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A review of IoT applications in healthcare

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ABSTRACT

Integrating Internet of Things (IoT) technologies in the healthcare industry represents a transformative shift with tangible benefits. This paper provides a detailed examination of IoT adoption in healthcare, focusing on specific sensor types and communication methods. It underscores successful real-world applications, including remote patient monitoring, individualized treatment strategies, and streamlined healthcare delivery. Furthermore, it delves into the intricate challenges to realizing the full potential of IoT in healthcare. This includes addressing data security concerns, ensuring seamless interoperability, and optimizing the use of IoT-generated data. The paper seeks to inspire practitioners and researchers by highlighting the practical implications of IoT in healthcare, emphasizing the ways IoT can enhance patient care, resource allocation, and overall healthcare efficiency.

1. Introduction

The Internet of Things, abbreviated as the IoT, is a revolutionary and rapidly evolving technology that has the promise to change the way we interact with our surroundings [1–3]. It is estimated that by 2025, there will be over 75 billion connected devices worldwide [4]. The healthcare industry is one of the sectors that is expected to benefit greatly from this growth.

IoT involves the interconnection of different kinds of physical subjects, types of equipment, and sensors via the Internet, enabling them to communicate with each other and share data [5,6]. In healthcare, IoT technologies are already being used to improve patient care and outcomes, offering new opportunities for remote monitoring [7,8], personalized treatment plans [9], and efficient healthcare delivery [10]. The IoT is also transforming industries beyond healthcare, such as manufacturing [11], transportation [12,13], and agriculture [14], and has the potential to reshape our society as a whole. As such, it is crucial to stay abreast of the latest developments in this exciting field and explore the ways in which IoT can be leveraged for positive change.

In addition to improving patient care, the IoT can substantially and greatly reduce healthcare prices by streamlining processes, automating routine tasks, and decreasing the need for expensive interventions. It enhances patient care by enabling real-time data collection and monitoring, thereby improving response times and patient outcomes. Secondly, IoT technologies streamline healthcare operations by automating administrative tasks, which not only saves time but also reduces the need for an extensive administrative workforce, resulting in cost savings. Moreover, routine tasks like vital sign monitoring and medication dispensing can be automated, decreasing the risk of errors and lowering labor costs. Most significantly, IoT's early detection and continuous monitoring capabilities help in averting costly medical complications, reducing hospitalizations, and mitigating the need for expensive interventions, ultimately lowering healthcare costs significantly. It can also improve patient engagement [15] by giving patients greater control over their healthcare, allowing them to track their health data and communicate more effectively with healthcare providers. Wearables and apps monitor vital signs, while patient portals offer access to medical records. Telemedicine and remote monitoring facilitate virtual appointments and real-time data sharing. Mobile apps help in self-management and data sharing, and secure messaging systems promote direct communication with healthcare providers. IoT devices automatically transmit data. Education and training are essential to ensure users can confidently navigate these technologies. By utilizing these tools, individuals become active participants in their healthcare, fostering better communication, engagement, and, ultimately, improved health outcomes.

The use of IoT in healthcare brings with it a host of challenges and limitations that must be carefully navigated. These include concerns

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about data privacy and security [16], interoperability issues [17], and the need for standardized protocols and regulations [18]. Data privacy and security concerns are paramount, as the collection and transmission of sensitive medical data require stringent safeguards to protect patient privacy. Interoperability issues can arise due to the multitude of vendors and technologies involved in the development of IoT devices, which can lead to data silos and inefficient communication [19]. Standardized protocols and regulations are also critical to ensure that IoT devices can seamlessly integrate with existing healthcare systems and networks.

Overall, the IoT is an exciting technology that is important for healthcare providers, policymakers, and researchers to stay abreast of the latest developments and work collaboratively to address the challenges and limitations associated with its use. This paper aims to contribute to this effort by providing a comprehensive overview of the IoT in healthcare and its potential to transform the healthcare industry.

2. IoT technologies in healthcare

2.1. Sensors

Sensors are an essential component of IoT devices. They can measure and transmit data from various sources, such as temperature, blood pressure, heart rate, glucose levels, and more. These sensors can be integrated into wearable devices, medical equipment, and even inside the human body. Tables 1–4.

Apart from these well-established sensor technologies, researchers have been striving to create more cutting-edge ones.

The VITALS system [20] is an online life-signs sensor that uses four physiological indicators perceived by clinical equipment. It includes a microcontroller, a wireless communication module, and a system for big data analysis. Life signs are extracted and transmitted to the analysis system every half an hour. The system was implemented for one week during the experiment and demonstrated improved care options, particularly for those with restricted access to medical care. The proposed heart rate sensor [21] utilizes the MAX30102 sensor, which emits visual light in the 650–670 nm wavelength range. The sensor is worn on the wrist and records the heart rate signal in the shape of a comparatively flat wave, which is then processed using the detrend method to obtain precise data. This research [22] aims to develop a novel sensor using micro pyramid-assisted piezoelectric film (MPF) technology to constantly monitor blood pressure non-invasively. The results show that the results measured in practice with this MPF sensor are comparable to those obtained with the more proven industrial products available currently. This study [23] presents a new method for continuous blood pressure monitoring that requires the use of only one signal and no additional sensors and does not require calibration. A pulse oximeter has been created to measure heart rate, blood oxygen saturation, and body temperature [24]. The device uses infrared light and sensors to detect body temperature without contact and displays it on an LCD screen and web browser. The paper [25] describes a novel paper-based capacitive humidity sensor that achieves ultra-high humidity sensitivity and high

Table 1
Common sensors.

Sensor Type	Measurement	Clinical Application (s)
Electrocardiogram	Electrical activity of the heart	Detecting arrhythmias, heart disease
Pulse Oximeter	Oxygen saturation levels and heart rate	Monitoring oxygenation during surgery, COPD, asthma
Blood Pressure	Blood pressure	Monitoring hypertension and hypotension
Glucose	Glucose levels in the blood or interstitial fluid	Monitoring diabetes
Temperature	Body temperature	Detecting fevers or hypothermia
Respiratory	Respiratory rate and rhythm	Monitoring breathing disorders such as sleep apnea

Table 2
A comparison of research on remote monitoring.

Reference	Year	Communication	Advantage (s)
[95]	2022	Wifi	● Continuous monitoring of vital health indicators ● Prompt resolution of issues by healthcare professionals.
[96]	2022	Cloud	● Alert Notification for Abnormal Events and Emergencies ● Validation of Effectiveness and Reliability
[97]	2022	Wifi	● Integration of IoT and medical promotion platform ● Evaluation of accuracy and performance ● Identification of optimal body parts for temperature monitoring
[98]	2022	Cloud	● Promotion of the integration of IoT and healthcare
[99]	2023	-	● Remote delivery of healthcare services with expert support, ● Efficient data collection and mining ● The overall enhancement of patient health surveillance efficiency.
[100]	2022	Cloud	● IoT Cloud Server Integration ● Real-Time Data Collection and Analysis ● Alert Mechanism ● Data Input Variety
[101]	2023	Cloud	● Focus on Post-Covid scenarios ● Co-morbidity monitoring
[102]	2023	Cloud	● Focused on emergency medical services ● Dependability and high success rate for IoT data broadcasts ● Exciting performance with high accuracy in vital sign
[103]	2023	Cloud	● Store and learn knowledge for future state prediction ● Achieves an impressive accuracy rate of 99.53 %
[104]	2023	Wifi	● Influenza Symptom-Based Detection ● Broad Application Scope

Table 3
A comparison of research on locating.

Reference	Year	Target	Advantage (s)
[105]	2023	Patients	● Development of a UAV-based radar array system ● Weighted CRB-based source localization
[106]	2023	Healthcare Resources	● Replacement of the existing barcode system ● Smart specimen transport box ● Cloud-based monitoring
[107]	2023	Patients	● Integration of multiple sensing technologies ● User-friendly interface
[108]	2023	Patients	● Supporting complex functionalities and address environment-wellness relationships ● Environmental sensing and wellness monitoring
[8]	2023	Patients	● Tracks critical health parameters ● Provides timely medical decisions based on abnormal values
[109]	2023	Patients	● In the context of the COVID-19 pandemic
[110]	2023	Healthcare Resources	● Potential Application in Healthcare ● Automatic Notification and Prompt Action ● Web Server Integration

Table 4
A comparison of research on personalized medicine.

Reference	Year	Target	Advantage (s)
[15]	2023	Customized treatment based on patient populations	● Fostering shared decision-making
[111]	2022	Personalized diabetes management	● Focus on Personalized Diabetes Management ● Contribution to Prognosis Improvement
[112]	2022	Individualized dietary recommendations	● IoT-based mHealth Monitoring System ● Consideration of Physical Activity ● Targeted at Children with Type 1 Diabetes
[113]	2022	Personalised dental prediction and treatment	● incorporating personalized medicine in dental care
[114]	2023	Personalized diabetes care	● Utilization of 5G technology for real-time monitoring of diabetic patients' health. ● Personalized care based on real-time data.
[115]	2023	Personalized monitoring	● The development of a hybrid algorithm for optimal feature selection
[116]	2022	Personalized monitoring	● Enabling quick adaptation of the well-generalized model

sensitivity with fast response/recovery. In addition, the proposed sensor exhibits great stability in the monitoring of breathing. It can provide an accurate recording of the breathing rate and depth of the patient in each respiratory pattern.

2.2. Communications

Communication technologies such as Bluetooth, Wi-Fi, and cellular networks are crucial for enabling data transfer between IoT devices and healthcare providers. These technologies help establish a seamless and real-time communication network between patients, healthcare providers, and medical equipment. Communication technologies such as Bluetooth, Wi-Fi, and cellular networks are instrumental in the seamless integration of IoT devices within healthcare. Bluetooth enables close-range, low-power connections, perfect for wearable health gadgets, allowing real-time monitoring and data transmission to patient smartphones [7]. Wi-Fi facilitates efficient data sharing within healthcare facilities, enabling the transfer of electronic health records and medical images. Cellular networks [26], including 4 G and 5 G, offer broad coverage for remote patient monitoring and telemedicine, ensuring healthcare providers have access to vital patient data regardless of location. Together, these technologies form a dynamic network that supports real-time communication, fosters timely decision-making, and enhances patient care. However, data security and privacy remain paramount considerations in their implementation.

There are several types of IoT communication technologies that are commonly used in healthcare, including:

2.2.1. Wi-Fi

Wireless internet connectivity is commonly used to connect IoT devices to the internet and allow data to be transmitted across short distances, as shown in Fig. 1. It was first presented in 1997 [27] and has since become one of the most widely used wireless communication technologies, providing trustworthy and fast connectivity to billions of devices globally [28]. This technology operates on the IEEE 802.11 standard [29], which provides the technical specifications for wireless local area networks (WLANs). Wi-Fi allows multiple devices to connect and communicate with each other.

In recent years, Wi-Fi technology has continued to evolve, with the introduction of new standards such as Wi-Fi 6 and Wi-Fi 6E [30]. These standards provide faster speeds, corrected security, and increased capacity, allowing the advancement of new applications and services that require high-speed connectivity and low latency. As Wi-Fi continues to develop and improve, it is expected to play an increasingly important role in the medical industry and other sectors that require reliable and fast wireless connectivity[31].

2.2.2. Bluetooth

The name "Bluetooth" was inspired by Harald Bluetooth, a Viking king who unified Denmark and Norway in the 10th century. The name symbolizes the idea of uniting different devices through wireless communication. Developed by the Swedish telecommunications company Ericsson in 1994, this wireless communication technology is often used to connect IoT devices and smartphones or other mobile devices. Bluetooth technology uses the frequency-hopping spread spectrum (FHSS) [32] to avoid interference from other wireless devices operating in the same frequency range. The technology operates in the unlicensed industrial, scientific, and medical frequency bands, typically within the

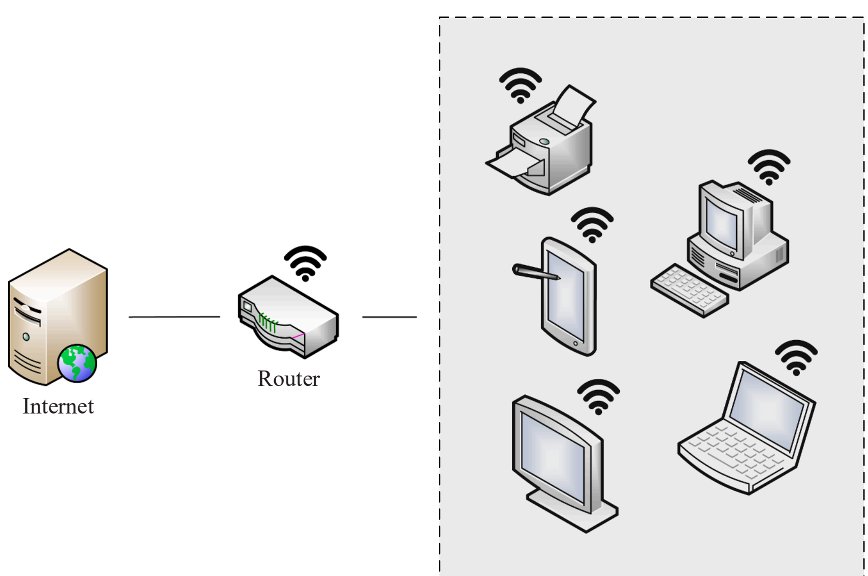

Fig. 1. Data transmitted across short distances through Wi-Fi.

range of 2.4–2.4835 GHz [33].

2.2.3. Zigbee

Zigbee is a low-power wireless communication protocol normally used for low data rate and long battery life IoT applications, such as remote patient monitoring devices. Zigbee was developed in the early 21st century [34], and the first version of the standard was released in 2004 [35]. Zigbee uses a mesh network topology, which gives. Key features of Zigbee include low power consumption, support for mesh networking, a focus on low data rates, and a cost-effective approach. It's known for its ability to enable devices to communicate wirelessly while conserving energy, making it well-suited for battery-powered IoT devices. This is achieved through the use of sleep modes, in which devices can turn off their radios and consume very little power when they are not actively sending or receiving data. Zigbee also uses a collision avoidance technique called CSMA-CA to reduce the likelihood of data collisions [36].

2.2.4. Near Field Communication (NFC)

Near Field Communication (NFC) [37] is a short-range wireless communication technology that allows devices to communicate with each other over a distance of a few centimeters, as shown in Fig. 2. NFC is based on Radio Frequency Identification (RFID) technology, which uses electromagnetic fields to transfer data wirelessly between two devices. NFC technology enables a wide range of applications, such as contactless payments, access control, and data exchange between devices [38].

2.3. Cloud

While the cloud itself is not a communication technology, Cloud [39–41] provides a platform for storing [42], managing[43], and analyzing colossal amounts of healthcare data generated by IoT devices [44], as shown in Fig. 3. It has revolutionized the way businesses and individuals access and use computing resources, making it easier and more cost-effective to store and process large amounts of data.

The origins of cloud computing can be traced back to the 1960s [45], when early versions of utility computing were first developed. However, it wasn't until the late 1990s that the concept of cloud computing began to take shape [46].

In the context of healthcare IoT, by using cloud computing to store and process medical data, healthcare providers can reduce costs, improve patient outcomes, and enhance the overall quality of care. For example, cloud computing can be used to store electronic health records securely [47], making it easier for healthcare professionals to access and share patient data across different organizations and systems [43]. It can also be used to store and analyze large amounts of data from wearable devices and other medical IoT devices, allowing healthcare providers to detect and treat diseases more effectively. Additionally, cloud computing can provide real-time insights into patient health, enabling healthcare professionals to make more informed decisions and improve patient outcomes.

2.4. Artificial Intelligence (AI)

AI algorithms have emerged as powerful tools in healthcare, particularly when combined with data from IoT devices. By leveraging the vast amount of data these devices generate, AI algorithms can provide real-time insights into patient health and enable personalized healthcare interventions.

Machine learning models [48], a subset of AI, can analyze and identify patterns in IoT data to predict disease progression and suggest personalized treatment plans. These models can learn from historical data and detect subtle changes or anomalies in a patient's health parameters, allowing for early detection of potential health issues.

In the context of IoT in healthcare, AI algorithms can analyze data from wearable devices and other IoT sensors to monitor life functions, activity rates [49], sleep patterns [50], and other relevant metrics. By continuously monitoring and analyzing this data, AI algorithms can provide clinicians with early warnings of health deteriorations or relapses, enabling timely interventions and improved patient outcomes.

Furthermore, AI algorithms can utilize the collected IoT data to generate individualized care schemes [51]. By considering individual patient characteristics, medical history, and real-time data, these algorithms can analyze large datasets to identify optimal treatment strategies tailored to each patient's specific needs.

Incorporating the synergistic capabilities of AI and IoT will unveil a transformative healthcare model poised with improved streamlining and a steadfast focus on patient-centric methodologies. This evolution is characterized by marked advancements in predictive preciseness, underpinned by a nuanced, personalized approach to therapeutic strategies, signifying a monumental shift towards a future of healthcare imbued with technological innovation and customized care pathways.

2.5. Blockchain

The combination of blockchain technology [52–54] and IoT in healthcare holds tremendous potential for enhancing data security and facilitating seamless data sharing among healthcare providers. Via harnessing the blockchain's decentralized and immutable nature [55], patient data can be safeguarded against unauthorized access, tampering, and breaches. Through its distributed ledger system, blockchain ensures that each transaction or data entry is cryptographically secured and linked to previous records, creating an unalterable chain, as shown in Fig. 4. This not only preserves the integrity of patient data but also provides transparency and accountability in data management.

With blockchain, healthcare professionals can securely access and exchange relevant patient information, regardless of geographical or organizational boundaries. This streamlined data sharing promotes better care coordination, as it allows healthcare providers to have a

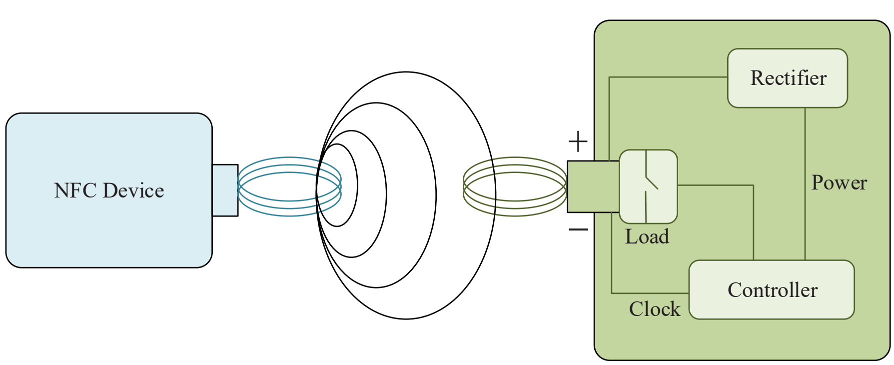

Fig. 2. NFC architecture.

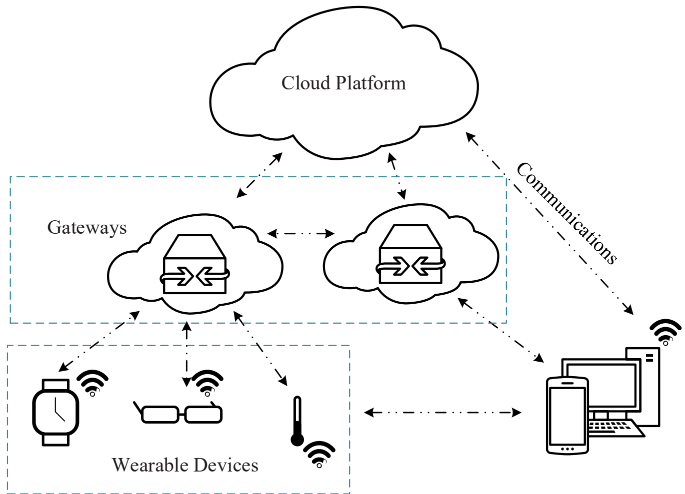

Fig. 3. Cloud computing in IoT.

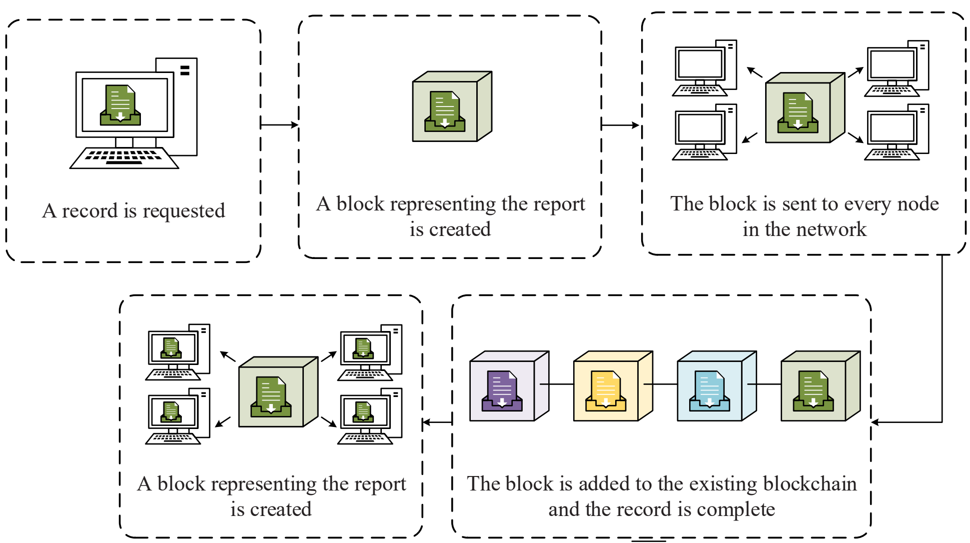

Fig. 4. How blockchain works.

comprehensive view of a patient's medical history and make informed decisions. Patients can have more control over their own data by granting permission for specific healthcare providers to access their information. The use of smart contracts, a self-executing code on the blockchain, automates data-sharing agreements and ensures compliance with privacy regulations, giving patients greater transparency and control over their data.

2.6. Edge computing

Edge computing [56,57] plays a pivotal role in IoT in healthcare, offering significant advantages in real-time data processing and improved performance.

In the context of IoT in healthcare, edge computing addresses the challenges posed by network latency and the need for fast response times [58]. Traditionally, IoT devices would transmit data to centralized cloud servers for processing and analysis, which can introduce delays in critical healthcare applications. However, with edge computing, data processing occurs at the edge of the network, near the data source itself.

One of the key benefits of edge computing in healthcare is reduced network latency [59]. By processing data locally on IoT devices, edge computing minimizes the time required for data to travel back and forth between the device and a distant cloud server [60]. This enables real-time or near-real-time analysis of healthcare data, crucial in time-sensitive applications such as remote patient monitoring, emergency response systems, and continuous health monitoring [61].

Furthermore, the introduction of edge computing significantly bolsters the integrity and confidentiality of data within IoT healthcare infrastructures. By ensuring that sensitive health-related information is retained and processed directly on the devices, edge computing minimizes the vulnerability to unauthorized intrusions and potential data compromise. In the realm of healthcare, where the sanctity of data is held in the highest regard, such an enhancement is instrumental in fortifying the resilience of information systems against breaches, thereby safeguarding patient data with reinforced security protocols. This approach underscores a meticulous consideration of privacy, substantiating a robust framework where data security is meticulously upheld.

Additionally, edge computing enables offline operation and resilience to network failures [62]. In scenarios where internet connectivity is intermittent or unavailable, edge devices can continue to function and process data locally, ensuring uninterrupted healthcare services and critical operations.

2.7. 5G

In the context of IoT in healthcare, 5G networks enable real-time communication [63], allowing healthcare providers to monitor remotely [64] and interact with patients in a continuous manner. The enhanced speed and low latency of 5G networks ensure that data can be transmitted and received almost instantaneously, enabling timely responses to critical healthcare situations.

One of the key advantages of 5G networks is their ability to support a vast number of connected devices [65]. This scalability is crucial in healthcare settings where numerous IoT devices are interconnected. The high capacity of 5G networks ensures that a large volume of data can be transmitted simultaneously, enabling healthcare providers to efficiently collect and analyze real-time patient data.

The reliability of 5G networks [66] ensures uninterrupted connectivity, which is essential in healthcare applications where continuous monitoring and real-time communication are critical. This reliability is particularly beneficial in remote areas or during emergency situations where access to healthcare services may be limited. With 5G networks, healthcare providers can deliver high-quality care remotely and bridge the gap between patients and medical experts. The reduced delay in data transmission ensures that healthcare providers can access and analyze patient information promptly, enabling timely diagnoses, treatment adjustments, and interventions.

Furthermore, 5G networks provide the foundation for advanced technologies in healthcare, such as augmented reality (AR) [67,68], virtual reality (VR) [69,70], and telepresence [71,72]. These technologies have the potential to revolutionize medical education [73,74], surgical training [75,76], and remote patient care [77,78] by enabling immersive experiences and remote collaboration among healthcare professionals.

3. IoT in different healthcare settings

3.1. Indoor healthcare environments

In indoor healthcare environments such as hospitals, IoT devices can be used to monitor patients, manage medical equipment, and track inventory. IoT sensors can also monitor environmental factors such as temperature, humidity, and air quality, which can help prevent the spread of infections.

In indoor healthcare environments, IoT offers helpful functions for tracking the location of patients and healthcare staff. Through utilizing wearable devices, RFID tags [79], or smartphone-based solutions, real-time monitoring of individuals' movements becomes possible. This technology facilitates efficient navigation, optimizes workflow, and enhances emergency response times, leading to improved patient care. This paper [80] proposes a deep CNN-LSTM architecture for indoor location estimation using a Passive Infrared (PIR) sensor in IoT healthcare systems. This paper [81] focuses on the use of an IoT model to analyze audience behavior in a resort, specifically emphasizing the indoor system for tracking individuals' movements and identifying their behavioral patterns.

Furthermore, indoor location technology enables the tracking and management of medical equipment and assets. By attaching RFID tags or utilizing sensor networks, healthcare providers can efficiently monitor medical devices' location, usage, and maintenance needs, ensuring their availability when needed and reducing costs associated with equipment loss or misplacement. This research [82] proposes a non-intrusive indoor location framework using wireless sensor networks for IoT healthcare. Through blockchain-based smart contracts, it implements role-based access control for system security.

IoT-based indoor localization systems also contribute to environmental monitoring in healthcare facilities. By deploying sensor networks, parameters such as temperature, humidity, air quality, and occupancy can be monitored in real-time [83]. This enables automated adjustments to ensure a comfortable and safe environment for patients and staff while also promoting energy efficiency and reducing the risk of healthcare-associated infections. This research [84] focuses on an indoor system for IoT healthcare using visible light communication. It investigates a MIMO VLC system that monitors indoor environments, collects data, and employs different modulation techniques for reliable communication. It offers an efficient solution for monitoring various data types in IoT healthcare applications.

In terms of security and emergency response, IoT in indoor healthcare environments facilitates the implementation of advanced surveillance systems, access control, and emergency call systems. These technologies enhance security measures, prevent unauthorized access, and enable swift responses to emergencies, ensuring the safety of patients, staff, and assets within the facility.

In hospitals, IoT devices such as wearable sensors and smart beds [85] can continuously monitor patient health, alerting healthcare providers to changes in vital signs or patient activity. This can help reduce the risk of adverse events and improve patient outcomes.

3.2. Outdoor healthcare environments

In addition to personal localization and remote patient monitoring, the integration of smart and IoT-enabled facilities in outdoor healthcare environments plays a pivotal role in enhancing the well-being of individuals.

Public spaces such as parks, recreational areas, and transportation hubs are now equipped with advanced healthcare amenities that leverage IoT technology to provide seamless healthcare access [86]. These smart facilities are designed to meet the diverse healthcare needs of the public efficiently.

One notable aspect of smart outdoor healthcare environments is the utilization of IoT-enabled kiosks. These interactive kiosks serve as information hubs, offering real-time data on nearby healthcare providers, medication dispensaries, and emergency contact numbers [87]. Individuals can access personalized health information, locate the nearest healthcare facilities, and receive immediate assistance in case of emergencies.

Furthermore, it is anticipated that in the future, smart parks and recreational areas could be equipped with fitness stations featuring IoT-connected exercise equipment [88]. These envisioned smart fitness stations would have the potential to monitor users' activity, provide personalized exercise recommendations, and track vital health metrics. It is envisioned that users may access these anticipated facilities through smartphone apps, potentially allowing for a tailored fitness experience based on individual health goals and preferences.

Transportation hubs also benefit from IoT integration. Automated external defibrillators (AEDs) [89] are now equipped with IoT sensors that continuously monitor their functionality. In case of any issues or malfunctions, automatic alerts are sent to healthcare providers, ensuring that these life-saving devices are always ready for use.

In summary, outdoor healthcare environments are evolving to embrace smart and IoT-enabled facilities that enhance the healthcare experience in public spaces. From interactive kiosks to connected fitness equipment and advanced navigation systems, these technologies ensure that healthcare resources are readily accessible, personalized, and responsive to the unique needs of individuals in outdoor settings.

3.3. Remote patient monitoring

IoT devices such as wearables and remote monitoring systems can be used to monitor patient health outside of traditional healthcare settings. Remote patient monitoring can help improve patient outcomes by detecting changes in health status early and enabling healthcare providers to intervene quickly [90].

Remote Patient Monitoring(RPM) utilizes technology, such as wearable devices, sensors, and telecommunication tools, to remotely monitor patients' health status, collect relevant health data, and facilitate virtual consultations between patients and healthcare providers. This approach allows for ongoing monitoring of vital signs, medication adherence, symptoms, and other health indicators without the need for frequent in-person visits.

One of the significant benefits of RPM is its ability to provide healthcare services to patients in remote or underserved areas [91]. Patients living in rural or geographically isolated locations may face challenges accessing specialized healthcare services. RPM bridges this gap by enabling remote monitoring and consultations, allowing healthcare providers to deliver timely interventions and guidance.

Moreover, RPM offers a convenient solution for patients with limited mobility, such as those with physical disabilities or chronic conditions that make travel difficult. By leveraging remote monitoring technologies, patients can receive the necessary healthcare support from the comfort of their own homes. Healthcare providers can remotely assess their condition, adjust treatment plans, and provide guidance without the need for frequent hospital visits.

For patients with paralysis or other mobility limitations, RPM provides a lifeline to healthcare. They can use wearable devices [92], such as smartwatches or wireless sensors, to track their health parameters, including heart rate, blood pressure, glucose levels, and more. The collected data is transmitted securely to healthcare professionals who can analyze it and provide appropriate medical interventions.

By implementing RPM, healthcare providers can ensure regular monitoring and early detection of health issues, reducing the risk of complications and hospital readmissions. This proactive approach to care management improves patient outcomes and enhances the overall quality of life for patients with limited mobility.

3.4. Smart cities

IoT technologies can be used to create smart cities that support healthier lifestyles. Smart cities can incorporate IoT devices such as smart traffic lights, air quality monitors, and noise sensors, which can help reduce the risk of respiratory illness, noise pollution, and accidents.

Governments have recognized the potential benefits of RPM in improving healthcare outcomes, reducing healthcare costs, and enhancing patient satisfaction. As a result, they have taken various actions to support and advance the adoption of RPM in healthcare systems.

Governments have been actively involved in establishing robust policies and regulations that prioritize patient data privacy and security in the context of RPM [93]. They enforce compliance with data protection laws, develop guidelines for secure data transmission and storage, and promote the use of encryption and authentication measures to safeguard patient information.

Additionally, governments allocate substantial funding and financial support to healthcare organizations to facilitate the implementation and integration of RPM into existing healthcare systems. They also invest in infrastructure development, such as broadband connectivity and telecommunication networks, to ensure remote monitoring services are accessible even in remote or underserved areas. Moreover, governments actively foster collaborations and partnerships among healthcare providers, technology companies, and research institutions to drive innovation, share best practices, and develop standardized protocols for RPM [94]. These collective efforts demonstrate governments' commitment to creating an environment that supports RPM adoption, improves healthcare delivery, and ultimately enhances patient outcomes.

For individuals, smart cities offer personalized healthcare experiences through technologies like telemedicine and wearable health devices. These tools provide remote access to medical professionals and real-time health monitoring, empowering individuals to actively manage their well-being. Additionally, smart cities facilitate convenient access to medical services, making healthcare more accessible.

On a public scale, smart cities contribute to better population health through data-driven insights. They can detect and mitigate environmental factors affecting public health, such as air pollution and disease outbreaks. Smart urban planning promotes active lifestyles with green spaces and efficient transportation systems. Moreover, these cities incorporate public health monitoring and control mechanisms. They can proactively track and manage health risks in public spaces, including early warning systems for potential disease outbreaks and real-time air quality alerts. Ultimately, smart cities create a healthier and more accessible healthcare ecosystem that benefits both individuals and the broader public, improving overall well-being.

4. IoT applications in healthcare

4.1. Remote monitoring

In the dynamic landscape of healthcare technology, the integration of the IoT into remote health monitoring represents a pivotal advancement, setting a novel paradigm in patient care and medical data management. Recent models leverage IoT to craft a nexus where portable physiological monitoring seamlessly intertwines with sophisticated expert systems [95], thus enabling an ecosystem that fosters accuracy, immediacy, and reliability in diagnosis and patient care. Navigating through the latest literature unveils a spectrum of innovations that collectively contribute to refining the reliability and efficiency of remote health monitoring systems. These developments are instrumental in driving forward the boundaries of technological integration in healthcare, catalyzing a phase marked by unprecedented precision and effectiveness in patient monitoring and care.

This study [96] presents a remote long-suffering monitoring system using IoT and cloud computing for accurate and constant health monitoring, abnormality detection, and alarm reports. The system includes a portable function for data visualization, loading, and real-time remote monitoring. It has been proven to measure biological parameters and tested for reliable performance in real-time data transmission.

The research [97] emphasizes the monitoring of remote patients' body temperature using embedded infrared sensors and WiFi connectivity in an IoT-based system. The prototype demonstrates accurate temperature measurement and offers guidance on the optimal body parts for effective temperature monitoring.

The proposal [98] suggests a secure and private integration of IoT with healthcare units to achieve a reliable and secure remote patient monitoring system. It utilizes secure authentication, communication, and privacy measures, including a smartwatch, server, and smartphone application for monitoring vital signs.

ML-based algorithms [99] enhance patient health surveillance through remote monitoring, efficient data mining, and improved healthcare services.

This study [100] presents a convenient electrocardiogram monitoring system that links patients and doctors through a cloud server. It allows remote monitoring, investigation, and alarms, reducing hospital appointments. Experimental results demonstrate trustworthiness and comparisons with existing techniques, followed by a system performance demonstration.

The paper [101] proposes using IoT-based remote patient monitoring with medical IoT wearables and ML algorithms to monitor Post-Covid patients and provide immediate medical assistance.

This paper [102] presents the implementation of a private backend server software for an IoT health monitoring system. The system uploads data to a cloud server after detecting vital signs. Compared to existing patient monitoring systems, the system demonstrates impressive performance and accuracy, achieving a high success rate for IoT data broadcasts.

The proposed framework in this study [103] utilizes a Convolutional Neural Network with Long-Short Term Memory (CNN-LSTM) to create a Patient Activity Monitoring System for accurate human action recognition. The results demonstrate a high accuracy rate of 99.53 %, surpassing existing algorithms by at least 4.73 %.

This research [104] proposes a smart system using IoT technology to assist patients with influenza symptoms in determining their COVID-19 infection status. The system enables quick medical care and tracking of patient mobility to analyze suspected behaviors, with potential applications in medical institutions, quarantine units, and airports.

4.2. Locating systems

Through real-time locating systems (RTLS), healthcare providers can quickly locate the position of patients, particularly in emergency and critical situations, enabling timely medical assistance and reducing the risk of patient harm. The research on RTLS extends beyond patient location and encompasses accurate and up-to-date information on healthcare resource locations. By implementing RTLS, healthcare facilities can effectively manage and track vital medical resources such as equipment, medications, and supplies, ensuring their timely availability, reducing search time, and preventing inventory shortages or delays in patient care.

This study [105] proposes an approach that leverages deep neural networks and spatial-spectrum fitting to achieve precise and effective source localization within UAV networks with radar arrays. The method enhances both the accuracy and real-time processing capabilities.

This study [106] utilizes RFID and NB-IoT technology to precisely track and monitor medical resources in the context of specimen logistics in a hospital. By integrating IoT capabilities such as real-time location tracking and environmental condition monitoring, the system enhances the efficiency and reliability of specimen transport. It effectively addresses the challenges associated with the logistics and management of medical resources.

This work [107] proposes a wearable device system suitable for individuals who are prone to getting lost, such as those with Alzheimer's disease. The system enables location tracking and step detection both indoors and outdoors. Data is documented and accessed through a user web application, allowing for anomaly detection, patient positioning, and warnings to caregivers. The system aims to enhance independence and provide peace of mind to caregivers.

The study [108] demonstrates the use of sensor-agnostic APIs and ontology modules to support complex functionalities and address environment-wellness relationships. It focuses on location-based applications, such as environmental sensing and wellness monitoring, and proposes an ontology-based approach.

This research [8] tracks critical health parameters in the direct. Data is conveyed to the cloud storing system and displayed to practitioners and affected roles through a mobile application. The system allows timely medical decisions based on abnormal values. The study [109] implemented similar functionality in the context of the COVID-19 pandemic.

The IoT-enabled embedded device [110], integrated with health care systems, monitors the trash levels in public bins. This IoT solution ensures timely waste management, reducing the city's risk of unsanitary conditions and potential health hazards.

The IoT-enabled embedded device, integrated with health care systems, not only monitors the trash levels in public bins but also holds the potential for future applications in managing medical waste in hospitals. By leveraging IoT technology, hospitals can implement similar monitoring systems for medical waste disposal. This would ensure efficient management of biomedical waste, reduce the risk of contamination, and maintain a hygienic environment within healthcare facilities. The adoption of IoT in hospital waste management can improve infection control practices and promote the safety and well-being of patients and healthcare workers.

4.3. Personalized medicine

In the realm of healthcare, the concept of Personalized Medicine has emerged as a groundbreaking frontier. This approach tailors medical treatment to the unique genetic, environmental, and lifestyle factors of individual patients, holding the promise of more effective and precise healthcare. To gain a deeper understanding of the current state of this evolving field, we delve into a comprehensive study that explores the latest advancements and trends in personalized medicine.

This study [15] validates the relationship between IoT adoption and patient care service engagement. The findings highlight the importance of personalized medicine and the need for a reliable computing environment to ensure privacy and security. The study provides a framework for healthcare providers to empower patients and improve the patient care delivery environment, fostering shared decision-making and superior care services.

This paper [111] focuses on utilizing the Latent Dirichlet allocation (LDA) model in the context of personalized diabetes management. The aim is to predict future treatment approaches. This emphasizes the potential of personalized diabetes management to enhance patient prognoses and signifies a noteworthy advancement in healthcare decision-making.

The target group of this study [112] is children with type 1 diabetes. The system considers the effect of activity on the extent of the patient's illness, allowing doctors to provide individualized dietary recommendations based on predicted changes in blood glucose levels. This study emphasizes the potential of IoT and mHealth technologies in delivering personalized healthcare solutions for pediatric diabetes management.

This paper [113] presents a personalized dental caries prediction model using machine learning. This personalized approach eliminates the hard detection process and enables dentists and patients to assess the risk of future severe dental infections.

This project [114] utilizes 5G technology to monitor diabetic patients' health in real-time, providing early alerts and personalized care.

This study [115] introduces a system that utilizes exhaled VOC analysis for personalized monitoring and disease diagnosis. It provides various benefits, including early diagnosis, cost reduction, and improved quality of care.

This study [116] proposes a meta-learning-based personalization approach for individualized health monitoring, which realizes better accuracy than accessible approaches in detecting vital signs and human activity.

5. Discussion

IoT has brought tremendous advancements to healthcare, empowering healthcare providers, patients, and systems alike. By harnessing the potential of IoT technology, the healthcare industry can improve patient outcomes, optimize resource utilization, and transform healthcare delivery into a more personalized and proactive approach. However, it is imperative to address security and privacy concerns to ensure IoT's responsible and ethical implementation in healthcare.

Medical IoT devices collect and transmit a large amount of sensitive information, including personal health data, medical history, and biometric measurements. In research settings, scholars must establish clear and transparent privacy policies and consent mechanisms to inform patients about the collected data, how it will be used, and with whom it will be shared. Patients should have control over their data and be able to provide informed consent for its usage. Anonymization techniques such as de-identification [117] or differential privacy [118] can be employed to protect patient privacy further while allowing for data analysis and research. This involves implementing robust authentication and access control mechanisms to ensure that only authorized individuals can access the devices and data. Encryption techniques should be employed to protect data during transmission and storage, preventing interception or tampering. Regular security audits and vulnerability assessments are necessary to identify and address any weaknesses or vulnerabilities in the system.

This is an area that many scholars are currently dedicated to researching. Progress has been made in the development of security protocols, encryption algorithms, and privacy-enhancing technologies specific to the healthcare domain. The paper [119] introduces a healthcare architecture that utilizes blockchain technology to tackle data management and security concerns and identify unauthorized activities in the communication chain. The experimental findings reveal a significant success rate in detecting hostile IoT devices.

This study [120] proposes a new key exchange protocol for healthcare applications. The protocol utilizes secure algorithms to ensure data security without compromising performance. It effectively blocks key exchange attacks and realizes improved performance.

This research [121] introduces Medi-Block, a secure healthcare system combining Blockchain and IoT. It enables remote patient monitoring and provides an additional security layer for personalized healthcare. The framework ensures privacy and maximizes the value of healthcare.

For healthcare providers, it is crucial to establish robust security protocols, including data encryption, access control mechanisms, and secure communication channels [122], to prevent unauthorized access and data breaches. Respecting patient privacy rights helps build trust within healthcare organizations and maintains ethical standards.

The healthcare IoT ecosystem faces unique challenges in ensuring security and privacy. It involves various devices and systems with different security functionalities and vulnerabilities. Healthcare providers must deal with the complexity of integrating and protecting these devices while complying with regulatory requirements, such as the Health Insurance Portability and Accountability Act (HIPAA) [123] in the United States or similar data protection laws in other countries/regions. The interoperability of different IoT devices and platforms also poses challenges in maintaining consistent security levels throughout the ecosystem.

Establishing clear and transparent privacy policies and consent mechanisms or legislation is crucial at the government level. Governments should develop privacy protection laws and regulations for healthcare IoT, clearly defining data collection, usage, and sharing principles. Additionally, appropriate regulatory bodies should be established to oversee and enforce privacy protection policies while imposing penalties for violations of privacy regulations.

Governments and relevant institutions should also provide education and training to enhance the privacy awareness and skills of healthcare professionals, enabling them to properly handle and protect sensitive data. Furthermore, public education initiatives should be launched to raise awareness among individuals about privacy protection.

In the realm of interoperability, aligning various IoT devices and platforms to uphold consistent security benchmarks across the ecosystem presents another layer of complexity. Therefore, a cohesive strategy that encapsulates comprehensive legislation, clear privacy policies, and robust enforcement mechanisms is essential to navigate the multifaceted security challenges intrinsic to the healthcare IoT landscape.

6. Optimizing IoT applications in healthcare: key strategies and implementation measures

Optimizing IoT applications in healthcare requires the implementation of key strategies and measures to ensure the effective and efficient utilization of this technology. By adopting the following approaches, healthcare organizations can maximize the benefits of IoT and enhance patient care:

6.1. Seamless integration and interoperability

One of the key strategies is to ensure the seamless integration of IoT devices and systems within the existing healthcare infrastructure. This involves developing standardized protocols and interfaces [116] that facilitate interoperability between different IoT devices, electronic health records (EHR) systems, and other healthcare applications. By enabling smooth data exchange and communication, healthcare providers can leverage the full potential of IoT to enhance care coordination and improve patient outcomes.

6.2. Robust security and privacy measures

Identity and access management serve as critical components in reducing security risks [124]. Multifactor authentication and stringent access controls are pivotal in bolstering security measures[125]. These protocols guarantee that only authorized individuals can access patient data, reducing the risk of unauthorized breaches. Additionally, it is vital not to overlook the security of the IoT devices themselves. Device manufacturers must integrate security features, such as secure boot and hardware-based security modules [126]. Consistent patching and firmware updates are also essential to counter emerging security vulnerabilities and threats. Data privacy represents yet another essential dimension. Techniques like data anonymization and de-identification protect patient privacy while still permitting valuable data analysis [127]. The incorporation of differential privacy methods further enhances privacy by introducing controlled noise into datasets. Healthcare organizations must place high priority on compliance with industry-specific regulations. These regulations establish stringent standards for patient data security and privacy, underlining the legal aspects of data protection. Promoting user training and awareness is a crucial endeavor. Informed healthcare staff and patients actively contribute to threat detection and reporting. Moreover, a well-defined incident response plan is imperative. This plan should delineate the necessary steps to take in the event of a security breach, assigning specific responsibilities to individuals or teams for each action. Lastly, third-party vendor assessment is a pivotal facet of healthcare IoT security. Rigorously evaluating the security practices of third-party vendors and service providers ensures their alignment with stringent security standards and protocols.

6.3. Data analytics and real-time insights

IoT generates vast amounts of data that, when properly analyzed, can provide valuable insights for healthcare decision-making. By leveraging advanced analytics techniques, such as machine learning and artificial intelligence, healthcare providers can gain real-time insights from IoT-generated data. These insights can support early detection of health conditions, proactive intervention, and personalized treatment plans, ultimately improving patient outcomes and operational efficiency.

6.4. Scalability and flexibility

As IoT technologies continue to evolve, healthcare organizations must ensure scalability and flexibility in their implementation. This involves designing IoT infrastructure that can accommodate future growth and the integration of new devices and applications. Scalable cloud-based platforms and architectures provide the necessary flexibility to adapt to changing healthcare demands, allowing for the seamless addition and management of IoT devices and data streams.

6.5. Government support and strategic location selection

Government involvement plays a crucial role in the successful implementation of IoT in healthcare. Governments can support the establishment of smart hospitals by providing incentives, funding, and regulatory frameworks that encourage the adoption of IoT technologies. Additionally, the selection of suitable locations for smart hospitals is important. Governments can support the establishment of smart hospitals by providing incentives, funding, and regulatory frameworks that encourage the adoption of IoT technologies. Factors such as proximity to healthcare facilities, availability of robust connectivity infrastructure, and accessibility to a skilled workforce should be considered to ensure the optimal functioning of IoT-enabled healthcare systems.

By implementing these key strategies and measures, healthcare organizations can optimize IoT applications in healthcare and unlock their full potential. This includes improving patient care, enhancing operational efficiency, and advancing healthcare research and innovation. It is vital for organizations to stay updated on technological advancements, collaborate with industry partners, and continuously evaluate and refine their IoT strategies to align with the evolving needs of the healthcare landscape.

7. Conclusion

This manuscript furnishes an exhaustive analysis of the intersection between the Internet of Things (IoT) and healthcare, delineating its transformative potential within the sector. Central to the discourse is the burgeoning relevance of personalized medicine, underscored by a framework of standardized protocols and rigorous regulations pivotal in safeguarding privacy and bolstering security infrastructures. Current incorporations of IoT technologies within healthcare paradigms have heralded enhanced patient care trajectories and improved clinical outcomes, heralding innovations in remote patient monitoring paradigms, individualized treatment architectures, and operational efficiencies in healthcare delivery frameworks.

However, it is imperative to recognize the spectrum of challenges that punctuate the seamless integration of IoT within healthcare ecosystems. These necessitate a symbiotic engagement amongst healthcare professionals, regulatory architects, and the broader research community to foster solutions that are both innovative and pragmatically viable.

While this contribution endeavors to provide nuanced insights and seminal contributions within the realm of healthcare-focused IoT, it is cognizant of the existence of additional seminal works and innovative strides within this dynamic field that may not have been encapsulated within the present discourse. In this vein, we extend our apologies for any inadvertent omissions. In summation, this manuscript aspires to augment the collaborative exploration of leveraging IoT technologies toward engendering transformative enhancements within healthcare landscapes and auxiliary domains.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The authors do not have permission to share data.

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