | Contact sensing offers a broader measurements range |
| For example:<br>• Vision-based sensors (i.e. cameras) have been employed to capture facial expressions<br>• Acoustical sensors can collect speech signals.<br>• Depth cameras are used to monitor gestures radars to track motion. | A common example of contact sensors is the wearable device (integrated different sensors):<br>• Inertial measurement units capture motion data.<br>• Blood volume pulse (BVP) sensors monitor the volume of blood passing through veins.<br>• Infrared sensors can measure body temperature.<br>• Electrodermal activity (EDA) sensors measure electrodermal activity. |

## 4. ICT in e-health

ICT involves technologies that address data processing and transmission of data. It is essential in various aspects of daily life, healthcare, business, education and government. ICT comprises computing and hardware devices, software, network infrastructure, communication technologies, data storage and management, cybersecurity and information systems. ICT plays an essential role in improving efficiency, communication and access to information across various sectors. These technologies are a foundational part of IT because they shape the infrastructure for communication, connectivity and data exchange. The integration of networking technologies with other IT components ensures that information can flow efficiently and securely within organisations and across the Internet. It requires a high level of QoS requirements that face many challenges barriers and limitations resulting in a smart choice. It takes into account the priority and the trade-off among these problems and challenges, which are solved by using innovative solutions, such as next generation technologies.

### *4.1 Next-generation technologies*

Next-generation technologies refer to advanced innovative and promising digital technologies that represent a significant leap forward from existing ones. These technologies can transform various industries and aspects of human life [1, 6]. Next-generation technologies play a significant role in addressing and mitigating the challenges of network performance in e-health services. The types of next-generation technologies can vary. Nevertheless, they generally encompass emerging fields that are at the forefront of scientific and technological progress. Figure 4 presents the candidate information technologies for e-health that contribute to solutions to the challenges facing the network performance of the e-health services [2, 26, 67].

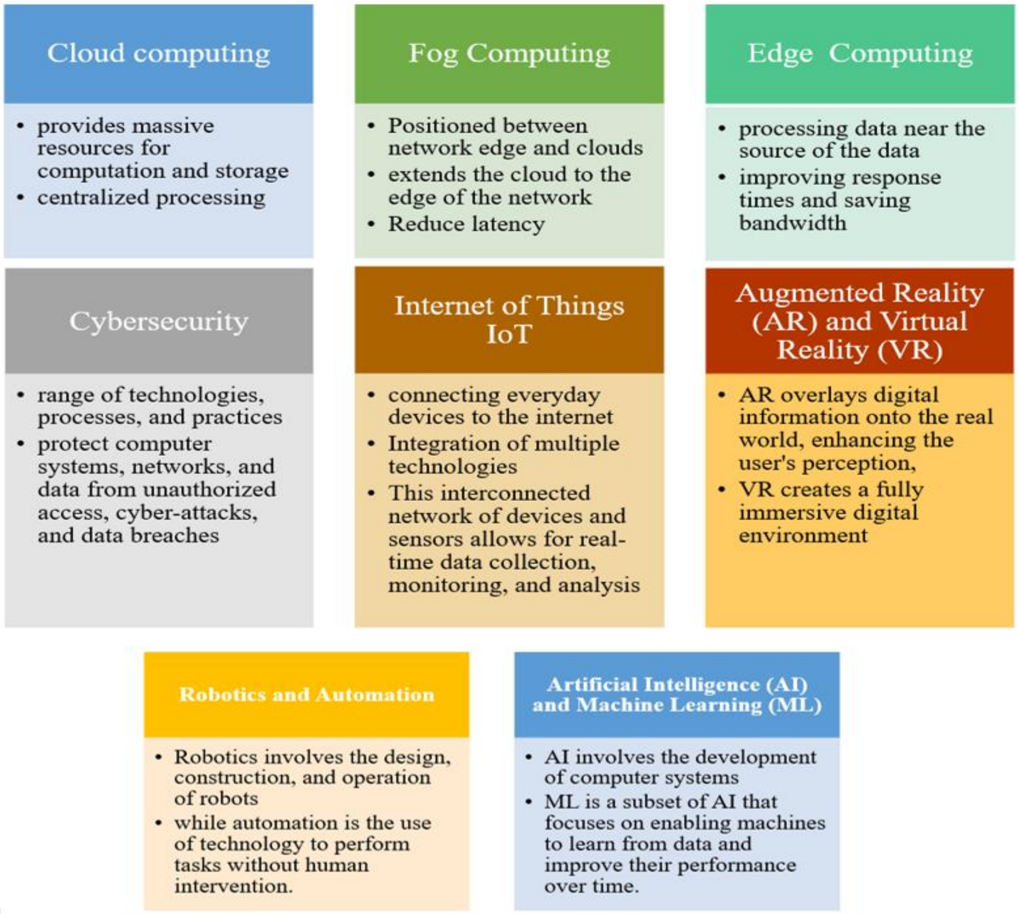


**Figure 4**. Available information technologies for e-health [14]

### *4.1.1 The Internet of Things (IoT)*

IoT is frequently discussed in IT, communication technologies and next-generation technologies because of its overlap among those fields. The convergence of traditional IT and emerging technologies makes IoT a bridge between established and cutting-edge technologies. IoT and its relationship with ICT and next-generation technologies are discussed in [14] as the integration of IoT technologies, such as sensors and actuators, connectivity in communication technologies, IoT platforms in cloud computing, security, edge computing, artificial intelligence (AI) and 5G. These innovations are a combination of traditional ICT with next-generation technologies. In addition, this integration in healthcare involves the interconnection of different physical subjects, types of equipment and sensors via the Internet, thus enabling them to communicate with each other and share data [7]. This network of devices and sensors allows real-time data collection, monitoring and analysis, thus leading to improved patient care, personalised treatment plans and streamlined healthcare delivery. Integration also encompasses the seamless incorporation of IoT devices and systems within the existing healthcare infrastructure. It involves the development of standardised protocols and interfaces to facilitate interoperability between different IoT devices, electronic health records (EHR) systems and other healthcare applications. Additionally, the integration of IoT technologies in healthcare requires robust security and privacy measures that maximise the benefits of IoT and enhance patient care [7, 57, 58]. Moreover, it can meet the healthcare requirements of smart cities in terms of security [68].

### *4.1.2 Cybersecurity in e-health*

Cybersecurity refers to the practice of protecting computer systems, networks and data from unauthorised access, cyberattacks and data hacking, thus ensuring secure communication, complying with regulations, securing medical devices and maintaining the continuity of healthcare services in the digital age. It encompasses a range of technologies, processes and practices that are designed to safeguard digital information and prevent it from being compromised [69, 70]. Key aspects of cybersecurity are included in Figure 5 [61].

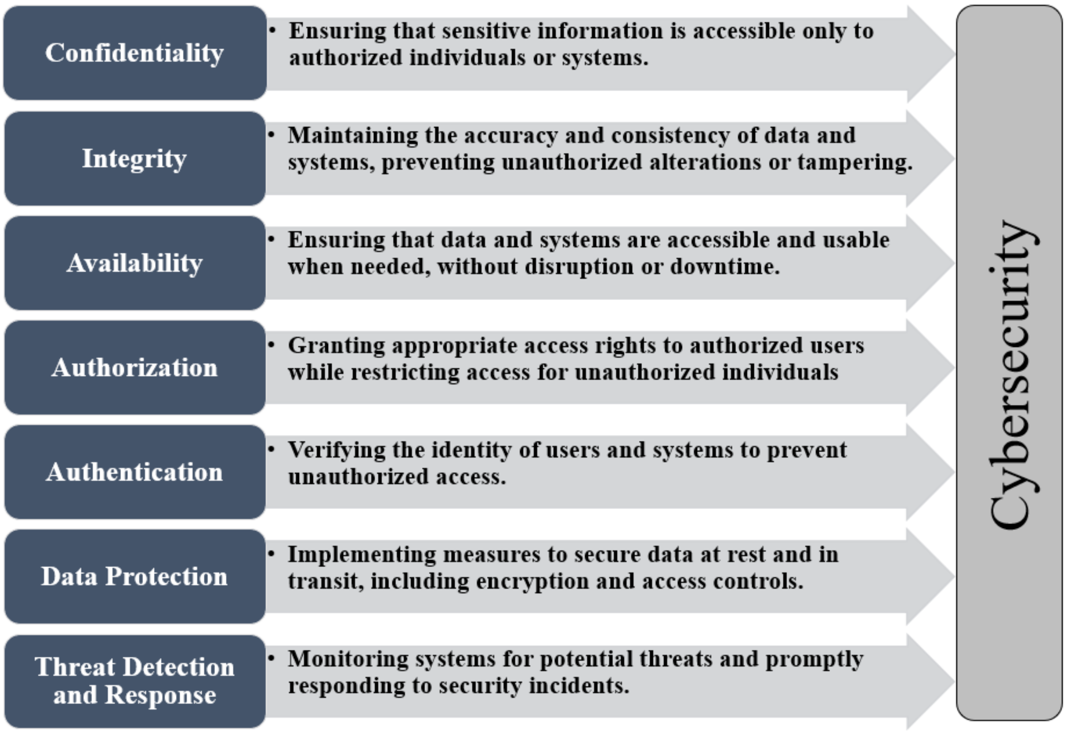


**Figure 5.** Security objectives [58]

In the context of healthcare, cybersecurity is especially significant because information about patients is sensitive in nature. Moreover, it can combat the possible effects of data breaches on patient safety and privacy. The integration of digital technologies in healthcare, MIoT and EHR requires effective cybersecurity capabilities to protect patient data and thus ensuring the integrity of healthcare system [71, 72]. Blockchain technology is often considered a tool for enhancing cybersecurity as well as other possible strategies and approaches to address the cybersecurity threads in the future. This technology includes the adoption of AI and machine learning, enhanced encryption techniques, continuous monitoring and threat intelligence, multifactor authentication, regular security assessments and audits, employee training and awareness, collaboration and information sharing, privacy-preserving techniques and development of standard frameworks. By adopting a combination of these strategies and approaches, organisations can effectively prepare themselves to address the increasing cybersecurity threats in the future and enhance their overall resilience against cyber-attacks [70, 72, 73, 74]. The World Economic Forum reported that almost 10 million documents of various kinds, including social security numbers, medical records for patients, test results and private information of healthcare professionals, were obtained. An average of 155,000 records have been compromised by attacks in this field; however, some reports say that over 3 million medical records across 33 countries have been compromised [71].

Blockchain technology is a decentralised and distributed ledger technology that is provided by securely records and verifies transactions across a network of computers, supply chain management and data integrity. Blockchain is the underlying technology for cryptocurrencies. It offers a promising solution for addressing the security and privacy concerns in healthcare, thus providing a foundation for secure and transparent management of sensitive medical data [57, 71]. It is most effective when used in conjunction with other cybersecurity measures and practices to create a comprehensive and robust security posture. Its common types are public blockchains (e.g. Bitcoin, Ethereum), private blockchains and consortium blockchains. The key benefits of using blockchain technology for healthcare services, as outlined in [1, 22] and its characteristics [61] include the following:

1. Decentralisation: Blockchain operates on a peer-to-peer network, thereby eliminating the need for a central authority or intermediary to validate transactions.
2. Transparency: Transactions recorded on a blockchain are visible to all participants in the network, thus enhancing trust and accountability.
3. Security: Blockchain uses cryptographic techniques to secure data, thus making it resistant to tampering and unauthorised changes.
4. Immutability: Once data are recorded on a blockchain, they cannot be altered or deleted, thus ensuring the integrity of the information.

These characteristics highlight the potential of blockchain technology to enhance the efficiency, security and accessibility of healthcare services through IoT [26].

#### *4.1.3 Cloud computing, fog computing and edge computing*

Cloud computing, fog computing and edge computing are crucial components of next-generation technologies. They play significant roles in the way data are processed, stored and accessed. They are related to data processing and storage but differ in terms of their proximity to the end devices and their capabilities, as shown in Figure 6 [19, 36].

##### *4.1.3.1 Cloud computing*

Cloud computing involves the delivery of computing services, including storage, servers, databases, networking, software and analytics, over the Internet. It offers on-demand access to a shared pool of configurable computing resources, which can be rapidly provisioned and released with minimal management effort. Cloud computing is typically performed in large data centres and provides massive resources for computation and storage. It is widely used in various applications, including healthcare and allows for the centralised processing of data [75].

##### *4.1.3.2. Edge computing*

Edge computing brings computation and data storage close to the location where it is needed, thereby improving response times and bandwidth saving. It involves processing data near the source of the data rather than relying on a centralised cloud server. This method is particularly useful in scenarios where real-time processing and low latency are critical, such as in healthcare applications. Edge computing devices are located at the edge of the network, and are close to the end devices. They can process and analyse data locally, thereby reducing the need to send all data to a centralised cloud server [13, 35].

#### *4.1.3.3 Fog computing*

Fog computing is an extension of edge computing and is often used interchangeably with it. It refers to a decentralised computing infrastructure in which data, computing, storage and applications are located between the data source and the cloud. Fog computing extends the cloud to the edge of the network, thus bringing the benefits of the cloud close to where data are generated. It can provide efficient data processing and analysis by distributing resources and services across a network [46].

In summary, cloud computing is centralised and provides vast resources over the Internet, while edge and fog computing bring processing and storage close to the data source, thus enabling faster response times and reduced reliance on centralised cloud servers. Each computing paradigm has its own advantages and is suited to different use cases, including those in smart healthcare applications. In [76], the authors proposed a method that indicated that edge-based deployment offers advantages in terms of energy consumption, network usage, cost, execution time and latency compared with fog and cloud deployment in the context of the proposed method.

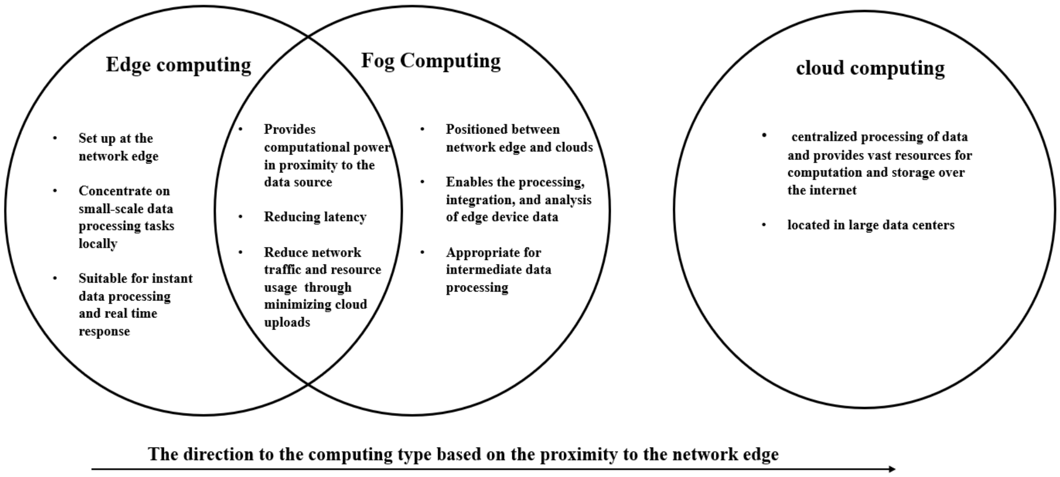


**Figure 6.** Cloud computing, fog computing and edge computing outlines [46]

### *4.1.4. Biotechnology and CRISPR*

Biotechnology involves the use of biological systems, organisms or derivatives to develop new products or applications. CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) is a revolutionary gene-editing technology. Their common types are genomic editing, synthetic biology and personalised medicine.

### *4.1.5. Quantum computing*

Quantum computing utilises the principles of quantum mechanics to perform computations that are infeasible for classical computers. It can solve complex problems much faster than traditional computers. Its common types are superconducting qubits, trapped ions and topological qubits.

### *4.1.6. Augmented reality and virtual reality*

Augmented reality (AR) overlays digital information onto the real world to enhance user perception, while virtual reality (VR) creates a fully immersive digital environment. Their common types are AR applications in gaming, navigation and healthcare and VR for training, simulations and entertainment.

### *4.1.7. Robotics and automation*

Robotics involves the design, construction and operation of robots, whereas automation is the use of technology to perform tasks without human intervention. Their common types are industrial robots, service robots, collaborative robots and process automation [27].

### *4.1.8 Artificial intelligence and machine learning*

AI involves the development of computer systems that can perform tasks that typically require human intelligence, such as visual perception, speech recognition, decision making and language translation. Machine learning is a subset of AI that focuses on enabling machines to learn from data to improve performance over time. AI and ML algorithms can optimise network performance by predicting and preventing potential issues. These technologies can be applied in network management and optimisation to identify patterns, anomalies and areas for improvement in real time. Examples of such types are deep learning, neural networks natural language processing and reinforcement learning, which are subfields of AI and ML [27].

### *4.1.9. 5G Technology*

The last next-generation technology to be discussed in this section is 5G communication technology. It was saved to the end of the section to be discussed so that it can be linked with the next section that focuses on the e-healthcare communication technologies. This technology is considered innovative under the next-generation technologies that are used to enhance the e-healthcare system. 5G networks are the fifth generation of mobile networks that enable real-time communication in the context of IoT in healthcare. Notably, it facilitates continuous patient interaction and remote monitoring. 5G networks' increased speed and reduced latency guarantee that data may be sent and received nearly instantly, thus allowing for prompt responses to urgent medical emergencies. The capacity of 5G networks to accommodate a large number of linked devices is one of the main advantages of 5G networks. This scalability is essential In healthcare settings, where many IoT devices are connected. Healthcare providers can effectively gather and analyse real-time patient data because of 5G networks' high capacity, which guarantees that a significant amount of data can be delivered concurrently. 5G networks' dependability guarantees continuous connectivity [14, 77]. In healthcare applications, real-time communication and continuous tracking are essential. This dependability is especially helpful in remote areas, such as during emergencies when access to medical treatment may be restricted. Healthcare professionals can provide high-quality remote treatment and reduce the distance between patients and medical professionals through 5G networks.

These next-generation technologies are continuously evolving. Their integration and widespread adoption have the potential to reshape industries, improve efficiency and enhance our daily lives.

## *4.2 Wireless Communication Technologies for e-health*

Communication technologies play a pivotal role in e-health systems because they link information technologies and patients' data by transmitting and processing information to improve healthcare outcomes [78]. These technologies enable remote patient monitoring, telemedicine and wearable health devices, thus allowing healthcare professionals to monitor and manage patients' health in real time. Wireless connectivity makes seamless access possible to EHRs and communication within healthcare facilities, thereby enhancing the mobility of healthcare professionals. Furthermore, services based on location improve workflow effectiveness. Meanwhile, immediate decision-making is supported by effective data transfer for imaging. Patient engagement is fostered through mobile health applications and emergency response benefits from rapid and coordinated communication. Overall, wireless networking technologies in healthcare have contributed to increased accessibility, improved collaboration and streamlined healthcare services.

Wireless networks are classified into four distinct groups based on their application area and signal range; Wireless Personal Area Networks (WPAN), Wireless Local-Area Networks (WLANs), Wireless Metropolitan-Area Networks (WMAN) and Wireless Wide-Area Networks (WWANs) [79], as illustrated in Figure 7. Wireless networks can also be classified into two major segments: short-range and long-range [49]. Short-range wireless describes networks that are restricted to a specific area. Local area networks (LANs) and personal area networks (PANs) are covered by this category. These networks often use licensed spectrum that is reserved for industrial, scientific and medical use. The available frequencies vary by country. The frequency bands that are commonly used are 2.4 GHz and 5 GHz and can be found worldwide [78]. In long-range networks, companies selling wireless connectivity as a service typically provide connectivity. This network extends over large areas, such as a WMAN, a state or province or an entire country. The aim of long-range networks is to provide wireless coverage worldwide. The WWAN network is the most widely used network for extended distances [80]. The most commonly wireless communication technologies for healthcare systems are listed in Table 5. Collectively, these wireless networking technologies support the digitalised and interconnected healthcare ecosystem by facilitating effective data sharing, communication and the implementation of innovative healthcare solutions. The particular requirements of every healthcare application as and the overall infrastructure of the healthcare setting determine which technology is best.

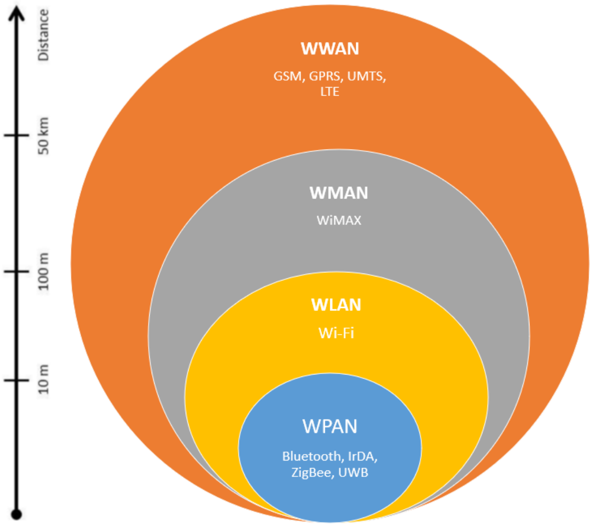


**Figure 7**. Wireless network classification [78]

**Table 5:** Most common wireless communication technologies for healthcare systems

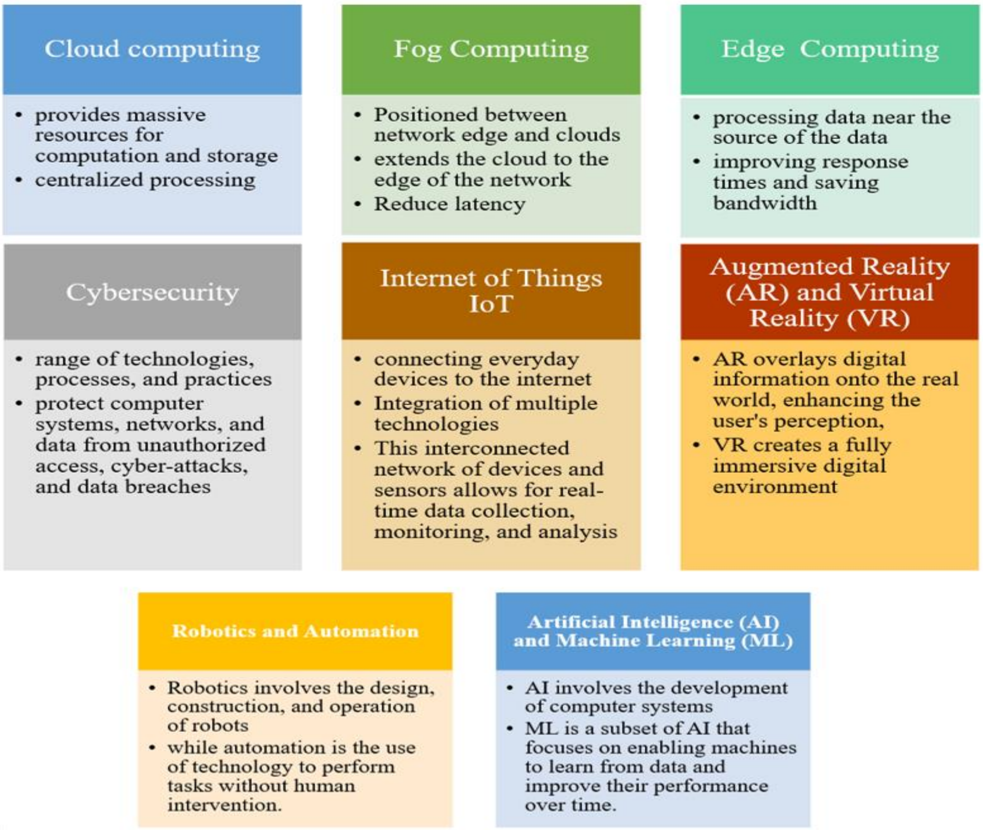
| **Networking technology for data transmission [32, 38, 49]** | | **Description** | **Applications** | **Frequency range MHz** [30] | **Transmission Data Rate Kbps** [30] | **Trans-mission distance** [30] |
|---|---|---|---|---|---|---|
| **Short Range** | **Wireless Local Area Networking (WLAN). Wi-Fi** | A standard that allows fast data transmission over short distances | Used in healthcare institutions to link computers, medical equipment and other devices. | 2500 - 5000 | 1000 - >9.6+E6 | 100 m |

| | | | | | | |
|---|---|---|---|---|---|---|
| | **Bluetooth v5** | Short-range wireless technology for device-to-device connectivity. | Commonly used for connecting medical devices, wearables and mobile devices within close proximity. | 2402 - 2481 | 1000-2000 | 400 m |
| | **RFID (Radio-Frequency Identification)** | RF is used to identify and track objects with RFID tags | Object detection. Asset tracking, patient identification and inventory management within healthcare settings. | 0.125 - 433 | 40-4000 | 100 m |
| | **Zigbee** | Low-power, low-data-rate wireless communication standard for short-range applications | Used in medical sensor networks, patient monitoring and home healthcare systems. | 868 - 2400 | 20 - 250 | 100m |
| | **NFC (Near Field Communication)** | Short-range wireless communication technology for data exchange between devices in close proximity. | Patient identification, access control and secure data transfer between devices. | 13.56 - 14 | 424 - 500 | <0.2 m |
| **Long Range** | **5G Wireless Networks** | Ultra-fast data transfer, low latency and extensive device connectivity | Remote surgeries, augmented reality applications, and high-bandwidth medical data transfer, autonomous vehicles | <800 - >30000 | 1+E6 - 20+6E | Several Km |
| | **LoRa (Long Range)** | The latest cellular network standard provides high-speed, low-latency communication. | Remote patient monitoring, tracking medical equipment and connecting devices in large healthcare facilities | >400 & <950 | > 0.3 _< 50 | 15 Km |
| | **WiMAX** | Similar to Wi-Fi but offers higher transfer rates, broader coverage and more subscribers. | offers high-speed wireless broadband for applications such as fixed wireless access | 2500-5800 | <30000 - >7000 | 5 Km |

| | | | | | |
|---|---|---|---|---|---|
| | | and point-to-point links, thus providing high-speed data connections | | | |
| **Cellular Technologies (2G, 3G, 4G):** | Mobile cellular networks provide wireless connectivity with varying data transfer speeds. | Mobile health (mHealth) applications, telemedicine and remote patient monitoring. | 2G:900-1900<br>3G:900-2100<br>4G:700-2800 | 2G: 9.6-100<br>3G: 144-2000<br>4G: 2000-1E+6 | Several Km |
| **Wearable Technologies (e.g. Smartwatches)** | Integration of various wireless technologies (Bluetooth, Wi-Fi) into wearable devices for health monitoring. | Continuous monitoring of health metrics, medication reminders and fitness tracking | | | |

### *4.3 Quality of service and network performance*

QoS refers to the ability of a network to provide a certain level of service to its users. It is a set of parameters that define the performance characteristics of a network, such as bandwidth, latency, reliability and availability by applying protocols and mechanisms for managing bandwidth, prioritising traffic, minimising latency and ensuring the reliability and availability of services [42]. These QoS parameters are used to ensure that the network meets the specific requirements of the applications and services that run on it as in the context of e-health services to support the delivery of healthcare services [46]. It includes tools to monitor and manage network performance. This feature allows administrators to identify issues, track performance metrics and optimise resource usage. It contributes to ongoing improvements and maintains a high level of network performance especially in environments where various applications have different requirements for data transmission. Each application may require a different QoS. For example, online consultations require high bandwidth, video caching and low latency in emergencies. Meanwhile, remote monitoring necessitates security, high reliability, long battery life and management of small data volumes. Remote surgery requires high reliability and low latency with a requirement of less than 300 ms round-trip time [65]. The QoS requirements are [20, 46] presented in Figure 8. All these requirements depend on the amount of the error data received. Hence, they are related to the rate of data transmission. Each e-healthcare application requires a different data transmission rate related to the speed and accuracy of data transmission [81, 82]. When implementing a network, communication protocols standards are essential to ensure reliable, secure and efficient communication within wireless networks. They provide a framework for devices to interact and exchange data in a standardised and organised manner, thus affecting the choice of the data size [78]. For example, the IEEE 802.15.6 standard addresses the specific requirements of different applications through its medium access control (MAC) layer, which provides flexibility to adapt the access scheme according to the specific users’ requirements. The MAC layer includes various protocols, such as CSMA/CA, TDMA, slotted aloha, scheduled access and polling and posting mechanisms. These protocols allow for tailored communication strategies to meet the diverse needs of applications in WBANs [81]. Table 6 shows the most crucial WBANs applications and the data transmission rates required to accomplish the application task successfully [81, 83].



**Cloud computing**
- provides massive resources for computation and storage
- centralized processing

**Fog Computing**
- Positioned between network edge and clouds
- extends the cloud to the edge of the network
- Reduce latency

**Edge Computing**
- processing data near the source of the data
- improving response times and saving bandwidth

**Cybersecurity**
- range of technologies, processes, and practices
- protect computer systems, networks, and data from unauthorized access, cyber-attacks, and data breaches

**Internet of Things IoT**
- connecting everyday devices to the internet
- Integration of multiple technologies
- This interconnected network of devices and sensors allows for real-time data collection, monitoring, and analysis

**Augmented Reality (AR) and Virtual Reality (VR)**
- AR overlays digital information onto the real world, enhancing the user's perception,
- VR creates a fully immersive digital environment

**Robotics and Automation**
- Robotics involves the design, construction, and operation of robots
- while automation is the use of technology to perform tasks without human intervention.

**Artificial Intelligence (AI) and Machine Learning (ML)**
- AI involves the development of computer systems
- ML is a subset of AI that focuses on enabling machines to learn from data and improve their performance over time.

**Figure 8.** QoS requirements in healthcare

**Table 6:** Most crucial WBANs applications and the data transmission rate required

| WBAN Applications | Signal | Freq (Hz)* accuracy(bits) = required Data Rate |
|---|---|---|
| **Sport and fitness** | Monitoring of:<br>• sweating<br>• respiratory rate<br>• body temperature<br>• pulse rate<br>• motion sensors | Up to 10 Kbps |
| **Health-care applications** | Monitoring of:<br>• vital signs<br>• ECG, EMG and EEG signals | Start from few bps up to 500 Kbps: |
| **Rescue and critical applications** | • vital signs monitoring<br>• voice<br>• GPS positions<br>• motion sensors | Up to 200 Kbps |
| **Newly emerging entertainment and AR applications** | • audio<br>• video signal | Reached beyond 1 Mbps. |

## 5. Sustainability in e-health

Sustainable healthcare refers to the integration of social, environmental, and economic issues into healthcare systems and practices to maintain long-term viability and effectiveness [24]. As shown in Figure 9 [84], it includes reducing the negative environmental effects of healthcare activities, optimising health outcomes and resource efficiency, advancing social justice and equitable access to healthcare and engaging the community in the decision-making process [68]. The aim of sustainable healthcare is to provide high-quality healthcare while minimising waste, energy consumption and environmental harm. The increasing carbon emissions and e-waste generated by IoT devices and data centres pose challenges to the ICT sector in this regard [6]. Some key points regarding these challenges are as follows:

1. Carbon Emissions: Emissions in the atmosphere have increased because of the rapid growth of communication networks, computational requirements, data storage and Internet traffic. An increased carbon footprint results from increased power consumption caused by the growth in data processing in IoT networks. In particular, fast emitters are found to be data centres, whose carbon footprint has increased dramatically over time.
2. Electronic Waste (e-waste): One of the most pressing challenges today is managing and producing e-waste from data centres and IoT devices. However, the issue of appropriate disposal and recycling techniques is highlighted by the fact that only a small percentage of this e-waste is internationally documented and recycled. The e-waste problem is exacerbated by the billions of batteries that must be disposed of to keep IoT devices operating throughout their lives.
3. Sustainability Concerns: To address these concerns, electronic device design, production, deployment and withdrawal must adhere to strict environmental criteria, especially those of the IoT. Energy harvesting and low-power chipsets have been designated as key areas of focus to lower energy consumption and the environmental impact of IoT development.

By encouraging energy-efficient solutions, cutting waste and emissions and increasing public understanding of how technology affects the environment, the Green Internet of Things seeks to make the world a greener place.

Sustainability can be achieved in healthcare systems by utilising green communications to form a communications network between the two sides of the healthcare IoT system. Green communications refers to the implementation of energy-efficient and environmentally friendly practices in communication systems [22]. It focuses on reducing the energy consumption and carbon footprint of wireless networks and improving sustainability while maintaining or enhancing network performance. Network performance parameters, such as throughput, latency and response time, must not be compromised. Hence, finding the right balance between energy efficiency and network performance is crucial to achieve optimal performance while minimising energy consumption [2, 31]. Different wireless network conditions and traffic patterns may require different trade-offs [36]. However, green communication methods aim to optimise the use of network resources, minimise power consumption and promote sustainability in wireless communication technologies [22]. They include strategies, such as sleep mode devices, energy-efficient protocols, resource allocation algorithms and other techniques that enhance energy efficiency and reduce environmental impact in wireless networks [2, 36]. The challenges and limitations mentioned above must be carefully considered when implementing green communication strategies in wireless networks. A thorough understanding of the network environment and the trade-offs between energy efficiency and network performance should also be established.

### *5.1 Solutions proposed to address the environmental impact of IoT devices*

Implementation considerations include initiatives and solutions proposed to address the environmental impact of IoT devices and promote sustainability in the ICT sector [26, 32, 35]. Table 7 outlines some key proposals.

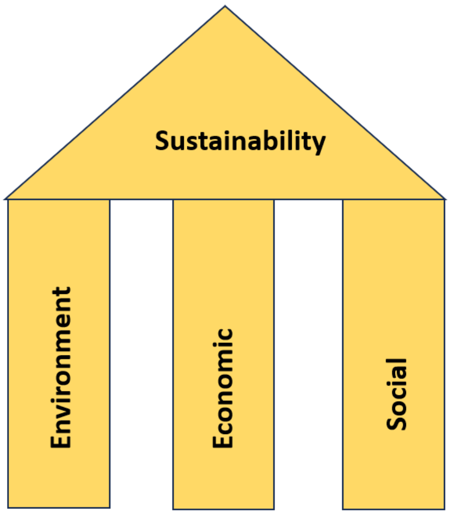


**Figure 9.** Three pillars of sustainability [84]

**Table 7**: Key proposals to address the environmental impact of IoT devices

| Key proposal | Means to address environmental impacts | Ref. |
|---|---|---|
| **Energy-efficient Hardware Design** | IoT devices can function effectively and use less power by utilising energy-efficient hardware parts and designs, thus lowering their carbon footprint. | [30] |
| **Green Internet of Things (GIoT)** | Strategies should aim to reduce harmful pollutants and CO2 emissions, participate in environmental conservation efforts and lower IoT device power consumption | [38] |
| **Software-based data traffic management techniques** | IoT devices can function effectively and use less energy by streamlining data traffic and cutting down on unnecessary data exchanges | [85] |
| **Behavioural Change Models** | Raise awareness of energy conservation among IoT device users and service providers | [30] |
| **Fog/Edge Computing** | A platform that brings cloud services closer to the network’s edge, decreasing power and latency while enhancing the bandwidth, mobility, security and privacy of data | [76] |
| **Circular Economy and Recycling** | Encouraging recycling and reuse goals through laws that support the design of things to be fixed rather than thrown away. | [30] |

The initiatives and solutions proposed in this study address the environmental impact of IoT devices by promoting energy efficiency, optimising data traffic, raising awareness about sustainability, leveraging edge computing technologies and adopting circular economy practises. By implementing these strategies, stakeholders in the ICT sector can reduce the environmental footprint of IoT technologies and promoting a sustainable future.

### *5.2 Energy efficient methods*

E-health systems often require energy-efficient methods to meet the QoS requirements. We present some of the most widely adopted energy management methods for achieving the energy efficiency needed to perform successful efficient e-health applications and systems.

### *5.2.1 Renewable energy resources and energy harvesting*

Renewable energy resources and energy harvesting involve capturing and utilising energy from natural sources. However, they differ in their focus and applications.

Renewable energy refers to energy derived from resources that are naturally replenished on a human timescale. These sources include sunlight, wind, rain, tides, waves, geothermal heat and biomass [39, 40, 86]

The primary goal of renewable energy is to generate electricity without depleting finite resources or causing harm to the environment. For example, solar panels convert sunlight into electricity [37], and wind turbines harness the kinetic energy of the wind to generate power.

Energy harvesting involves capturing and converting small amounts of energy from the environment into usable electrical power. Unlike large-scale renewable energy projects, energy harvesting is often used to power small, low-energy electronic devices or sensors [2, 43].

Energy harvesting technologies can leverage various sources, including ambient light, vibrations, radio frequency signals and thermal gradients [21, 30, 87], as illustrated in Figure 10 [88]. Energy harvesting typically focuses on obtaining small amounts of power continuously or intermittently to maintain or extend the life of batteries; in some cases, it eliminates the need for batteries altogether [2, 21].

Renewable energy sources focus on producing electricity on a large scale to power homes, industries and infrastructure, Energy harvesting is the process of capturing small amounts of energy for particular uses usually in remote or difficult-to-reach places. Solar cells and piezoelectric devices are two examples of energy harvesting technologies that are similar to those used in renewable energy systems. The scale and type of application are the primary differences [38].

Developments in materials and technologies for renewable energy may affect or require adaptations for energy harvesting equipment. For example, small-scale energy harvesting applications and large-scale solar farms can benefit from advancements in the durability and efficiency of solar cells.

Energy harvesting is often used in wireless sensor networks, wearable devices and IoT applications to provide a sustainable and continuous power source for these devices [47]. Renewable energy sources and energy harvesting involve capturing energy from the environment. However, they differ in scale, purpose and application. Both are also considered environmentally friendly and can enhance sustainability. Renewable energy is primarily concerned with large-scale electricity efficiency and sustainability to make communication in wireless systems greener [2]. It allows the achievement of sustainable healthcare system applications in the urban and rural areas. The most relevant energy harvesting sources and their corresponding energy harvesters are stated in Figure 10. systems can achieve long-term uninterrupted monitoring, reduce power consumption and minimise the need for battery [21, 25, 89], this advantage contributes to the overall energy. By harnessing renewable energy sources through energy harvesting techniques, wireless generation, while energy harvesting focuses on capturing small amounts of energy for low-power electronic devices and sensors.

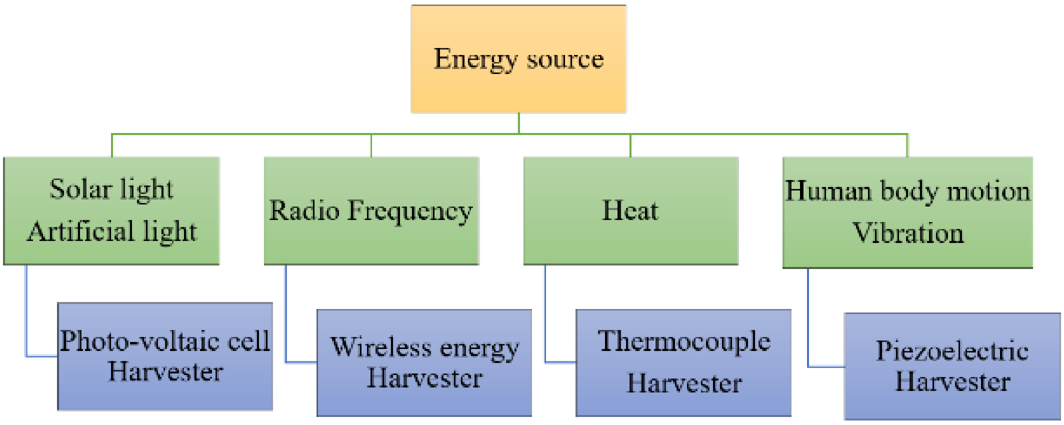


**Figure 10**. Most relevant energy harvesting sources and their corresponding energy harvester [88]

### *5.2.2 Data compression*

One strategy to reduce the energy consumption is data compression. Reducing the quantity of sent data is the goal of several data reduction techniques, including aggregation, communication compression, adaptive sampling and data compression [20, 90]. The goal of communication compression is to lessen that packets that are being sent and received. A data stream that can be represented with fewer bits is created by data compression. To increase a WBSN's lifespan, data compression techniques can be used on sensor nodes or intermediate nodes (cluster heads) to compress the collected vital signs prior to transmission. Therefore, reducing the power consumption of the transceiver unit is an effective strategy to minimise the energy consumption of the WBSN node [91]. Generally, compression works best when it is done at cluster head [20, 28]. Data compression can be lossless or lossy methods depending on the adopted case and application sensitivity and requirements [86, 87].

### *5.2.3 Communication protocols*

A smart and sustained MIoT system must conserve the energy in an optimal manner by using the convenient and developed communications protocols that are defined by standards that are suited to the specific technologies for establishing the data exchange of the application system [62]. The protocols to be discussed in this section are IEEE 802.15.4 and IEEE 802.15.6 as well as the routing protocols [92].

The IEEE 802.15.4 and IEEE 802.15.6 standards have a significant impact on the development of low-power wireless communication technologies especially for IoT and e-healthcare applications. It focuses on how data are transmitted between devices at the local level that are sharing the same channel. IEEE 802.15.4 is a specification that outlines the medium access control (MAC) and physical (PHY) layers for low-rate wireless personal area networks (LR-WPANs). It is commonly employed in applications that require for short-range communication, low power consumption and low data rates, such as smart homes, industrial automation and healthcare monitoring [93]. Operating in unlicensed frequency ranges (2.4 GHz, 868 MHz, and 915 MHz), IEEE 802.15.4 supports data speeds of up to 250 kbps, thus making it a perfect option for resource-constrained devices that require lengthy operational lifetimes on limited battery resources. IoT ecosystem development is facilitated by several protocols, such as Thread, 6LoWPAN and ZigBee, which rely on the IEEE 802.15.4 standard for dependable low-power communication [32]. Nevertheless, IEEE 802.15.6 is made especially for WBANs, which allow wearable and implantable medical devices to have ultra-low power, reliable, short-range wireless communication [44]. The IEEE 802.15.6 standard defines three PHY layers, that is, narrowband (NB), ultra-wideband (UWB), and human body communications (HBC) layers depending on the application, which can be medical or nonmedical [93]. The IEEE 802.15.6 offers increased security and privacy methods to protect data confidentiality and integrity, particularly given the sensitivity of medical data. This aspect is crucial for telemedicine applications and continuous health monitoring. While both standards underline low-power communication, IEEE 802.15.6 stands apart from IEEE 802.15.4 because of its emphasis on body-centric communication and strict energy efficiency criteria especially in the healthcare industry where power conservation and dependability are crucial. Together, these standards provide a solid foundation for the development of e-healthcare systems, thus allowing for safe, effective and continuous patient monitoring in real-world environments. In the context of routing protocols, heterogeneous and complicated network topologies, such as WBANs, can be made flexible, manageable and efficient with the help of the SDN method. Given the restricted energy of the sensor nodes, the network lifetime in the software-defined WBAN (SD-WBAN) design must be increased. One of the most significant energy-consuming operations in SD-WBANs is the routing process [33]. Cicioğlu and Çalhan [31] proposed a WBAN architecture based on the SDN approach with a new energy-aware routing algorithm for healthcare architecture that performs the most appropriate route determination with a central and reactive (on-demand) approach among many SD-WBAN users.

### *5.3 Energy consumption analysis of the MIoT*

For the sustainability of e-health applications, applying energy efficient methods, such as energy harvesting over the sensor technology near the patient body (Figure 10), as well as applying the data compression technique on the processed data before its transmission can enhance the system efficiency in terms of latency, energy consumption because of transmission, improved resource allocations and enhanced network performance because of decreased retransmissions and congestion. The amount of the harvested energy can compensate for the amount of the consumed energy by the compressor. It will enhance the restricted battery lifetime of the sensor and promote useful harvesting when combined with data compression. Moreover, it can help obtain feasible energy harvesting and renewable solar systems with small dimensions. In addition, applying convenient and developed communication protocols will be beneficial [25, 43].

To clarify the feasibility of any proposed energy harvesting techniques and the applied data compression technique, an energy consumption analysis for the basic units of the MIoT sensor technology must be conducted. This examination can compare it with the energy produced by the proposed harvesters and the energy consumed by the transmission process. This approach can explain the positive impact of the data compression on the percentage transmission energy consumption because the compression ratio is equal to the amount of energy saved from the transmission process as mentioned in the literature [90, 94, 95]. The additional power consumed by the data compression process is assimilated by the energy harvesting. Meanwhile, the profit reduces the size of data largely with the same information approximately. The basic units of the MIoT are the sensing unit, processing unit, transmission unit and storage unit. A compression unit is added if the system uses the data compression technique [96]. Most studies agree with taking only the sensing, processing and transmission units into account in the energy consumption analysis. In this way, he energy consumption analysis can be conducted properly [85]. Others neglect all the units' consumptions except the transmission unit for its extremely high energy consumptions compared with other units. Several energy efficient protocols, such as those used for managing the units' mode of operation (duty cycling) and for the simplicity of analysis, can be applied. It only has two modes of operations: the active and sleep modes. For the sensing units, the typical recording response time for each sensor type is assumed, as illustrated in the corresponding datasheets. Equations (1) to (12) [41, 97] express the analysis for the general

MIoT node depending on the general energy consumption rule, which is equal to the consumption current * operating voltage * time delay.

$E\_active + E\_sleep,$ (1)
$E\_active = Iactive * V * t_a,$ (2)
$E\_sleep = Isleep * V * t_s,$ (3)

The MIoT unit daily energy consumption =
where:
Iactive: active mode current consumption in ampere
Isleep: Sleep mode current consumption in ampere
V: Operating voltage in volts, which is mostly equal to 3.3 V [98].
$t_a$: Daily active time in seconds
$t_s$: Daily sleep time in seconds

The general active and sleep time for all the sensor basic units can be found as:

$t_a = n * T,$ (4)
$t_s = 24\ h - t_a,$ (5)
where:
n: Daily no. of sensor measurements
n = 24 hours * 3600 seconds / measurement period in seconds, (6)
where:
The measurement period is the time taken by the sensor to sense a signal from the body (in seconds)
T: unit processing time delay in seconds. Depending on the clock frequency and the rate of the technology used. T is repeated by n times. See table 8.

To find the overall MIoT energy consumption by the assumed units:

Daily Energy Consumption (Ed)
= Ed_sensing + Ed_ADC + Ed_processing + Ed_compression + Ed_ transmission (Joule/day), (7)
which is also equal to summation of (E_active + E_sleep) for each unit. Hence;

Ed_Sensing = E_s Active + E_s Sleep
$= [(I_{sa} * V * t_{sa}) + (I_{ss} * V * t_{ss})] * n,$ (8)
where:
$I_{sa}$: Sensor active current in Ampere
$I_{ss}$: Sensor sleep current in Ampere
$t_{sa}$: Sensor active time in seconds
$t_{ss}$: Sensor sleep time in seconds

In the same way, the other units' energy consumptions can be found as:

Ed_ADC = E_ADC Active + E_ADC Sleep
$= [(I_{ADCa} * V * t_{ADCa}) + (I_{ADCs} * V * t_{ADCs})] * n,$ (9)
Ed_processing = E_p Active + E_p Sleep
$= [(I_{pa} * V * t_{pa}) + (I_{ps} * V * t_{ps})] * n,$ (10)
Ed_compressor = E_c Active + E_c Sleep
$= [(I_{ca} * V * t_{ca}) + (I_{cs} * V * t_{cs})] * n,$ (11)
Ed_transmission = E_t Active + E_t Sleep
$= [(I_{ta} * V * t_{ta}) + (I_{ts} * V * t_{ts})] * n,$ (12)
where:
$I_{pa}$: microcontroller active current in ampere
$I_{ps}$: microcontroller sleep current in ampere
$t_{pa}$: microcontroller active time in seconds
$t_{ps}$: microcontroller sleep time in seconds
$I_{ADCa}$: ADC active current in ampere
$I_{ADCs}$: ADC sleep current in ampere
$t_{ADCa}$: ADC active time in seconds
$t_{ADCs}$: ADC sleep time in seconds
$I_{ca}$: compressor active current in ampere
$I_{cs}$: compressor sleep current in ampere
$t_{ca}$: compressor active time in seconds
$t_{cs}$: compressor sleep time in seconds
$I_{ta}$: transmitter active current in ampere
$I_{ts}$: transmitter sleep current in ampere
$t_{ta}$: transmitter active time in seconds
$t_{ts}$: transmitter sleep time in seconds

After applying the necessary calculations using the above equations, an indication can be obtained for the energy consumed by the MIoT units and the necessary battery capacity to be equipped. The appropriate energy harvesting technique with the appropriate harvesters dimensions can be applied to support sustainability. With these necessary calculations, a clear insight to the capability limits of the application can be obtained to test the effectiveness or help select the appropriate communication network or devices used. In other words, if the calculations results are outside of the acceptable ranges of the required energy for a specific required distance and required application data transmission rate (as in Table 6), when used with the chosen communication network, changing the electronics devices with efficient devices is a solution is faster and consumes less energy. Each device has its own clock speed, which needs the corresponding power consumption (as illustrated in Table 8). A communication network that is used with its infrastructure, such as the related Tx module model or the microcontroller device can be changed. Each wireless communication network with its specific coverage distance (listed in table 7) cannot deliver the data to the required distance unless it has sufficient power. Maintaining signal quality and data throughput requires powerful electronics, transmission power, and frequently complex processing (such as signal amplification before transmission). Hence, a longer network coverage distance typically results in increased energy usage. Low-power electronics and optimal coverage techniques (such mesh or multi-hop networks) are frequently utilised to balance energy and distance requirements for effective, Internet-enabled e-healthcare networks.

These energy consumptions analysis can be made to test and improve the e-health system performance in several directions. It can also be considered as the first step in paving the way to use the sustainable methods with the MIoT devices. This approach is a novel thought for supporting sustainability and is not found in all the studies mentioned in Table 1.

**Table 8:** MIoT basic units processing time delay

| Unit | Symbol | **Unit (component) processing time delay equation (in seconds)** [99, 100] |
|---|---|---|
| **Sensor** | $T_s$ | $t_R$ |
| **ADC** | $T_{ADC}$ | $1/F_{ADC}$ * ADC accuracy bits |
| **Processor (microcontroller)** | $T_{MCU}$ | (number of operations / $F_{MCU}$ )* ADC accuracy bits |
| **Compressor** | $T_{comp}$ | (number of uncompressed sensor bits) / C_Rate) + β*CR |
| **Transmitter** | $T_{TX}$ | (Compressed data bits/ R) |

Where:
$t_R$: Response time of the sensor in seconds (the time taken to read (sense) a signal from the body)
$F_{ADC}$: Analogue to digital convertor clock frequency in hertz
$F_{MCU}$: Microcontroller clock frequency in hertz
C_Rate: the compressor compression rate
β: Algorithm complexity factor (depend on the coding technique).
R: transmission rate of the RF module

## 6. Conclusions

Electronic healthcare systems based on integrated technologies, such as communications technology, information technology and sensor technology, have led to access to healthcare services provided by applications that meet all the requirements for the success of this service. This research concluded that e-health applications and services can be classified according to different categories, such as their mobility into fixed, wearable, portable, implanted and smart clothing. In addition, they can be classified based on their position in indoor and outdoor applications as well as based on context information, such as emergency or nonemergency services. Each healthcare application has its own requirements, such as selecting the type of sensory technology that is suitable for the type of data to be collected as well as choosing the type of communication network to fulfil its requirements based on speed and size of data transmission as well as distances. Selecting traditional information technology that will be used with emerging technologies has emboldened the development of health care services to become efficient, reliable, robust, inexpensive, personalised; Hence, enhanced services have optimised patient outcomes. The use of sustainability in healthcare systems is critical to providing environmentally friendly and user-friendly solutions by providing renewable energy sources either at the base station of the communications network to operate application devices or sensor nodes. These strategies have decreased fossil fuel energy consumption and emissions of environmentally contaminated carbon footprints and pollution. They have also reduced the need for frequent battery switches, thus resulting in cost-savings. This kind of sustainability can be achieved by applying green wireless communication network strategies. IoT technology, which is a combination of integrated technologies, such as sensors and actuators, communication technologies, IoT platforms (cloud computing), cybersecurity, edge computing, artificial intelligence and 5G, can be applied to monitoring health care systems to enhance sustainability and maximise the benefits of IoT and enhance patient care. The most common energy-efficient methods used to enhance the sustainability of e-health systems include data compression and appropriate energy-harvesting techniques; when combined, they can be incorporated into the power supply while saving energy [41]. Data compression reduces the data size to be transmitted. Hence, the transmission energy consumption and delay are improved. However, the computational processing complexity increases because of the compression algorithms performed by the compressor, which consumes more energy. The additional power consumed by data compression is assimilated by energy harvesting. Meanwhile, the profit reduces the size of data with approximately the same information, thus improving the power supply and network performance and enhancing the sustainable storage.

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