*applied sciences*

MDPI

*Review*

# Real-Time Remote Patient Monitoring: A Review of Biosensors Integrated with Multi-Hop IoT Systems via Cloud Connectivity

**Raihan Uddin and Insoo Koo ***

Department of Electrical, Electronic and Computer Engineering, University of Ulsan, Ulsan 44610, Republic of Korea; raihan80@mail.uslan.ac.kr

* Correspondence: iskoo@ulsan.ac.kr

**Abstract:** This comprehensive review paper explores the intricate integration of biosensors with multi-hop Internet of Things (IoT) systems, representing a paradigm shift in healthcare through real-time remote patient monitoring. The strategic deployment of biosensors in different locations in medical facilities, intricately connected to multiple microcontrollers, serves as a cornerstone in the establishment of robust multi-hop IoT networks. This paper highlights the role of this multi-hop IoT network, which efficiently facilitates the seamless transmission of vital health data to a centralized server. Crucially, the utilization of cloud connectivity emerges as a linchpin in this integration, providing a secure and scalable platform for remote patient monitoring. This cloud-based approach not only improves the accessibility of critical health information but also transcends physical limitations, allowing healthcare providers to monitor patients in real-time from any location. This paper highlights the transformative potential of this integration in overcoming traditional healthcare limitations through real-time remote patient monitoring.

**Keywords:** remote patient monitoring; Internet of Things; biosensors; multi-hop IoT networks; cloud connectivity



**Citation:** Uddin, R.; Koo, I. Real-Time Remote Patient Monitoring: A Review of Biosensors Integrated with Multi-Hop IoT Systems via Cloud Connectivity. *Appl. Sci.* **2024**, *14*, 1876. https://doi.org/10.3390/app14051876

Academic Editors: Teen-Hang Meen, Charles Tijus, Po-Lei Lee, Cheng-Fu Yang and Chun-Yen Chang

Received: 20 December 2023
Revised: 22 February 2024
Accepted: 22 February 2024
Published: 25 February 2024



## 1. Introduction

The Internet of Things (IoT) is an evolution in technology that allows electronic devices and sensors to communicate with each other over the Internet. This highlights the IoT's rise as a groundbreaking technology that makes it possible to link and share data between various systems and devices [1]. The IoT is an ecosystem in which everything is virtually represented and accessible on the Internet, enabling the smooth combination of physical and digital worlds [2]. Integration of the IoT into healthcare has sparked important developments, transforming patient care and management. These developments have resulted in IoT applications such as fitness tracking, health education, and healthcare coordination, making a major contribution to the spread of knowledge in this field [3]. Demonstrating the growing prominence and significance of the IoT in healthcare research, scientometrics analysis offers a more comprehensive view of the field [4].

Healthcare in the Internet of Things (H-IoT) emphasizes the development of IoT health sensor nodes and investigations of the benefits of blockchain technology in the field of healthcare sensor networks [5] in order to provide a thorough knowledge of IoT implementation; its applications highlight trends in healthcare and other industries [6]. Moreover, the IoT delves into new technologies in smart health research, with a focus on applications related to health monitoring [7].

Real-time remote patient monitoring (RPM) is becoming progressively more important in the healthcare industry owing to its benefits, such as controlling diseases, providing overall healthcare, and improving patient care. RPM makes it possible to continuously monitor patients' conditions in real-time, which helps to identify illnesses early, and facilitates preventative measures. The method improves patient outcomes while also helping to identify crucial circumstances early on, and maybe avert untimely deaths [8]. The ability of RPM to enhance patient involvement, to increase treatment accessibility, and to maximize healthcare resources highlights the significance of this technology [9].

Additionally, RPM technologies, which are a subset of digital health platforms, make it easier for patients to receive evaluations outside of conventional healthcare venues, enhancing the delivery of healthcare and expanding the scope of care outside of clinical environments [9]. Doctors can now remotely monitor patients, manage their illnesses, and provide feedback thanks to the integration of smart healthcare support with RPM. This enhances the efficiency and personalization of healthcare management [10]. Real-time RPM is essentially changing the way healthcare is delivered by making it more patient-centered, preventative, and sensitive to each patient's customized requirements.

Cutting-edge technology like biosensors and multi-hop IoT systems is essential in many industries, including healthcare and data collection, under certain conditions. In terms of biosensors, they are a type of device that combines biological components (enzymes, antibodies, and nucleic acids) with physical transducers to produce measurable signals in response to specific biological substances or changes in physiological conditions. In the healthcare sector, biosensors are crucial for vital signs monitoring, where they play a key role in the detection and measurement of biomolecules or physiological changes associated with essential functions such as heart rate, blood pressure, oxygen saturation, etc. This integration of biosensors into vital signs monitoring enables real-time data collection, contributing to improved diagnostics and patient care. According to emerging research [11], biosensors are an essential component of artificial intelligence (AI) systems designed for the healthcare industry. These biosensors, which are frequently included in IoT networks, make it feasible to obtain data effectively and help to resolve healthcare issues.

An optimized AI system makes use of IoT biosensors for healthcare applications, demonstrating the integration of biosensors with multi-hop IoT systems. Biosensors and multi-hop communication function well together when using the LEACH-M approach, which involves several hops for effective data collection in IoT networking systems [11].

Cloud connectivity has revolutionized healthcare monitoring, offering scalable solutions for data storage, analysis, and accessibility. Recent research underscores the impact of cloud computing in this domain, emphasizing its multifaceted benefits.

Cloud-based health monitoring frameworks, leveraging smart technologies, showcase the integration of wearables and cloud computing into promising healthcare techniques [12]. The synergy of the cloud and the IoT significantly influences remote healthcare, enhancing patient outcomes and monitoring capabilities [13]. Improved analysis and monitoring of medical data, large storage capacities for electronic health records (EHRs), and instantaneous access to critical information are key advantages of cloud connectivity in healthcare. Cloud-based intelligent healthcare monitoring systems that integrate cloud computing and health monitoring offer comprehensive solutions to healthcare providers [14].

Smart healthcare systems based on cloud–Internet integration illustrate the connectivity potential for data sharing and analysis [15]. Cloud computing approaches in healthcare, encompassing health monitoring applications, provide a holistic overview of research and applications in the field [16]. Cloud connectivity plays a pivotal role in enhancing healthcare monitoring, providing a foundation for innovation, efficiency, and improved patient care.

This comprehensive review explores the integration of biosensors with multi-hop IoT systems via cloud connectivity, with a focus on real-time patient monitoring. Figure 1 shows the overall structure of the paper. At its core, the review delves into the technological intricacies, focusing on seamless data transmission and reliability. Emphasizing technological integration, it examines how these systems collaborate for seamless data transmission in patient monitoring scenarios, extending their scope to various healthcare applications while addressing challenges such as technological limitations and security. The paper also highlights opportunities for future research and serves as a roadmap for advancements in real-time patient monitoring methodologies.

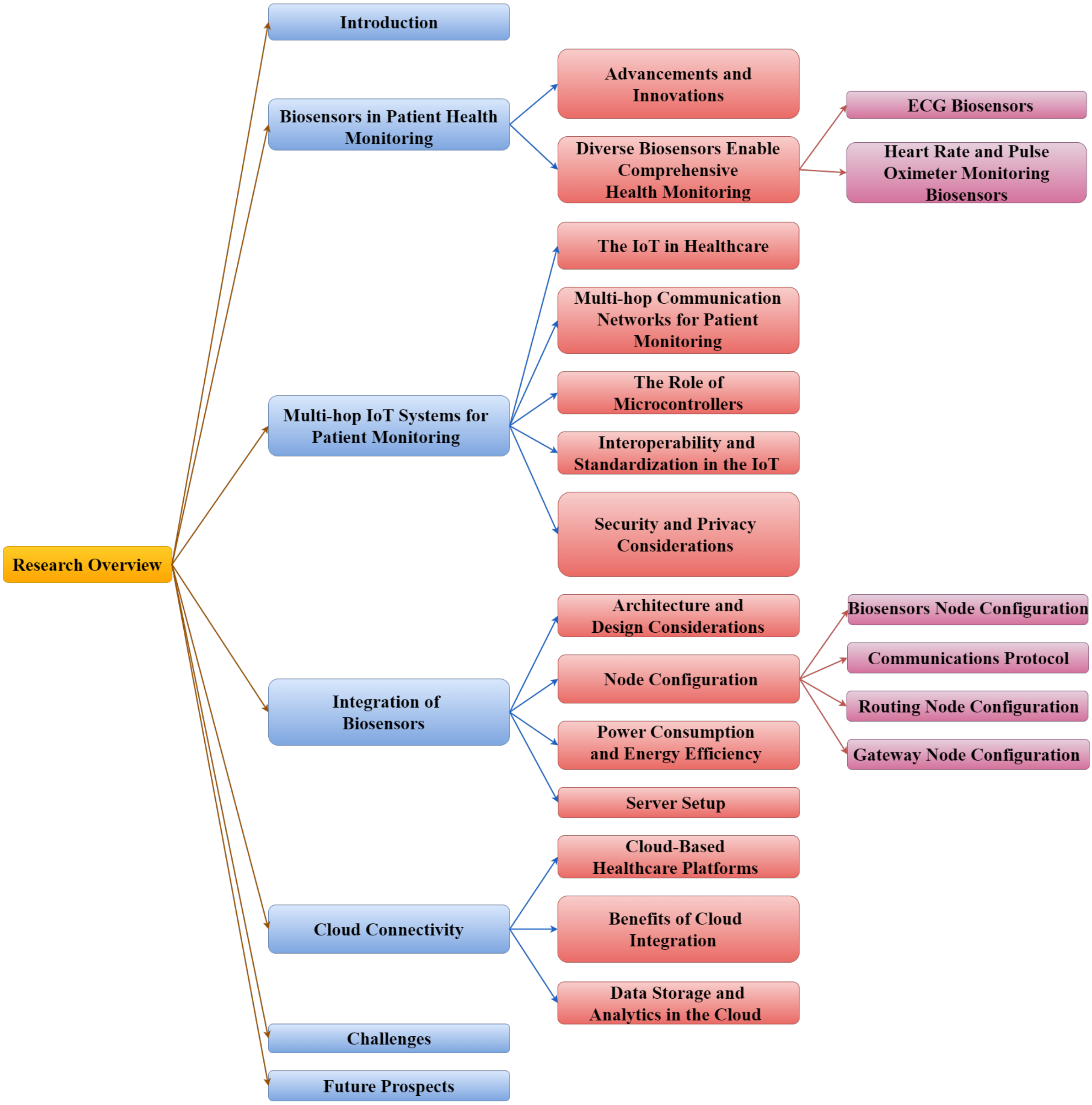


**Figure 1.** Overview of this paper's research.

## 2. Biosensors in Patient Health Monitoring

### *2.1. Advancements and Innovations*

In recent years, there has been a remarkable transformation in biosensor technology, marked by significant advancements and innovative developments [17]. One of the key trends driving this evolution is the move toward miniaturization and the emergence of wearable biosensors.

The traditional bulky biosensors have given way to compact, miniaturized versions, offering patients a novel means of continuous health monitoring [18]. This shift in form factor holds particular significance because it allows individuals to seamlessly integrate biosensors into their daily lives without hindering routine activities.

A noteworthy aspect of miniaturization is the rise in wearable biosensors. These devices, often designed as discreet patches or accessories, provide users with the convenience of constant health parameter monitoring [19,20]. The reduced size not only enhances user comfort but facilitates prolonged usage, enabling uninterrupted data collection over extended periods.

Another stride forward is the development of flexible and stretchable biosensors. Innovations in materials, such as flexible polymers and advanced composites, have empowered the creation of biosensors that can conform to the natural contours of the body. This adaptability ensures improved skin contact, thereby enhancing the accuracy of health parameter measurements, especially in dynamic environments [21].

Intelligent data processing has become a cornerstone of biosensor innovation with the integration of artificial intelligence and machine learning (ML) algorithms [22]. These algorithms play a crucial role in transforming raw biosensor data into actionable insights. Real-time processing and analysis enable the detection of patterns and anomalies, contributing to early identification of health issues.

Biosensors equipped with AI-driven decision-support systems are now at the forefront of healthcare technology [23]. These systems provide valuable assistance to healthcare professionals by offering intelligent interpretations of biosensor data. This not only aids in timely medical interventions but also contributes to a more nuanced understanding of patient health.

The concept of multi-parameter biosensors represents a significant leap forward in health monitoring capabilities [24]. Modern biosensors are designed to measure multiple health parameters simultaneously, providing a holistic view of the patient's well-being. This comprehensive approach enhances diagnostic capabilities, allowing for more accurate health assessments and supporting a personalized healthcare strategy.

However, the ongoing advancements in biosensor technology, encompassing miniaturization, flexibility, intelligent data processing, and multi-parameter capabilities, are ushering in a new era of remote and continuous healthcare monitoring. These innovations collectively contribute to making patient health monitoring more accessible, accurate, and adaptable to individual needs.

### *2.2. Diverse Biosensors Enable Comprehensive Health Monitoring*

This section delves into key biosensors crucial for comprehensive patient health monitoring, featuring cutting-edge technologies such as the AD8232 for electrocardiogram (ECG) monitoring, and the MAX30102 for heart rate and pulse oximeter monitoring. Both biosensors are examined in detail, elucidating technological advancements, underlying principles, specifications, features, and their pivotal roles in facilitating real-time patient care.

#### 2.2.1. ECG Biosensors

Overview:

In the realm of biosensors, ECG biosensors, particularly those represented by cutting-edge technologies like the AD8232 shown in Figure 2, hold a distinctive position. These biosensors are meticulously engineered for continuously monitoring the heart's electrical activity, providing invaluable insights into cardiovascular health [25].

Principle of Operation:

The operational principle of ECG biosensors revolves around the configuration of the electrodes (Figure 3) that are strategically placed on the patient's chest. These electrodes serve as the front-line components capturing the intricate electrical impulses generated with each heartbeat. The captured signals undergo a transformative process, resulting in graphical ECGs [26]. This graphical representation of the heart's rhythm serves as a diagnostic tool for identifying various cardiac conditions.

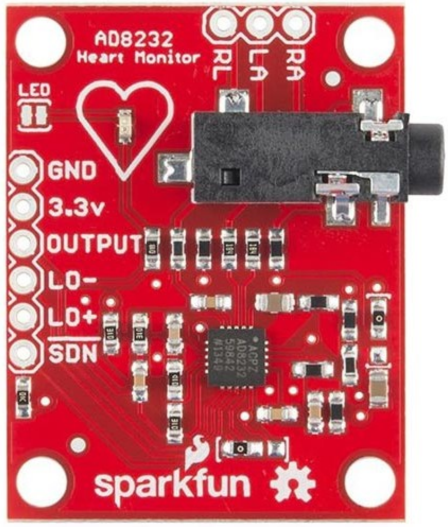


**Figure 2.** The AD8232 biosensor is a compact, single-lead, front-end empowering monitor of ECG signals.

**Figure 3.** Electrodes of the AD8232 biosensor are placed on the patient's body.

Specifications:

- Electrode configuration: Multiple electrodes, strategically positioned on the chest, ensure comprehensive coverage and accurate signal capture.
- Frequency range: Operating within a specific frequency range is paramount for faithful representations of heart signals.
- Signal resolution: High resolution is a critical specification, ensuring that the biosensor can precisely interpret the complex patterns inherent in ECGs.

Features:

- Fully integrated single-lead ECG front-end: All-in-one ECG front-end functionality for simplified integration.
- Common-mode rejection ratio (CMRR): A high CMRR of 80 dB (dc to 60 Hz) ensures precise signal acquisition.
- Versatile electrode configurations: Supports two- or three-electrode configurations for adaptable monitoring setups.
- Qualified for automated applications: Certified and designed for reliability in automated applications.
- Single-supply operation: Operates seamlessly on a single supply voltage ranging from 2.0 V to 3.5 V.
- Fast restore: This feature enhances filter settling for improved signal quality.

- Compact size: Dimensions are 3.5 cm × 3 cm for space-efficient and portable applications.

Patient Monitoring Aspects:

In the patient monitoring landscape, ECG biosensors have emerged as indispensable tools. Their real-time capabilities facilitate continuous cardiac monitoring, enabling the prompt detection of irregularities in the heart rhythm. This real-time monitoring proves instrumental in early intervention, ultimately mitigating the risk of adverse cardiac events.

### 2.2.2. Heart Rate and Pulse Oximeter Monitoring Biosensors

Overview:

Heart rate and pulse oximeter monitoring, exemplified by sophisticated biosensors like the MAX30102 (Figure 4), are pivotal in assessing cardiovascular health [27]. These biosensors monitor heartbeats per minute in a continuous and non-invasive manner. Additionally, they play a crucial role in pulse oximetry, measuring oxygen levels in the blood.

The MAX30102 biosensor stands out as a superior choice for multi-hop IoT systems, offering key advantages in terms of accuracy and efficiency. This biosensor is well known for accurately measuring vital signs such as the heart rate and oxygen level with high sensitivity and minimal power consumption. Its compact design makes it a preferred solution for multi-hop IoT systems, enabling seamless integration into networked devices. The MAX30102's exceptional ambient-light-filtering capabilities enhance data accuracy, ensuring reliable performance even in challenging environments. Overall, the combination of accuracy, efficiency, and versatility makes the biosensor an outstanding choice for real-time patient monitoring.

Principle of Operation:

The core of these biosensors relies on the application of photoplethysmography (PPG) [28]. Commonly integrated into wearable devices, heart rate and pulse oximeter monitors utilize PPG sensors casting light onto the skin. Variations in the reflected light caused by changes in blood flow form the basis for accurate heart rate and oxygen level calculations.

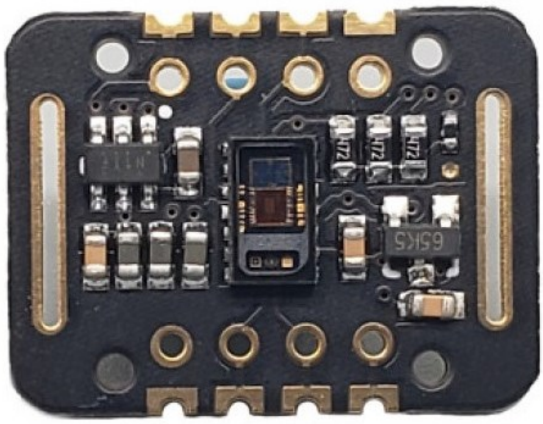

**Figure 4.** The MAX30102 sensor continuously monitors oxygen levels and heart rate.

Specifications:

- Light source: LEDs are commonly used in PPG-based biosensors.
- Photodetector: The intensity of reflected light is a crucial component in the precise calculation of heart rate.
- Sampling rate: A higher rate contributes to enhanced accuracy in measuring heart rates.

Features:

- Power supply: The MAX30102 operates within a versatile power supply range of 3.3 V to 5.5 V, providing flexibility for integration with various microcontroller platforms.
- Current during measurements: The biosensor draws approximately ∼600 µA, ensuring efficient power consumption while actively capturing physiological data.

- Current during standby mode: In standby mode, the MAX30102 exhibits an ultra-low draw of ∼0.7 µA, contributing to power conservation when not active.
- Red LED: The biosensor features a red LED with a wavelength of 660 nm, optimized for specific absorption characteristics in blood, which is essential for accurate PPG measurements.
- Infrared LED: Equipped with an IR LED using the 880 nm wavelength, the MAX30102 enables detection of variations in light absorption, crucial for SpO2 calculations.
- Temperature range: The MAX30102 operates reliably across a wide range, from −40 °C to +85 °C, ensuring consistent performance in diverse environmental conditions.
- Temperature accuracy: With an accuracy of ±1 °C, the biosensor provides precise temperature measurements, enhancing overall health monitoring capabilities by incorporating temperature data.

Patient Monitoring Aspects:

The significance of heart rate and pulse oximetry biosensors lies in their capacity to provide continuous and non-invasive tracking of cardiovascular performance [29]. Figure 5 illustrates a method to detect the heart rate and perform pulse oximetry. Real-time data on heart rates and oxygen levels is instrumental in assessing overall fitness, in monitoring stress responses, and promptly identifying potential cardiac abnormalities. With its advanced features, the MAX30102 exemplifies the effectiveness of this biosensing technology in comprehensive patient care.

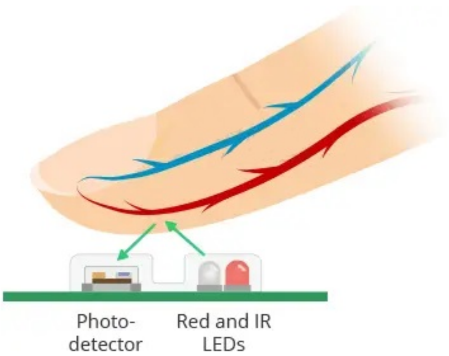


**Figure 5.** Heart rate and oxygen level detection through a photodetector using red and IR LEDs creates a photoplethysmogram [30].

## 3. Multi-Hop IoT Systems for Patient Monitoring

### *3.1. The IoT in Healthcare*

Integration of the IoT into the healthcare sector represents a pivotal development with far-reaching implications for patient care, operational efficiency, and health outcomes. One of the key areas where the IoT is making a significant impact is patient care. Wearable sensors and implantable devices equipped with IoT capabilities enable continuous monitoring of vital signs. This real-time tracking not only enhances the quality of patient care but allows proactive interventions, particularly in managing chronic conditions [3]. Patients can benefit from personalized, data-driven insights into their health, fostering a more engaged and informed approach to well-being.

Beyond traditional healthcare settings, the IoT facilitates remote patient monitoring, as shown in Figure 6. This is particularly crucial in remote or under-served areas, where access to healthcare may be limited [31]. Devices that measure vital signs or ensure medication adherence empower individuals to actively participate in managing their health, irrespective of geographic constraints.

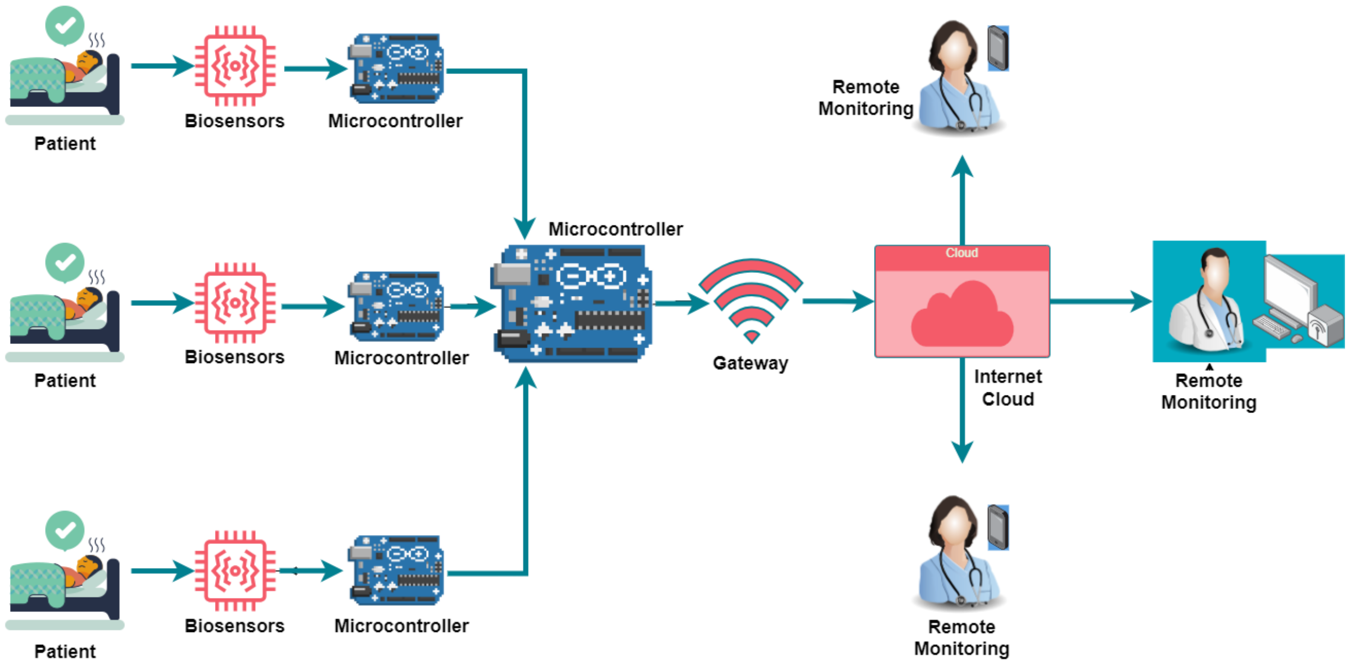


**Figure 6.** Remote monitoring via IoT healthcare systems.

The data generated by IoT devices serve as a goldmine for healthcare analytics. ML algorithms can analyze this vast amount of health data, leading to improvements in diagnostic accuracy, resource allocation optimization, and the development of personalized treatment plans [32]. Predictive modeling becomes a powerful tool for anticipating and preventing health issues, contributing to more effective healthcare strategies.

On the operational front, implementing smart healthcare infrastructures enabled by the IoT streamlines hospital and clinic operations. Automated inventory management, predictive equipment maintenance, and optimized energy usage contribute to cost-effectiveness and create a seamless healthcare environment. These operational efficiencies, in turn, can enhance the overall quality of healthcare services.

However, integration of the IoT in healthcare comes with its own set of challenges. Privacy and security concerns loom large as sensitive health data are transmitted and stored. Robust cybersecurity measures, strict adherence to regulations, and continuously monitoring for vulnerabilities are imperative to addressing these concerns, ensuring the integrity and confidentiality of patient information.

### *3.2. Multi-Hop Communication Networks for Patient Monitoring*

Multi-hop communication networks offer transformative possibilities for enhancing patient monitoring systems within the medical sector. By employing a multi-hop approach, health-monitoring devices can seamlessly communicate across extended distances, presenting a paradigm shift in how healthcare data are collected and transmitted [33].

In the medical sector, where patient monitoring is often distributed across various locations, multi-hop communications plays a pivotal role in overcoming geographic constraints [34]. This approach facilitates the creation of interconnected networks, enabling health monitoring devices to communicate through a series of intermediate nodes. As a result, even in geographically dispersed environments, healthcare providers can obtain real-time data from patient monitoring devices, fostering a comprehensive and continuous health surveillance system.

Moreover, the reliability and redundancy inherent in multi-hop architectures significantly contribute to improved patient care. In scenarios where a direct communications link may face disruptions or interference, the multi-hop network dynamically reroutes data through alternative paths, ensuring uninterrupted transmission. This redundancy is crucial for critical health data, where timely and continuous monitoring is imperative for effective decision making.

The scalability of multi-hop communications is particularly advantageous for the medical sector. As healthcare facilities expand or integrate new monitoring devices, the multi-hop architecture accommodates these additions seamlessly, without requiring a direct connection to a central hub [35]. This scalability aligns with the evolving nature of healthcare demands, allowing flexible and efficient system growth.

The application of multi-hop communications in patient monitoring holds immense potential for revolutionizing healthcare. It addresses geographic challenges, enhances reliability, and offers scalability, ultimately contributing to the creation of robust and responsive health monitoring systems in the medical sector [36].

### 3.3. The Role of Microcontrollers

Microcontrollers in multi-hop IoT systems are pivotal, serving as the backbone that orchestrates communication and coordination among devices within the network. In the context of multi-hop communication, microcontrollers act as intelligent nodes that facilitate the seamless exchange of information between devices, contributing to the efficiency and reliability of the overall system [37].

At the heart of multi-hop IoT systems, microcontrollers manage the flow of data by coordinating communication between devices on different hops. These devices, equipped with microcontrollers, not only receive and process data locally but also make informed decisions on forwarding data to subsequent nodes in the network. This intelligence allows for dynamic and adaptive routing, optimizing the transmission path based on factors such as network conditions and energy efficiency.

Microcontrollers play a crucial role in addressing the specific needs of health monitoring applications within multi-hop IoT systems. They enable the integration of various sensors and actuators, allowing collection of diverse health-related data and the execution of responsive actions. For instance, in a health monitoring scenario, a microcontroller on each hop can aggregate data from wearable sensors, process them locally to extract relevant information, and then transmit condensed and meaningful insights to the next node in the network [38].

Furthermore, microcontrollers contribute to the energy efficiency of multi-hop IoT systems by implementing power management strategies. They can control the sleep–wake cycles of devices, optimizing energy consumption and extending the overall network's lifespan, which is particularly crucial in healthcare applications where continuous monitoring is essential [39].

Several microcontrollers are commonly used in multi-hop IoT networks due to their features, power efficiency, and connectivity options. Some popular microcontrollers for working with multi-hop IoT networks include the following:

- ESP8266: Known for its low cost and built-in wireless fidelity (Wi-Fi) capabilities, the ESP8266 is widely used for IoT systems.
- ESP32: An advanced version of the ESP8266, the ESP32 includes both Wi-Fi and Bluetooth connectivity, making it suitable for a broader range of applications.
- Arduino: While not specifically a microcontroller, the Arduino platform, especially boards like Arduino Uno and Arduino Nano, is frequently used for IoT prototyping due to its ease of use and extensive community support.
- Raspberry Pi: Although more of a single-board computer than a microcontroller, Raspberry Pi is often used in IoT projects for its processing power, connectivity options, and versatility.
- Nordic nRF52 series: These microcontrollers are known for their low power consumption and are commonly used in IoT devices like wearables and Bluetooth-enabled gadgets.

In essence, the role of microcontrollers in multi-hop IoT systems is multifaceted, encompassing data management, intelligent routing, sensor integration, and energy optimization. Their capabilities are instrumental in creating resilient, adaptive, and energy-efficient networks, making them indispensable for the success of health monitoring applications and beyond.

### 3.4. Interoperability and Standardization in the IoT

Interoperability and standardization are foundational principles in the IoT, playing a pivotal role in ensuring seamless communication and functionality across a diverse array of devices and systems. These principles are particularly crucial as IoT ecosystems continue to grow and encompass various industries, including healthcare, smart cities, industrial automation, and more.

Interoperability is the linchpin of effective communication in the vast and interconnected landscape of the IoT. In the realm of health monitoring, interoperability ensures that devices, irrespective of their manufacturers, can communicate seamlessly. This is achieved through the adoption of standardized communications protocols such as Message Queuing Telemetry Transport (MQTT), Constrained Application Protocol (CoAP), and Hypertext Transfer Protocol (HTTP). These protocols facilitate a universal language for devices, promoting a harmonious environment where disparate components work together cohesively [40].

Standardization is the cornerstone that supports the edifice of interoperability. It involves the establishment of common frameworks, protocols, and specifications. Organizations such as the Internet Engineering Task Force (IETF), the Institute of Electrical and Electronics Engineers (IEEE), and the International Organization for Standardization (ISO) contribute to the development of these standards. Through industry-wide collaboration, stakeholders define and adhere to a set of norms that ensure uniformity across diverse IoT devices and platforms [41].

In the context of health monitoring within the IoT, interoperability allows for the integration of an extensive array of sensors, wearables, and medical devices into a cohesive network. Standardized data formats and communication protocols are crucial in this scenario. They ensure that information flows seamlessly between devices, maintaining data consistency and integrity. This interoperability is fundamental to creating a unified and comprehensive view of health data, allowing for more accurate diagnostics and personalized healthcare solutions.

Interoperability and standardization are pivotal in ensuring the scalability of IoT ecosystems. As IoT devices proliferate in number and variety, adherence to established standards becomes imperative. This ensures that new devices can seamlessly integrate into existing networks, promoting a future-ready infrastructure. Scalability is essential for accommodating the continuous influx of emerging technologies and innovations in health monitoring, providing a flexible framework that can evolve with the dynamic landscape of the H-IoT [42].

### 3.5. Security and Privacy Considerations

In the multifaceted landscape of multi-hop IoT patient monitoring, ensuring robust security and privacy measures is paramount. The interconnected web of devices collecting and transmitting health data necessitates stringent safeguards to protect the confidentiality and integrity of sensitive information. Security measures are designed to thwart unauthorized access, data breaches, and malicious attacks that could compromise the privacy of the individuals being monitored.

The foundation of a secure IoT patient monitoring system lies in the implementation of advanced encryption protocols. End-to-end encryption ensures that health data transmitted across the multi-hop network is comprehensively protected. Protocols such as Transport Layer Security (TLS) and Secure Sockets Layer (SSL) play a pivotal role in establishing secure communication channels, and safeguarding data from interception and unauthorized tampering during transit [43].

Controlling access to health data is a multifaceted challenge in a multi-hop IoT environment. Implementing robust access-control mechanisms and authentication protocols ensures that only authorized entities can interact with and retrieve sensitive health information. This involves the use of secure login credentials, biometric authentication, and role-based access controls to limit data access based on the user's role and responsibilities.

Embedding privacy principles into the design of IoT patient monitoring systems is crucial. The concept of privacy by design emphasizes integrating privacy features from the outset rather than as an afterthought. Additionally, adopting a data minimization strategy ensures that only necessary and relevant health data are collected, reducing the risk associated with unnecessary data exposure. These principles collectively contribute to a privacy-centric approach that aligns with regulatory frameworks and ethical considerations [44].

Security in multi-hop IoT health monitoring extends beyond initial implementation. Continuous monitoring of the network for anomalies, coupled with real-time threat detection mechanisms, fortifies the system against evolving cybersecurity threats. Intrusion detection systems and anomaly detection algorithms play a vital role in identifying and mitigating potential security breaches promptly.

Adhering to established regulatory standards and frameworks is imperative in the healthcare sector. Regulations such as the Health Insurance Portability and Accountability Act (HIPAA) in the United States or the General Data Protection Regulation (GDPR) in Europe set stringent requirements for the protection of health data. Ensuring compliance with these standards not only fortifies security and privacy but also safeguards against legal liability [45].

Human factors remain a significant consideration in the security and privacy of multi-hop IoT health monitoring. Educating users, including healthcare professionals and patients, about cybersecurity best practices and privacy awareness is crucial. Empowered users are better equipped to recognize potential security threats, to adhere to privacy guidelines, and to actively contribute to maintaining a secure patient monitoring environment.

## 4. Integration of Biosensors

The integration of biosensors with multi-hop IoT systems is emerging as a cornerstone in revolutionizing healthcare services, particularly in the area of real-time remote patient monitoring in hospitals. The motivation for this integration lies in the ability to deploy multiple biosensors in different locations within medical facilities, seamlessly connected by multi-hop IoT systems. This strategic deployment enables comprehensive and simultaneous monitoring of patients in different wards, critical care units, and even remote areas, providing healthcare professionals with a holistic view of patient health. The potential of this integration to transform the approach to real-time remote patient monitoring functions from a traditional hospital service emphasizes how important it is. Through multi-hop communication, biosensors can transmit real-time health data over long distances, enabling healthcare providers to access critical information without physical constraints. This not only increases the efficiency of healthcare services, but also facilitates early detection of abnormal conditions, timely intervention, and improved patient outcomes. The value of integrating biosensors with multi-hop IoT systems in hospitals lies in its potential to create a connected and responsive healthcare environment where real-time remote patient monitoring becomes a reality, overcoming traditional healthcare limitations.

### *4.1. Architecture and Design Considerations*

The integration of biosensors with multi-hop IoT systems in healthcare heralds a transformative era in remote patient monitoring and health data acquisition. The architecture and design of such systems require careful consideration to ensure seamless functionality, real-time data transmission, and effective utilization of biosensor-generated information. This section delves into the key architectural and design considerations vital to successful integration of biosensors with multi-hop IoT systems in healthcare applications.

A foundational aspect of designing multi-hop IoT systems for biosensor integration is the adoption of a scalable and modular architecture. Scalability ensures that the system can efficiently handle the increasing number of connected biosensors, accommodating the growing demands of healthcare applications [46]. A modular architecture allows for flexibility, enabling the integration of diverse biosensors with varying functionalities without compromising overall system coherence.

In the landscape of multi-hop IoT systems, edge computing and fog computing are instrumental in optimizing data processing and decision making. Edge computing, situated at each intermediate node in the multi-hop path, enables localized data processing. This occurs at the periphery of the network, reducing reliance on a central server [47]. Each intermediate node is treated as an *edge*, facilitating distributed processing and potential latency reduction. Fog computing, a strategic extension of edge computing, operates through strategically placed fog nodes within a multi-hop network. These nodes perform advanced processing and data aggregation, contributing refined data for transmission to a central server [48]. The central server, located at the end of the multi-hop path, conducts the final analysis and decision making. The combined utilization of edge and fog computing in multi-hop IoT systems minimizes the burden on central servers, enhances real-time capabilities, and optimizes data-processing efficiency. This distributed processing model strategically leverages intermediate and fog nodes, ultimately improving the overall efficiency and responsiveness of patient monitoring systems.

Dynamic routing algorithms play a crucial role in the functionality of multi-hop IoT networks, which are inherently dynamic due to the changing nature of the network topology. These algorithms are designed to optimize data transmission paths, ensuring reliable and efficient communication between biosensors and the central data collection point. One prominent dynamic routing algorithm is Ad hoc On-Demand Distance Vector (AODV). *On-demand* means establishing a route between nodes only when necessary. When a node requires a route to another node, AODV initiates a route-discovery process. It maintains routing tables at each node to store information about the discovered routes, and these tables are updated dynamically based on the changing network conditions. AODV is particularly suitable for multi-hop environments because it adapts to variations in the network topology. Another noteworthy algorithm is Dynamic Source Routing (DSR), which is an on-demand algorithm that discovers routes as needed. However, it distinguishes itself by utilizing source routing, where the complete route is included in the packet header. This eliminates the need for intermediate nodes to maintain routing tables, simplifying the process and making it suitable for dynamic multi-hop environments [49].

Real-time data analytics is a critical aspect in the design of biosensor-integrated multi-hop IoT systems. This capability allows the immediate processing of biosensor data, ensuring timely detection of anomalies and facilitating prompt decision making, particularly in healthcare applications. To enable real-time analytics, these systems implement analytics engines that can process biosensor data on the fly [50]. This means that data are analyzed as they are generated, without the need to store large volumes of data before analysis. This approach reduces latency and enables a swift response to emerging health-related insights [51]. ML algorithms play a pivotal role in enhancing the capabilities of these systems. By incorporating ML into the analytics process, the system gains the ability to derive meaningful and actionable insights from biosensor data [11]. ML algorithms can identify patterns, trends, and potential anomalies in real time, contributing to personalized and predictive healthcare. The significance of real-time data analytics in biosensor-integrated multi-hop IoT systems lies in the capacity to provide healthcare professionals with immediate and relevant information. This rapid analysis of biosensor data not only supports timely decision making but also opens avenues to personalized healthcare solutions [52]. The combination of real-time analytics and ML contributes to a more efficient and effective healthcare ecosystem by harnessing the full potential of biosensor data.

The IoT employs various architectures, including three-layer, four-layer, and five-layer structures [53], but structures vary depending on the optimum design for the IoT. In multi-hop IoT system design, the five-layer structure shown in Figure 7 is suitable, comprising the physical layer, protocol layer, transport layer, application layer, and business layer [54]. The physical layer, also known as the perception layer, involves biosensors connected to multi-hop nodes as microcontrollers for collecting data. The protocol layer facilitates sensor-data transfer between the sending node and the receiving node via multiple intermediary nodes using communications protocols such as Mesh Networking, Wi-Fi, Zigbee, Thread, and BLE Mesh. The transport layer assumes responsibility for providing connection-oriented and reliable communications. It ensures accurate delivery of data to the destination by employing the Transmission Control Protocol (TCP), commonly used when prioritizing reliability and data integrity, guaranteeing error-free transmission of all data. Internet Protocol (IP) plays a critical role in device addressing, enabling routers to appropriately route data packets to their intended destinations. On the other hand, TLS and its precursor, SSL, are accountable for securing communications channels. These protocols employ encryption algorithms, safeguarding data confidentiality and integrity throughout transmission. The application layer provides specific IoT services like smart healthcare under various application protocols like Advanced MQTT, which works for efficient and scalable communications through a publish-subscribe model, and CoAP, which is responsible for facilitating resource-constrained device interactions using a lightweight, RESTful approach. HTTP serves as the foundation for web-based communications, with Hypertext Transfer Protocol Secure (HTTPS) encrypting the data for transfer in IoT applications. The business layer in the IoT, in collaboration with cloud platforms like Amazon Web Services (AWS), Microsoft Azure, Google Cloud Platform (GCP), IBM Cloud, and Oracle Cloud, manages overall IoT application and service operations. It oversees high-level analysis reports, creates flowcharts and graphs, analyzes results, and suggests improvements for devices and services deployed in the IoT ecosystem. Integration with these cloud platforms allows robust management, scalability, and advanced analytics, contributing to the efficient functioning and optimization of IoT applications and services.

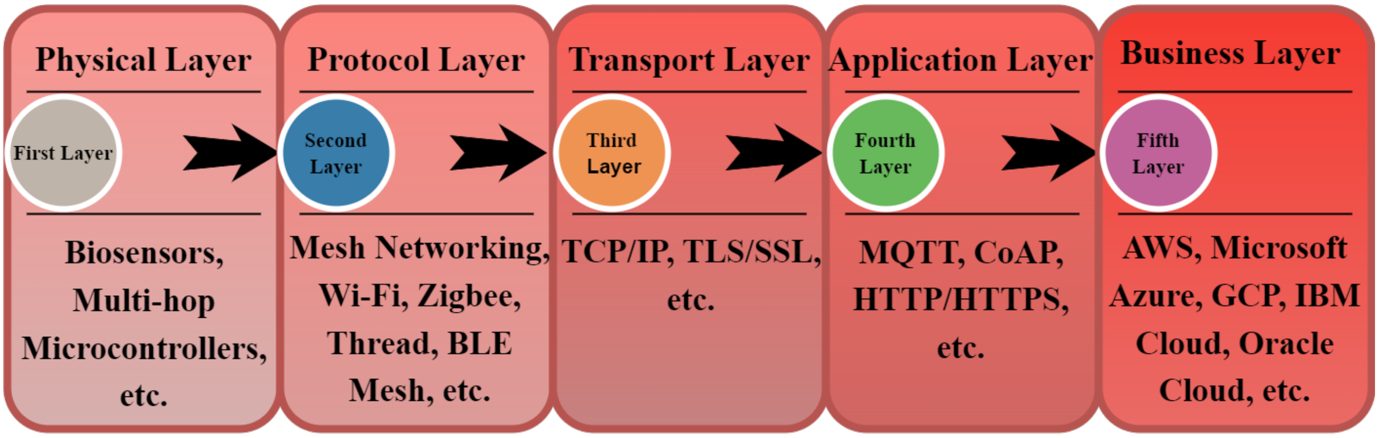


**Figure 7.** The five-layer IoT structure.

### *4.2. Node Configuration*

The configuration of nodes in multi-hop networks is a critical aspect that significantly influences the efficiency and performance of the entire network. In the context of patient monitoring systems utilizing multi-hop communications, configuring nodes appropriately is paramount to ensuring seamless data transmission, minimal latency, and optimal resource utilization. In the realm of multi-hop IoT networks, the configuration of nodes holds paramount importance, and the ESP32-WROVER-E microcontroller shown in Figure 8 stands out as a notable example due to its widespread adoption and versatility among microcontrollers [55]. In the context of patient monitoring systems leveraging multi-hop communication, the configuration of ESP32 nodes plays a critical role in shaping the efficiency and performance of the entire network.

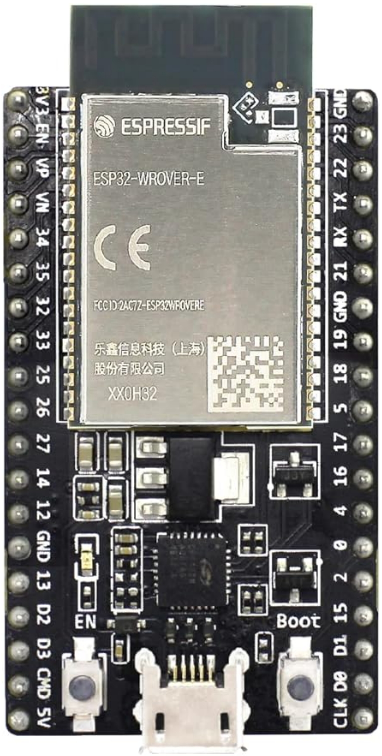


**Figure 8.** The ESP32-WROVER-E is an enhanced version of the ESP32 microcontroller.

In the context of multi-hop networks, ESP32's configuration requires careful consideration of numerous specifications. The following details outline key parameters and settings crucial for optimal ESP32 node configuration, ensuring seamless integration into the patient monitoring ecosystem.

- Wireless communications setup: The ESP32 supports various wireless communications protocols like Wi-Fi and Bluetooth, making it suitable for multi-hop networks. Configuring these communication interfaces ensures seamless connectivity between nodes.
- Network topology design: Designing an effective network topology is crucial. ESP32 nodes can be configured in a mesh topology, allowing each node to communicate with nearby nodes to form a multi-hop network.
- Power management: Efficient power management is vital for patient monitoring devices, especially those relying on batteries. The ESP32's deep-sleep and low-power modes can be configured strategically to optimize power consumption, extending the node's operational life.
- Data packet handling: Configuring how data packets are handled during transmission is key. ESP32 nodes can be programmed to efficiently manage packet routing, error handling, and acknowledgment mechanisms, ensuring reliable data delivery in patient monitoring scenarios.
- Dynamic routing algorithms: ESP32 nodes can implement dynamic routing algorithms such as AODV or DSR. These algorithms adapt to changes in network conditions, automatically adjusting the routing paths based on factors like node mobility or signal strength.
- Security measures: Implementing security measures is essential in patient monitoring systems. ESP32 nodes can be configured to use encryption and authentication protocols, safeguarding sensitive health data as they traverse the multi-hop network.
- Quality of service: Configuring QoS parameters ensures that critical health data receive priority treatment. ESP32 nodes can be set to prioritize specific types of data, guaranteeing timely delivery and minimizing delays in transmitting vital health information.

4.2.1. Biosensors Node Configuration

In the integration of biosensors with microcontrollers, establishing a reliable connection is fundamental to ensuring accurate data acquisition and transmission. The attachment process involves several considerations for different types of biosensor.

For ECG biosensors like the AD8232, establishing a secure connection involves connecting the electrodes to the microcontroller's analog input pins. This configuration ensures precise reception of ECG signals, which is crucial for accurate patient monitoring. The ESP32 microcontroller, equipped with analog input capabilities, plays a pivotal role in capturing and processing real-time ECG data. The circuit design is shown in Figure 9. Its processing capabilities enable the implementation of real-time ECG signal processing algorithms, contributing to accurate heartbeat detection.

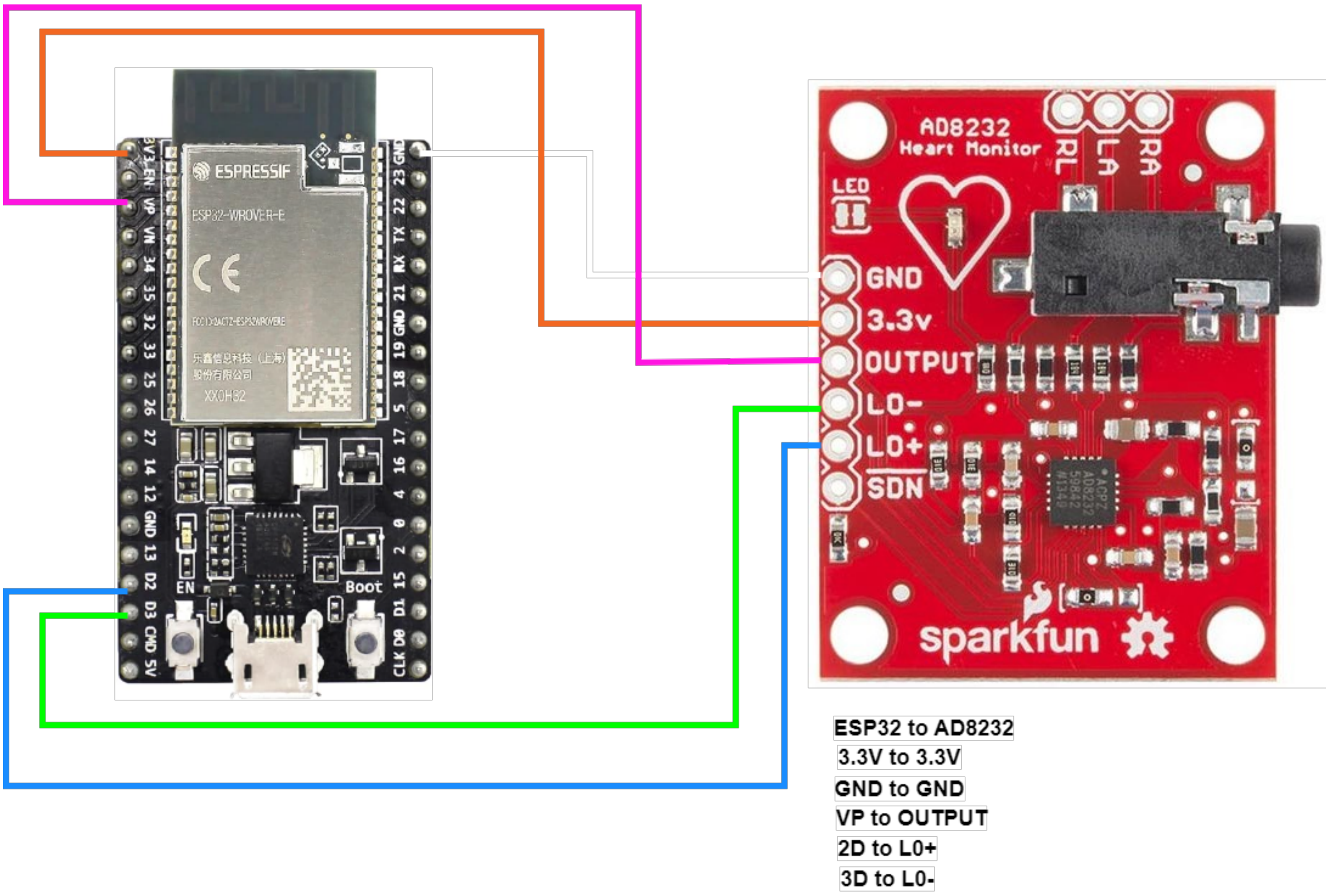


**Figure 9.** Circuit diagram of ESP32 and AD8232 integration for reading a real-time ECG signal.

The MAX30102 biosensor, designed for heart rate and pulse oximetry monitoring, employs a PPG method using a photodetector plus red and IR LEDs. Configuring this biosensor with the ESP32 involves several key steps. First, the ESP32's GPIO pins are utilized to establish connections with the necessary MAX30102 interfaces, including I2C for communication. The I2C protocol allows efficient data exchange between the ESP32 and MAX30102. Next, the red and IR LEDs of the MAX30102 are connected to the appropriate GPIO pins of the ESP32. These LEDs cast light onto the skin, and the photodetector captures the reflected light, generating the PPG waveform. The ESP32 is programmed to read and process PPG data from the MAX30102, which the circuit design in Figure 10 shows. The real-time processing capabilities of the ESP32 enable the extraction of vital information, such as heart rate and oxygen saturation levels, from the PPG waveform.

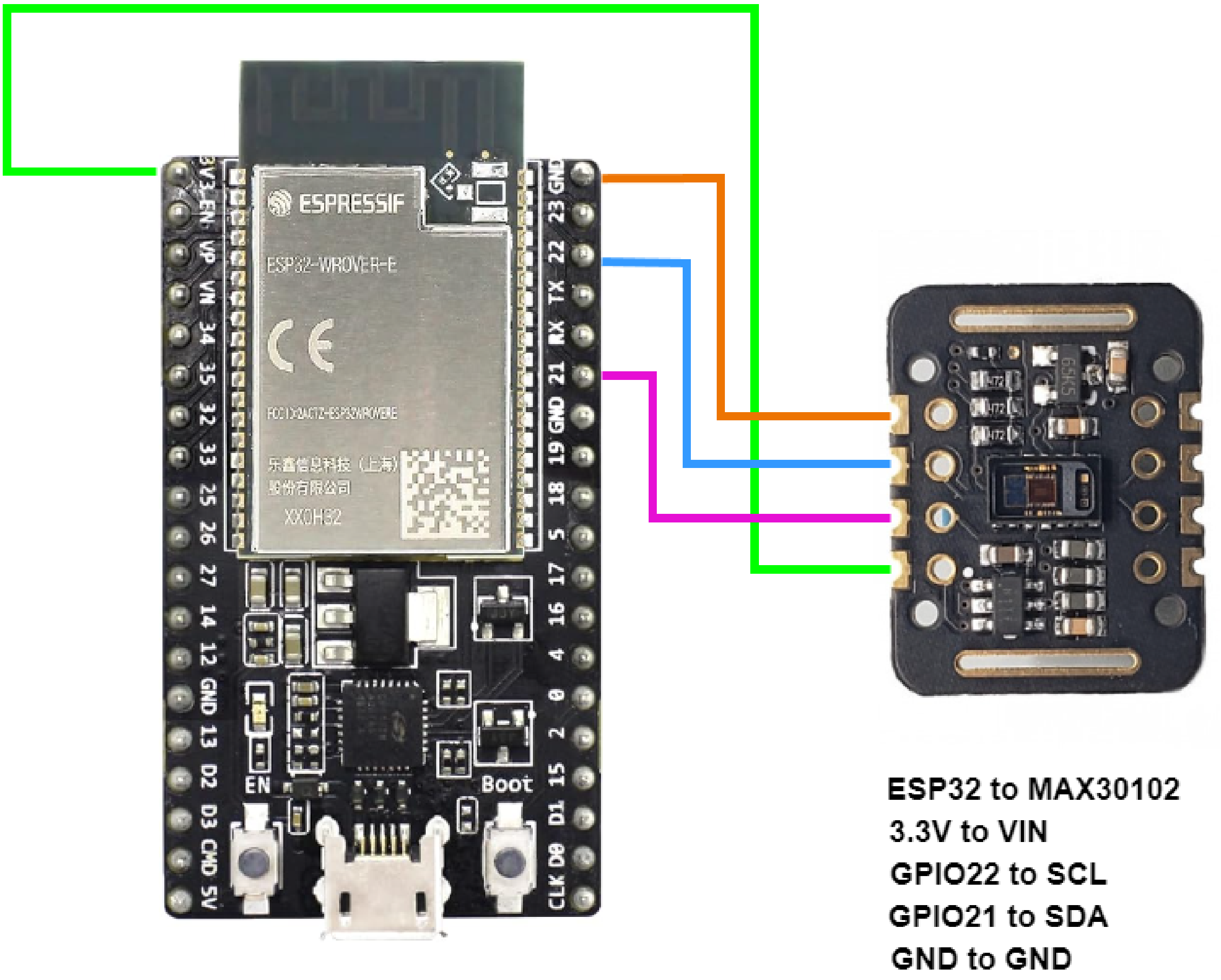


**Figure 10.** The ESP32 and MAX30102 integrate into a circuit design for monitoring pulse oximetry and heart rate in real time.

In establishing a multi-hop IoT system for health monitoring, the integration of biosensors with microcontrollers like the ESP32 becomes pivotal. Several kinds of biosensor that can detect vital signs such as blood oxygen level, heart rate, and ECG play a crucial role in the multi-hop communications network, facilitating seamless transmission of health data across nodes. This collaborative approach enhances the efficiency and reliability of health monitoring systems by leveraging biosensors attached to microcontrollers. The interconnected nature of biosensors within a multi-hop IoT framework ensures robust and continuous health data monitoring, offering a promising avenue for advancements in remote health monitoring systems. Some of the recent studies into patient monitoring through biosensors in the IoT healthcare realm are shown in Table 1.

**Table 1.** Summary of biosensor patient monitoring systems based on the IoT.

| Reference | Aims and Contributions | Methodology | Biosensors Used | Evaluation Metrics |
|---|---|---|---|---|
| [56] | To develop a deep learning IoT system for real-time remote monitoring and early detection of health issues. | The systems employed deep learning algorithms integrated with IoT technology for real-time data collection, transmission, analysis, and alert generation to enable early detection of health issues. | MAX30100, AD8232, MLX90614. | Blood oxygen level, heart rate, ECG signal data, and body temperature. |
| [57] | To advance healthcare monitoring through integration of the IoT with a specific focus on ECGs and vital signs, offering a holistic end-to-end solution. | The focus was on designing and implementing an end-to-end solution for capturing, analyzing, and displaying physiological data in real time. | AD8232, MLX90614, MAX30100. | Heart signals, heart rate, blood oxygen levels, and body temperature. |
| [58] | To design a monitoring system that allows doctors to monitor asthmatic patients from a remote area. | Designing and integrating IoT technologies for capturing asthma-related data, developing a remote monitoring platform, conducting data analysis, and ensuring ethical considerations to create an effective IoT-based remote asthma patient monitoring system. | MAX30100, MLX90614, DHT11, MQ-135, AD8232. | Pulse oximetry, heart rate, body temperature, room temperature/humidity, air quality, and ECG. |
| [59] | To develop a digital system using a pulse oximeter and fuzzy logic for early prediction and screening of hypoxemia, utilizing SpO2 values. | Developed a non-invasive hypoxemia detection system using the MAX30102 sensor and fuzzy logic, integrating the IoT for data storage in Google Firebase and an Android application for result visualization. | MAX30102. | Hypoxemia. |
| [60] | Addressing the increased risk of cardiovascular diseases in an aging population and individuals with chronic diseases, with a focus on continuous vital sign monitoring and real-time health status awareness. | Employing photoelectric volumetric methods for pulse and blood oxygen measurement, calculating SpO2 using specific formulas, and implementing hardware and software designs for real-time monitoring and data processing. | MAX30102. | Heart rate, and blood oxygen saturation. |

**Table 1.** *Cont.*

| Reference | Aims and Contributions | Methodology | Biosensors Used | Evaluation Metrics |
|---|---|---|---|---|
| [61] | To propose an innovative design for an IoT-enabled interconnected healthcare system for wireless patient biomonitoring using sensor patches. | This paper addresses gaps in IoT applications in health, compares IoT architectures for digital health, conducts a comparative survey, investigates wireless (BLE and RFID) to communicate with a Biosticker Smart Box, and provides a detailed design of a decoupled architecture with solutions and strategies. | Biostickers. | ECG, heart rate, respiration rate, oxygen saturation, temperature. |
| [62] | This paper examines IoT in healthcare, highlights IoT's penetration in healthcare, discusses future trends like bio- and nano-IoT, and emphasizes WBANs' importance in monitoring patient vital signs. | This paper details the design of a prototype system using MicaZ wireless modules for pulse oximeter sensors and evaluates its performance in terms of network formation, stability, energy efficiency, and data accuracy. | SpO2 sensor oximeter cards. | Oxygen saturation level, heart rate, and plethysmogram. |
| [63] | The paper highlights a potential role for IoT and artificial intelligence technologies in improving health and preventing chronic conditions. | The paper demonstrates the integration of biosensors for vital signs monitoring, introduces a 1D CNN-based BP estimation model using 1-channel ECG signals, and develops a wireless biosensor patch with an IoT connection for blood pressure monitoring. | MAX30205, Ag/AgCl electrodes coated with hydrogel, PAM-7Q, BNO055, ADS1293. | Body temperature, electrocardiography, blood pressure, tracking user's position, human activity. |
| [64] | This work aims to develop an IoT-enabled point-of-care (PoC) diagnostic device for monitoring creatinine levels in serum samples, which is important for the early diagnosis of kidney disease. | The paper utilizes a creatinine-selective molecularly imprinted polymer-coated interdigital sensor, fabricated using electrochemical impedance spectroscopy, connected to a low-power microcontroller and an IoT-associated cloud server for quantitative measurement of serum creatinine levels, allowing remote access by oncologists/nephrologists. | An interdigital sensor coated with creatinine selective molecularly imprinted polymer (MIP) by utilizing electrochemical impedance spectroscopy (EIS). | Creatinine levels from urine or serum. |

#### 4.2.2. Communications Protocol

Multi-hop IoT systems support various communication protocols and technologies to enable the relay of information across multiple nodes. The choice of communication method depends on factors such as range, power consumption, data rate, and the specific requirements of the IoT application. Every communication technology contributes to the flexibility and scalability of a multi-hop IoT system. This section focuses on some of the common communications methods that are used in multi-hop IoT networks.

- Mesh networking: This is a fundamental and decentralized communication protocol for multi-hop IoT networks, which incorporates a resilient and self-sustainable structure that enables continuous operation even in the face of node failures [65]. In this decentralized approach, each node acts as a source and relay point, allowing data to be dynamically rerouted along alternative paths in the event of disruption [66]. This self-sustainable capability reduces the risk of data loss, and the scalability of mesh networks accommodates a growing number of devices, increasing overall robustness. The dynamic topology of mesh networks seamlessly adapts to changes, allowing nodes to join or leave without affecting connectivity. In multi-hop IoT scenarios, mesh networks extend coverage beyond the range of individual nodes, contributing to reliability although introducing some latency due to the multi-hop nature [67]. In contrast, dynamic routing in mesh networks optimizes the data paths to minimize communication delays.
- Wi-Fi: A common wireless communication protocol in multi-hop IoT systems, it operates in the 2.4 GHz and 5 GHz frequency bands and uses the IEEE 802.11 family of standards for broad compatibility and high data rates [68]. It uses CSMA/CA for channel access and supports both infrastructure and ad hoc networking modes [69]. Wi-Fi's flexibility extends to multi-hop scenarios through mesh networking, improving coverage and reliability, which is critical in environments where direct communication between devices is difficult [70]. Its high data rates, suitable for bandwidth-intensive applications, work with TCP/IP for seamless Internet integration and broad device compatibility. Security is addressed through WPA3, which provides robust encryption and authentication, while WPA2 or WPA3 Enterprise enhances security in corporate environments. Despite the benefits of Wi-Fi, power consumption is a challenge, particularly for battery-powered IoT devices, so a balance between data speed and energy efficiency is required when designing effective multi-hop Wi-Fi IoT networks.
- Zigbee: Based on IEEE 802.15.4 [71] and operating in the 2.4 GHz ISM band, Zigbee uses DSSS modulation for robust communication in multi-hop IoT systems. It uses CSMA-CA to minimize collisions, supports multiple topologies, and addresses with 16-bit and 64-bit identifiers [72]. Zigbee defines application profiles and clusters and adopts the Zigbee 3.0 standard for interoperability across vendors [73]. Efficiency is ensured, with security provided by AES encryption and authentication, and networks consist of coordinator, router, and end device types. The Zigbee stack, under Zigbee 3.0, improves the level of compatibility and is being used in smart homes and industrial IoT [74]. Despite advantages such as low power consumption and mesh networking, Zigbee faces challenges such as limited data rates and potential interference in the 2.4 GHz band. These issues need to be recognized in different applications to effectively implement Zigbee in multi-hop IoT systems.
- Thread: A communication protocol tailored for the IoT is essential for building reliable multi-hop networks that operate over low-power wireless networks using an IPv6-based protocol. Its mesh topology allows devices to communicate directly, extending coverage through multi-hop communication and ensuring secure data transmission with banking-class encryption and authentication mechanisms [75]. Thread optimizes power consumption for low-power devices and supports sleep modes to extend battery life [76]. With its mesh topology, Thread scales effectively, accommodating a wide range of devices and increasing scalability. However, Thread provides a robust solution for multi-hop IoT networks with features such as mesh topology, IPv6 addressing, security, low-power operation, interoperability, dynamic routing, and scalability [77].
- Bluetooth low-energy mesh: Designed for low-power, short-range communications, BLE becomes a powerful solution for scalable, multi-hop IoT networks when inte-

grated into a mesh topology [78]. In a BLE Mesh network, devices work together to relay data, extending coverage beyond point-to-point connections with flexibility and resilience [79]. BLE is particularly energy efficient, making it suitable for battery-powered IoT devices, which is critical in remote or impractical battery replacement scenarios [80]. Its interoperability allows devices from different manufacturers to communicate seamlessly within the BLE Mesh network, fostering an open ecosystem. BLE Mesh provides security through encryption and authentication, ensuring data confidentiality and integrity. With versatility in areas such as smart homes, industrial IoT, healthcare, and asset tracking, BLE Mesh's configuration flexibility and ease of deployment contribute to its widespread adoption in various IoT scenarios [81].

#### 4.2.3. Routing Node Configuration

- Routing algorithm: Routing nodes, a crucial part of multi-hop IoT networks, use dynamic algorithms such as AODV and DSR to efficiently route data through the network [82]. AODV dynamically establishes routes based on the current state of the network, which is crucial for dynamic IoT environments. In contrast, DSR focuses on real-time route discovery, optimizing transmissions through route caching. Both AODV and DSR are able to handle dynamic environments, adjust routing paths, and adapt to topology changes for reliable communication in IoT scenarios [83]. Following an on-demand routing approach, AODV and DSR establish routes only when needed, conserving network resources and promoting energy efficiency. AODV uses sequence numbers for route identification, and DSR efficiently manages routing through route caching, adopting a decentralized approach for scalability. In a multi-hop IoT network, AODV initiates route discovery when a device needs to send data. Using AODV, the source node broadcasts route request (RREQ) messages to its neighbor nodes when it needs a route. Neighboring nodes receiving the RREQ either forward it or respond with a route reply (RREP) if they have a valid route, while intermediate nodes record the route back to the source in the RREQ. In DSR, the source node determines the complete route to the destination as a network link, with each intermediate node acting as a routing node. However, depending on network conditions, energy efficiency, and application requirements, routing nodes in multi-hop IoT networks use AODV and DSR for efficient route discovery, maintenance, and forwarding, as shown in Figure 11.

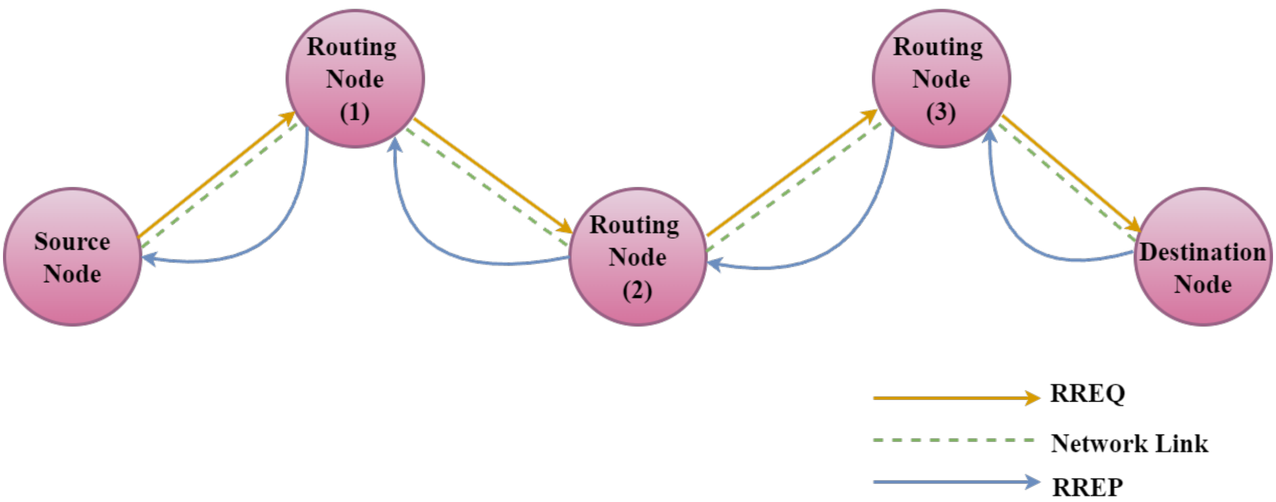


**Figure 11.** A routing protocol diagram for AODV and DSR.

- Memory and processing power: Memory resources are an important factor for effective routing-node configuration in multi-hop IoT networks, as they play a vital role in storing routing tables and network topology information [84]. In dynamic IoT environments, sufficient memory allows for rapid adaptation to frequent network topology changes, ensuring efficient routing decisions [85]. Insufficient memory can lead to increased latency and packet loss, impacting performance [86]. Processing power is also essential, especially for dynamic routing algorithms such as AODV and DSR, which require efficient execution to reduce latency and improve network responsiveness [87]. In resource-challenged IoT environments, it is a critical balancing act between adaptability and resource management. As networks grow, the demand for memory and processing power increases, requiring scalable routing node configurations to ensure continued reliability and performance. Memory and processing power are essential for maintaining efficient routing, adaptability, and overall network performance in multi-hop IoT networks.

#### 4.2.4. Gateway Node Configuration

- Data aggregation: Data aggregation in IoT networks involves gateway nodes strategically collecting and consolidating data from multiple sensor nodes to optimize network efficiency and resource utilization [88]. This process minimizes the amount of data transmitted, improving resource utilization and reducing congestion in scenarios with many sensor nodes [89]. Data aggregation contributes to energy efficiency by minimizing the need for frequent and energy-intensive transmissions directly from sensor nodes [90]. It also optimizes bandwidth usage by transmitting aggregated data sets, which is particularly beneficial in bandwidth-limited scenarios [91]. Aggregating data at gateway nodes allows for better control and validation, improving data integrity and minimizing errors during transmission [90]. In summary, data aggregation is crucial for efficiency, congestion reduction, energy optimization, bandwidth conservation, and data integrity in IoT networks, highlighting the strategic importance of gateway nodes in facilitating the seamless functioning of the IoT ecosystem.
- Connectivity: In IoT networks, gateways play a crucial role in ensuring robust connections to back-end servers or cloud platforms. Gateways utilize reliable protocols such as MQTT, CoAP, or HTTP/HTTPS and adapt to application-specific requirements [46]. It establishes connectivity using wired solutions such as Ethernet for stability and high bandwidth, or wireless technologies such as 4G/5G and Wi-Fi when wired connections are inconvenient [92]. Gateways may incorporate load balancing to efficiently distribute traffic and ensure optimal system performance. In the event of hardware failure or network disruption, redundancy measures such as dual interfaces or failover mechanisms increase reliability. With encrypted communication channels such as TLS and SSL, security is prioritized to protect data from unauthorized access [93]. The connectivity configuration is designed to be scalable to support the growing number of devices and increasing data loads, which is crucial for adapting to evolving requirements and expanding the IoT ecosystem [94]. In summary, the connectivity configuration of gateways includes protocol selection, wired or wireless solutions, load balancing, redundancy measures, security implementation, and scalability, all of which contribute to reliable and efficient connections between the IoT network and the back-end infrastructure.
- Data processing: In multi-hop IoT systems, gateway nodes play a very significant role beyond data collection, performing complex data processing tasks to improve system efficiency and responsiveness. The gateway acts as an intelligent hub where data are carefully pre-processed, starting with filtering to remove irrelevant information and optimize the payload for transmission [95]. In addition, gateway nodes employ compression techniques to minimize the size of data packets, addressing bandwidth constraints and reducing network congestion, thereby improving the speed of data transmission [84]. Gateway nodes also perform basic analytics tasks, extracting initial insights from collected data and providing valuable information for immediate decision making at the network edge [96]. By performing data processing at gateway nodes, the processing load on centralized servers is reduced, latency is reduced, response times are improved, and resource utilization is optimized. This approach

is particularly beneficial for real-time decision-making scenarios, as local processing capabilities contribute to faster action without overloading central servers [97]. In summary, data processing at gateway nodes ensures streamlined data transmission, reduces network congestion, and improves responsiveness in dynamic, multi-hop IoT environments.

### 4.3. Power Consumption and Energy Efficiency

Efficient management of power consumption is a critical aspect of integrating biosensors into multi-hop IoT systems. This section explores key considerations and strategies to enhance energy efficiency in biosensor nodes within a multi-hop communications framework.

Biosensor nodes are configured with low-power design principles to minimize energy consumption during sensing, data processing, and communication tasks. This involves optimizing hardware components, employing energy-efficient microcontrollers, and utilizing low-power sensing technologies [98].

To conserve power during periods of inactivity, biosensor nodes need to implement sleep modes. By transitioning into low-power states when not actively sensing or communicating, the nodes reduce overall energy consumption, extending the operational lifespan of the device [99].

Biosensors are configured with adaptive sampling rates based on contextual factors. Adjusting the sensing frequency in response to variations in environmental conditions or user requirements ensures that energy is allocated efficiently, avoiding unnecessary data collection.

To supplement power sources, biosensor nodes may integrate energy harvesting mechanisms like solar panels or kinetic energy harvesters. Renewable energy sources contribute to prolonged operational lifetimes, especially in remote or off-grid deployment scenarios [100].

Multi-hop communications introduces the concept of duty cycling, where biosensor nodes selectively activate their communication modules at scheduled intervals. This intermittent communication strategy balances the need for timely data transmission with energy conservation, particularly in scenarios with low data rate requirements. Moreover, energy-efficient routing algorithms are employed in multi-hop communications to minimize the distance and number of hops between biosensor nodes and the gateway. This reduces the energy expended during data relay, contributing to overall energy efficiency in the network [101].

Furthermore, biosensor nodes employ dynamic power management techniques to adapt to varying operational conditions. This includes adjusting the transmission power of communication modules based on the proximity of neighboring nodes, and optimizing energy usage for reliable data transmission [102]. In addition, biosensor nodes incorporate mechanisms for estimating the remaining battery life or energy reserves. This information is valuable for proactive maintenance, allowing system administrators to replace or recharge batteries before nodes become non-operational.

In summary, the integration of biosensors with multi-hop IoT systems requires meticulous attention to power consumption and energy efficiency. By implementing low-power design, sleep modes, adaptive sampling rates, energy harvesting, duty cycling, optimized routing algorithms, dynamic power management, and lifetime estimation, biosensor nodes can operate efficiently within the constraints on energy resources, ensuring prolonged and reliable functionality in diverse IoT applications.

### 4.4. Server Setup

Server setup in multi-hop IoT systems is a complex yet integral component meticulously designed to handle the intricacies of data flow from edge devices to the core. This comprehensive technical configuration encompasses several key aspects, where gateways are configured with MQTT or CoAP, facilitating efficient data transmission within the network. These protocols ensure seamless communication between edge devices and the designated servers [103,104].

High-speed wired or wireless connections are leveraged to optimize data transfer between gateways and servers. This ensures swift and reliable data ingestion, which is critical for real-time analytics and decision making [105].

Upon receiving data, the server environment is tailored for optimal storage and organization. Databases like MongoDB are employed, providing an efficient structure to store diverse datasets generated by distributed sensor nodes [106].

The server setup includes implementation of advanced analytics engines, utilizing powerful algorithms and ML models [107]. These engines unravel intricate patterns, trends, and anomalies within the incoming data, enabling meaningful insights.

Robust security measures are integrated to fortify the integrity and confidentiality of processed data. This includes implementation of TLS/SSL for secure data transmission, access-control mechanisms, and intrusion detection systems [108]. Compliance with industry standards such as ISO/IEC 27001 and GDPR is ensured through continuous security audits using tools like Nessus.

The server setup is designed to be scalable, accommodating the dynamic nature of incoming data in multi-hop IoT networks. This scalability ensures that the system can seamlessly handle a growing volume of data and devices [109]. Acting as the nerve center of the multi-hop IoT system, the server setup orchestrates a seamless flow of data from the edge to the core. The configuration is tailored to support efficient storage, advanced analytics, and fortified security protocols.

The server setup is a pivotal element that establishes the foundation for informed decision making in multi-hop IoT systems. The technical configuration ensures a holistic approach to data management, from reception and storage to analysis and security, contributing to the overall effectiveness and reliability of the network.

## 5. Cloud Connectivity

### *5.1. Cloud-Based Healthcare Platforms*

The integration of cloud computing technologies into healthcare systems has ushered in a transformative era, reshaping patient care, data management, and overall system efficiency [110]. This innovative approach leverages the scalability, accessibility, and computational power of cloud platforms to address challenges faced by traditional healthcare systems, marking a significant paradigm shift.

In the realm of health monitoring, cloud-based platforms provide a dynamic and interconnected ecosystem. Patient data can be securely stored, analyzed, and shared among healthcare professionals, departing from traditional localized systems [111]. This introduces a new era of real-time monitoring, predictive analytics, and streamlined collaboration, where scalability, interoperability, and data security play pivotal roles in shaping the future of health monitoring.

Cloud-based patient monitoring platforms revolutionize healthcare delivery, incorporating advanced technologies for patient care. These platforms encompass solutions for remote patient monitoring, data analytics, wearable technologies, and IoT integration [112]. Remote patient monitoring platforms utilizing cloud computing capabilities enable real-time transmission and storage of patient data, empowering healthcare professionals to make timely interventions.

This transformative shift in healthcare leverages the capabilities of cloud-based platforms, fostering innovation, efficiency, and interconnected healthcare ecosystems. The convergence of cloud computing and healthcare technologies represents a fundamental change in how healthcare services are delivered and how health-related data are managed and utilized.

Several cloud platforms cater to the specific needs of patient monitoring, offering robust features and services tailored to the healthcare industry [111]. Below are listed some prominent cloud platforms commonly utilized in the healthcare domain.

- Amazon Web Services: AWS is a widely adopted cloud platform that provides a comprehensive set of services for healthcare applications. It offers scalable computing

power, storage, and databases, along with tools for ML and analytics. AWS has established itself as a reliable choice for healthcare organizations aiming to leverage cloud capabilities.
- Microsoft Azure: Microsoft is another major player in the cloud services arena, offering a range of Azure tools and services suitable for patient monitoring applications. Azure provides scalable infrastructure, data storage, and advanced analytics. Its compliance certifications make it an attractive option for healthcare providers concerned with regulatory requirements.
- Google Cloud Platform: GCP offers a suite of cloud services that can be employed for patient monitoring solutions. Google Cloud's data analytics and ML tools, combined with its robust infrastructure, make it a contender for healthcare organizations seeking cloud solutions.
- IBM Cloud: A platform for healthcare organizations to build, deploy, and manage applications and with a focus on security and compliance, IBM Cloud offers services for data storage, processing, and analytics, making it suitable for patient monitoring systems.
- Oracle Cloud: Known for its database and cloud infrastructure services, Oracle Cloud has been increasingly utilized in the healthcare sector. It provides scalable and secure solutions for storing and managing health data, ensuring compliance with industry regulations.

These cloud platforms offer a range of services, including data storage, computing power, analytics, and ML, which are integral to patient monitoring applications. The choice of a specific platform depends on factors such as the organization's existing infrastructure, compliance requirements, and specific use-case needs.

### *5.2. Benefits of Cloud Integration*

As healthcare continues its digital transformation, the integration of cloud computing into remote patient monitoring stands out as a pivotal advancement. This convergence holds the promise of revolutionizing how healthcare professionals monitor and engage with patients remotely. By harnessing the capabilities of cloud technology, RPM experiences a paradigm shift, unlocking new dimensions of real-time data transmission, analysis, and seamless connectivity. This section delves into the benefits of integrating cloud solutions in remote patient monitoring, exploring the transformative impact on patient care, data management, and healthcare delivery.

- Real-Time monitoring: Cloud-based platforms play a pivotal role in real-time monitoring of patients. Through instant data processing, these platforms ensure timely responses to critical changes in a patient's condition [113]. This capability is instrumental in enhancing the effectiveness of healthcare interventions by providing up-to-the-minute insights into a patient's status.
- Scalability and storage: The scalability of a cloud infrastructure is a key advantage in managing the ever-growing volume of health data. Cloud-based platforms can seamlessly accommodate this influx of data, supporting long-term storage for trend analysis and personalized treatment plans [114]. This scalability ensures that healthcare providers have access to a comprehensive and historical view of patient data, facilitating informed decision making.
- Interoperability: Cloud integration fosters interoperability in the healthcare ecosystem. By consolidating health data from various sources, cloud-based platforms provide healthcare providers with access to comprehensive patient profiles. This interconnectedness enhances well-informed decision making by offering a holistic view of a patient's health history and ongoing treatment [115].
- Data security and privacy: Ensuring the security and privacy of sensitive health information is paramount in healthcare. Cloud-based platforms address these concerns by implementing robust security measures. The sophisticated security protocols employed by these platforms safeguard patient data, instilling confidence in both healthcare providers and patients regarding the confidentiality of their health information.

- Predictive analytics: Cloud platforms equipped with ML algorithms empower healthcare professionals with predictive analytics capabilities. By analyzing historical and real-time health data these algorithms can foresee health trends and potential issues. This proactive approach allows for interventions before conditions escalate, contributing to more effective and personalized healthcare [116].
- Remote consultations: Seamless integration with telemedicine solutions is a notable benefit of cloud-based platforms. This integration reduces the necessity for in-person visits, fostering remote consultations. Patients can connect with healthcare providers virtually, facilitating access to medical expertise without the constraints of geographical distance. This aspect is particularly valuable in ensuring continuity of care, especially in situations where physical visits might be challenging.
- Care coordination: Health information exchange (HIE) [117] facilitated by cloud-based platforms enhances care coordination. By providing a centralized repository for health data, these platforms foster collaboration among different healthcare entities. This shared information ensures that all involved parties are on the same page regarding a patient's health, leading to more coordinated and effective healthcare delivery.

The beneficial aspects of cloud-based platforms for patient monitoring extend across various dimensions, from real-time monitoring to care coordination. These platforms stand as pillars of innovation, reshaping healthcare practices to make them more responsive, interconnected, and patient-centric.

### *5.3. Data Storage and Analytics in the Cloud*

The integration of cloud computing in healthcare has ushered in a new era of managing and extracting value from vast and complex datasets. This section delves into the transformative landscape of data storage and analytics in the cloud, elucidating the multifaceted benefits and advancements that cloud platforms bring to healthcare systems.

Cloud-based solutions offer scalable storage options, ensuring healthcare organizations can efficiently manage the ever-growing volume of health-related data [118]. The capabilities of cloud data warehouses and the interoperability of cloud environments play pivotal roles in organizing, integrating, and retrieving diverse healthcare data types. Real-time data processing, predictive analytics, and ML further elevate the potential of cloud-based platforms, providing timely insights, identifying trends, and supporting proactive healthcare interventions.

Moreover, cost-efficient storage models, robust backup mechanisms, and compliance with data governance standards address the financial considerations and regulatory requirements of the healthcare sector. Cloud analytics not only empowers healthcare professionals with actionable insights but also fosters collaborative research initiatives by providing shared platforms for data-driven innovation.

The following components explore the fundamental aspects of data storage and analytics in the cloud, emphasizing their collective impact on improving patient care and the overall efficiency of healthcare operations.

- Scalable storage solutions: Cloud platforms provide scalable and flexible storage solutions, accommodating the exponential growth in healthcare data. This scalability ensures that healthcare organizations can seamlessly expand their storage capacities based on evolving needs, supporting long-term data retention and accessibility.
- Data warehousing: Cloud-based data warehouses serve as centralized repositories for diverse healthcare data types, including EHRs, medical imaging, and patient-generated data [111]. These platforms offer efficient data organization, indexing, and retrieval, thus streamlining access for healthcare professionals.
- Interoperability and data integration: Cloud environments promote interoperability by enabling seamless integration of disparate healthcare data sources. This interoperability ensures that data from various healthcare systems, devices, and sources can be harmoniously stored and accessed, fostering a comprehensive view of patient health.
- Real-time data processing: Cloud analytics facilitates real-time data processing, allowing healthcare providers to access up-to-the-minute information critical for de-

cision making [118]. Real-time analytics empowers healthcare professionals with timely insights, particularly in emergencies or when monitoring rapidly changing health conditions.

- Predictive analytics and ML: Cloud-based platforms leverage advanced analytics, including predictive analytics and ML algorithms, to derive meaningful insights from healthcare data [119]. These technologies enable the identification of patterns, trends, and potential health risks, supporting proactive interventions and personalized treatment plans.
- Cost-efficient storage: Cloud providers offer cost-efficient storage models, allowing healthcare organizations to optimize storage expenses based on actual usage [117]. Pay-as-you-go models and tiered storage options contribute to cost-effectiveness, aligning with the financial considerations of healthcare entities.
- Data backup and disaster recovery: Cloud-based storage includes robust data backup and disaster recovery features. Automated backup processes and redundant storage mechanisms ensure data resilience, protecting against data loss due to unforeseen events or system failures.
- Data governance and compliance: Cloud platforms adhere to stringent data governance standards and regulatory compliance requirements in the healthcare industry, such as HIPAA [120]. Compliance with these standards is essential to safeguarding patient privacy, confidentiality, and the integrity of healthcare data.
- User-friendly analytics: Cloud platforms often integrate user-friendly analytics tools and dashboards, enabling healthcare professionals to derive insights without advanced technical expertise. This accessibility promotes the widespread adoption of analytics-driven decision making across various levels of healthcare organizations.

In summary, the integration of cloud-based data storage and analytics transforms healthcare by enhancing efficiency, promoting innovation, and improving patient outcomes. Data storage and analytics in the cloud represent a paradigm shift in how healthcare organizations manage and leverage information. The scalable, interoperable, and analytics-driven nature of cloud platforms contributes to enhanced patient care and overall operational efficiency within the healthcare ecosystem.

## 6. Challenges

The integration of biosensors with multi-hop IoT systems, facilitated by cloud connectivity, introduces a transformative approach to patient monitoring. While this innovative paradigm holds immense potential for delivering real-time and personalized healthcare insights, it is not without its challenges. Addressing the challenges in Figure 12 is essential to ensuring the seamless operation, reliability, and security of such interconnected systems. This section delves into the major challenges associated with the integration of biosensors in a multi-hop IoT network, emphasizing the need for strategic solutions to overcome these hurdles. From energy efficiency to security and privacy concerns, each challenge plays a crucial role in shaping the effectiveness and viability of biosensor-based patient monitoring systems. An in-depth exploration of these challenges sets the stage for devising comprehensive strategies that harness the full potential of biosensors in enhancing patient care through cloud-connected IoT frameworks.

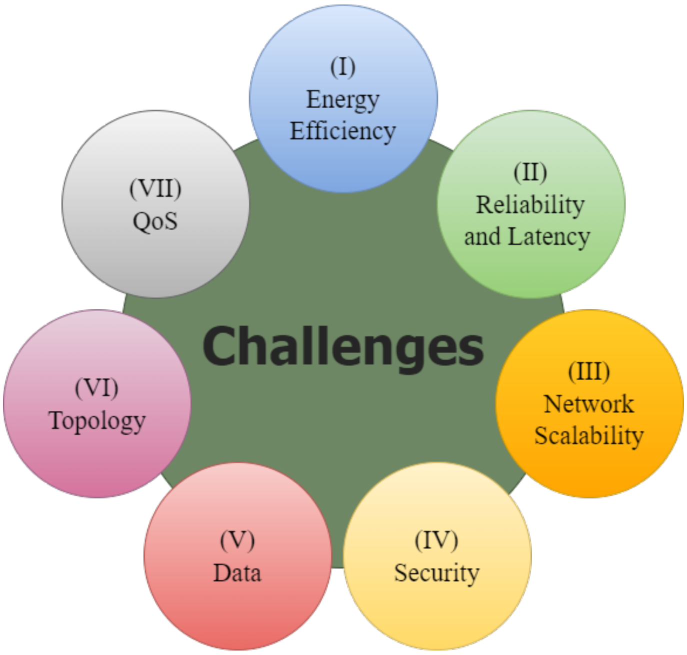


**Figure 12.** Challenegs for patient monitoring with multi-hop IoT systems.

- Energy efficiency: Energy efficiency poses a critical challenge in integrating biosensors with multi-hop IoT systems for patient health monitoring through cloud connectivity. The limited power resources inherent in biosensors, especially those for implantation, give rise to this challenge [121].
  Ensuring the prolonged battery life of biosensors is crucial, considering their small battery sizes or reliance on harvested energy. Strategic energy management becomes imperative to extending operational life.
  The optimization of data transmission is another facet, demanding efficient protocols and algorithms to minimize energy consumption during transmission. This optimization ensures biosensors can operate for extended periods without frequent battery replacements [122].
  Energy harvesting mechanisms, such as solar or kinetic energy, are often employed in biosensors. However, the intermittent nature of these sources introduces challenges in maintaining a consistent power supply, impacting the reliability of patient monitoring systems.
  Addressing these energy-efficiency challenges calls for a multidisciplinary approach, incorporating advancements in sensor technology, communication protocols, and energy management strategies. Overcoming these hurdles is pivotal for the sustainability and effectiveness of biosensor-based patient monitoring in multi-hop IoT networks via cloud connectivity.
- Reliability and low latency: Ensuring reliability and low latency in biosensors integrated with multi-hop IoT systems for patient health monitoring through cloud connectivity presents significant challenges.
  Reliability challenges arise due to the vulnerability of wireless communication in multi-hop IoT networks. Signal interference, packet loss, and network congestion can compromise the seamless transmission of health data from biosensors to the cloud. Ensuring a robust communications infrastructure and implementing error correction mechanisms are vital for maintaining data reliability [123].
  Low latency is crucial for real-time patient monitoring, especially in critical medical situations. Delays in data transmission can impact timely interventions. Achieving low latency requires optimizing communication protocols, minimizing signal processing time, and ensuring efficient routing in a multi-hop network [124].

Moreover, the reliability and low latency challenges are interconnected. Overcoming one often involves addressing aspects of the other. Balancing the need for real-time data with reliable transmission is a complex task that necessitates careful consideration of network design, data processing algorithms, and communications protocols. Successfully tackling these challenges is essential for maximizing the effectiveness of biosensors in multi-hop IoT systems for patient health monitoring via cloud connectivity.

- Network scalability: Network scalability in biosensors integrated with multi-hop IoT systems for patient health monitoring introduces several challenges. The surge in health data from an increasing number of biosensors poses challenges for managing and processing large volumes efficiently.
  Scalability issues may lead to delays and inefficiencies in handling the growing data load. Scaling the network infrastructure requires careful planning to accommodate additional biosensors, involving the expansion of server capacity, storage resources, and computational capabilities [125]. Seamless integration of new nodes into the existing network presents challenges, particularly with diverse biosensor types.
  Maintaining reliable communications becomes challenging with a growing number of biosensors, increasing the risk of signal interference, packet collisions, and communication failures. Consistent and dependable communications pathways are crucial for effective patient monitoring.
  Scalability introduces security challenges, providing more entry points for potential cyber threats. Robust security measures that scale with network size are essential to safeguarding sensitive health data from unauthorized access.
  Addressing these challenges requires a comprehensive approach, incorporating advancements in network architectures, data management, and security protocols to ensure the scalability and sustainability of biosensor-integrated multi-hop IoT systems for patient health monitoring through cloud connectivity.
- Security and privacy: Security and privacy pose critical challenges in biosensors integrated with multi-hop IoT systems. Ensuring the confidentiality and integrity of health data transmitted across the network is paramount. The distributed nature of multi-hop IoT systems introduces vulnerabilities, and unauthorized access to sensitive patient information is a significant concern. Implementing robust encryption mechanisms becomes crucial in order to secure data during transmission and storage in the cloud. Authentication and access-control measures must be stringent to prevent unauthorized users from accessing health data [126].
  Privacy concerns arise owing to the nature of health information; ensuring compliance with regulations such as HIPAA is essential. Unauthorized disclosure of patient data can lead to severe consequences, making data encryption and access controls imperative. Balancing the need for data sharing among healthcare professionals with patient privacy rights poses a complex challenge. Consent mechanisms and transparent communication regarding data usage become crucial components of addressing privacy concerns [43].
  The dynamic nature of IoT networks, with constant data exchange between biosensors and the cloud, requires continuous monitoring and updates to security protocols. Potential threats, such as malware or denial-of-service attacks, demand proactive measures to detect, prevent, and mitigate security breaches. Collaborative efforts between technology developers, healthcare providers, and policymakers are necessary to establish comprehensive security and privacy frameworks that address the unique challenges posed by biosensor-integrated multi-hop IoT systems in cloud-connected patient monitoring.
- Data aggregation and fusion: Data aggregation and fusion in biosensors present several challenges. The complexity of aggregating heterogeneous data from diverse biosensors requires standardized formats and protocols to ensure interoperability. Integrating data seamlessly while maintaining accuracy and reliability is a fundamental challenge given the variations in sensor types, data rates, and formats [88].

Ensuring the timeliness of data aggregation is crucial for real-time patient monitoring. Delays in data fusion could impact the ability to respond promptly to critical health events. Coordinating the simultaneous transmission of data from multiple biosensors in a multi-hop IoT network introduces synchronization challenges. Managing temporal misalignments in data streams becomes necessary to derive meaningful insights.
The sheer volume of data generated by biosensors necessitates efficient storage and processing strategies in the cloud. Aggregating and fusing large datasets for long-term analysis requires a scalable cloud infrastructure and optimized algorithms. Striking a balance between real-time processing and long-term storage for trend analysis is a key challenge in designing effective data aggregation and fusion mechanisms.
Moreover, maintaining data integrity during the aggregation process is critical for accurate health assessments. Addressing issues such as data duplication, noise, and outliers is essential to ensuring the reliability of aggregated information. Collaborative efforts across the healthcare and technology sectors are essential to developing standardized protocols, scalable cloud solutions, and sophisticated algorithms that effectively tackle the challenges associated with data aggregation and fusion in cloud-connected patient monitoring systems [11].

- Mobility and dynamic topology: Mobility and dynamic topologies pose significant challenges in biosensors integrated with multi-hop IoT systems. In the healthcare context, patients move between different locations, leading to dynamic changes in the network topology. Managing the seamless handover of data transmission from one sensor to another becomes critical to ensuring continuous monitoring without disruptions.
The dynamic nature of patient movement introduces challenges related to network reconfiguration. A multi-hop IoT system must adapt to changes in the network topology caused by the mobility of patients or devices. This requires robust protocols for efficient routing, addressing, and re-establishing connections to maintain data flow.
Additionally, the mobility of biosensors and patients can result in unpredictable variations in signal strength and quality. Ensuring reliable communication between biosensors and the IoT gateway, even in the presence of mobility-induced signal fluctuations, is a key challenge. Effective mechanisms for signal compensation and error correction have become essential to maintaining the integrity and accuracy of health data [127].
A dynamic topology introduces complexities in managing network resources, including bandwidth allocation and energy consumption [128]. Optimizing these resources to accommodate a changing topology while minimizing disruptions and energy consumption is a crucial challenge. Collaborative research is vital to developing adaptive algorithms, communications protocols, and energy-efficient solutions that address the challenges associated with mobility and dynamic topologies in cloud-connected patient monitoring systems.
- QoS-based performance, costs, and resource constraints: Addressing quality-of-service challenges in biosensors integrated with multi-hop IoT systems for patient health monitoring involves navigating complex considerations related to performance, cost, and resource constraints.
Ensuring optimal performance is a multifaceted challenge. The diverse nature of health data, including real-time vital signs and sensor readings, demands a balance between timely data transmission and acceptable accuracy. Striking this balance is critical for providing healthcare professionals with reliable and up-to-date information for effective decision making.
Cost constraints pose challenges in implementing and maintaining robust QoS in the H-IoT. Balancing the need for advanced technologies with budgetary constraints requires innovative solutions. Cost-effective sensor deployments, energy-efficient communications protocols, and scalable cloud resources are essential components in addressing this challenge [129].

Resource constraints encompass various aspects, including bandwidth limitations, storage capacities, and computational capabilities. Designing QoS-aware algorithms and protocols that optimize resource utilization while meeting the demands of patient monitoring applications is a complex task. This involves considerations for efficient data compression, prioritization mechanisms, and adaptive resource allocation strategies.

Overall, navigating the challenges of QoS-based performance, costs, and resource constraints involves a holistic approach that integrates technological advancements, cost-effective solutions, and resource-efficient algorithms. Collaborative efforts among healthcare practitioners, technologists, and researchers are crucial for developing sustainable and effective systems that meet QoS requirements in patient health monitoring through cloud-connected IoT platforms.

## 7. Future Prospects

The future prospects of real-time patient monitoring, as envisaged in the context of biosensors integrated with multi-hop IoT systems via cloud connectivity, hold immense potential for transformative changes in the healthcare landscape. The trajectory of technological advancements anticipates several key developments that collectively promise to revolutionize healthcare delivery [130].

One pivotal aspect revolves around the continual refinement of biosensors. The future sees a shift towards more compact, energy-efficient, and versatile biosensor designs. This evolution is geared towards enabling continuous and unobtrusive health monitoring, ensuring that individuals can seamlessly integrate monitoring into their daily lives without disruption. Moreover, advancements in biosensor technologies aim to enhance the accuracy and reliability of health data, providing a robust foundation for informed medical decision making.

The integration of 5G technology stands out as a game-changer in the future of real-time patient monitoring. With reduced data transmission latency, the communication between biosensors, IoT devices, and cloud platforms is poised to become virtually instantaneous. This not only enhances the overall speed and efficiency of healthcare data exchange but also opens up avenues for new applications and possibilities in remote health monitoring [131].

Artificial intelligence and ML are expected to play an increasingly integral role in shaping the future of patient monitoring. These technologies bring advanced analytical capabilities to the table, enabling precise predictions, early anomaly detection, and the generation of personalized health insights. ML algorithms will continuously learn from vast datasets, improving their accuracy and contributing to more effective healthcare interventions [132].

Blockchain technology has emerged as a prospective solution to addressing critical issues of data security and interoperability in healthcare systems. The decentralized and secure nature of blockchain can safeguard sensitive health information, ensures patient privacy, and fosters trust in healthcare systems. The use of blockchain also has the potential to streamline data sharing among different healthcare entities, contributing to a more interconnected and efficient healthcare ecosystem [133,134].

In chronic disease management, future prospects indicate a broader implementation of real-time monitoring. This approach holds promise for more effective care, allowing healthcare providers to intervene promptly in response to changing health conditions, potentially reducing hospitalizations and improving the overall quality of life for patients dealing with chronic illnesses.

The technological landscape also envisions the use of human–computer interaction principles to enhance user interfaces, making them more intuitive and user-friendly [135]. This is particularly crucial to ensure that individuals, including those with limited technological proficiency, can easily navigate and benefit from real-time patient monitoring systems.

The future of real-time patient monitoring extends beyond individual health management to broader implications for human health. Advanced monitoring systems are expected to contribute significantly to human health management, enabling more comprehensive epidemiological studies and proactive public health interventions. The availability of real-time data on a large scale offers unprecedented opportunities to understand health trends, identify potential outbreaks, and implement timely interventions to safeguard public health.

Furthermore, the future envisions seamless integration of real-time patient monitoring with telemedicine solutions. This integration aims to reduce the necessity for in-person visits, particularly in situations where a physical presence might be challenging or impractical. Comprehensive virtual health platforms are expected to emerge, offering a holistic approach to healthcare that combines real-time monitoring with remote consultations, fostering a more patient-centric and accessible healthcare model [130].

While technological advancements are at the forefront of future prospects, ethical considerations, and human-centric design principles play equally critical roles [136]. The responsible development and implementation of real-time patient monitoring technologies require careful attention to ethical standards, ensuring that patient privacy is upheld and data are used responsibly. Human-centric design ensures that these technologies are accessible, user-friendly, and tailored to the diverse needs of individuals, fostering inclusivity in healthcare.

The future of real-time patient monitoring presents a multifaceted landscape characterized by advancements in biosensor technologies, the integration of cutting-edge communications technologies, and the transformative impact of AI. These developments collectively promise to redefine healthcare, ushering in an era marked by personalized, technologically advanced, and ethically sound practices. The potential benefits extend from individual health management to broader health initiatives, setting the stage for a holistic and interconnected healthcare ecosystem.

**Author Contributions:** Conceptualization, R.U. and I.K.; methodology, R.U.; validation, I.K.; formal analysis, R.U.; investigation, R.U.; writing—original draft, R.U; writing—review and editing, I.K.; visualization, R.U.; supervision, I.K.; project administration, I.K.; funding acquisition, I.K. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was supported in part by the National Research Foundation of Korea (NRF) through the Korean Government's Ministry of Science and ICT (MSIT) under Grant NRF-2021R1A2B5 B01001721, and in part by the Regional Innovation Strategy (RIS) through the NRF funded by the Ministry of Education (MOE) under Grant 2021RIS-003.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Kumar , S.; Tiwari, P.; Zymbler, M. Internet of Things is a revolutionary approach for future technology enhancement: A review. *J. Big Data* **2019**, *6*, 1–21. [CrossRef]
2. Mouha, R.A. Internet of things (IoT). *J. Data Anal. Inf. Process.* **2021**, *9*, 77–101.
3. Rejeb, A.; Rejeb, K.; Treiblmaier, H.; Appolloni, A.; Alghamdi, S.; Alhasawi, Y.; Iranmanesh, M. The Internet of Things (IoT) in healthcare: Taking stock and moving forward. *Internet Things* **2023**, *22*, 100721. [CrossRef]
4. Bovenizer, W.; Chetthamrongchai, P. A comprehensive systematic and bibliometric review of the IoT-based healthcare systems. *Clust. Comput.* **2023**, *26*, 3291–3317. [CrossRef]
5. Kumar, M.; Kumar, A.; Verma, S.; Bhattacharya, P.; Ghimire, D.; Kim, S.H.; Hosen, A.S. Healthcare Internet of Things (H-IoT): Current Trends, Future Prospects, Applications, Challenges, and Security Issues. *Electronics* **2023**, *12*, 2050. [CrossRef]
6. Chataut, R.; Phoummalayvane, A.; Akl, R. Unleashing the power of IoT: A comprehensive review of IoT applications and future prospects in healthcare, agriculture, smart homes, smart cities, and industry 4.0. *Sensors* **2023**, *23*, 7194. [CrossRef] [PubMed]
7. Kelly, J.T.; Campbell, K.L.; Gong, E.; Scuffham, P. The Internet of Things: Impact and implications for health care delivery. *J. Med. Internet Res.* **2020**, *22*, e20135. [CrossRef] [PubMed]
8. Boikanyo, K.; Zungeru, A.M.; Sigweni, B.; Yahya, A.; Lebekwe, C. Remote patient monitoring systems: Applications, architecture, and challenges. *Sci. Afr.* **2023**, *20*, e01638. [CrossRef]

9. Mantena, S.; Keshavjee, S. Strengthening healthcare delivery with remote patient monitoring in the time of COVID-19. *BMJ Health Care Inform.* **2021**, *28*, e100302. [CrossRef]
10. Taiwo, O.; Ezugwu, A.E. Smart healthcare support for remote patient monitoring during COVID-19 quarantine. *Inform. Med. Unlocked* **2020**, *20*, 100428. [CrossRef]
11. Khan, S.; Singh, Y.V.; Singh, P.; Singh, R.S. An Optimized Artificial Intelligence System Using IoT Biosensors Networking for Healthcare Problems. *Comput. Intell. Neurosci.* **2022**, *2022*, 2206573. [CrossRef] [PubMed]
12. Subasi, A.; Bandic, L.; Qaisar, S.M. *Cloud-Based Health Monitoring Framework Using Smart Sensors and Smartphone*; Academic Press: Cambridge, MA, USA, 2020; pp. 217–243.
13. Kumar Pandey, A.; Maneria, S. *Cloud Computing Methods Based on IoT for Better Patient Data Planning: A Research*; IEEE: Piscataway, NJ, USA, 2022; pp. 396–402. [CrossRef]
14. Parane, K.A.; Patil, N.C.; Poojara, S.R.; Kamble, T.S. *Cloud Based Intelligent Healthcare Monitoring System*; IEEE: Piscataway, NJ, USA, 2014; pp. 697–701. [CrossRef]
15. Guo, B.; Ma, Y.; Yang, J.; Wang, Z. Smart healthcare system based on cloud-internet of things and deep learning. *J. Healthc. Eng.* **2021**, *2021*, 4109102. [CrossRef]
16. Faridi, F.; Sarwar, H.; Ahtisham, M.; Jamal, K. Cloud computing approaches in health care. *Mater. Today Proc.* **2022**, *51*, 1217–1223. [CrossRef]
17. Smith, A.A.; Li, R.; Tse, Z.T.H. Reshaping healthcare with wearable biosensors. *Sci. Rep.* **2023**, *13*, 4998. [CrossRef] [PubMed]
18. Song, Z.; Zhou, S.; Qin, Y.; Xia, X.; Sun, Y.; Han, G.; Shu, T.; Hu, L.; Zhang, Q. Flexible and Wearable Biosensors for Monitoring Health Conditions. *Biosensors* **2023**, *13*, 630. [CrossRef]
19. Zhang, S. Current development on wearable biosensors towards biomedical applications. *Front. Bioeng. Biotechnol.* **2023**, *11*, 1264337. [CrossRef] [PubMed]
20. Ye, S.; Feng, S.; Huang, L.; Bian, S. Recent progress in wearable biosensors: From healthcare monitoring to sports analytics. *Biosensors* **2020**, *10*, 205. [CrossRef]
21. Zhu, P.; Peng, H.; Rwei, A.Y. Flexible, wearable biosensors for digital health. *Med. Nov. Technol. Devices* **2022**, *14*, 100118. [CrossRef]
22. Jin, X.; Liu, C.; Xu, T.; Su, L.; Zhang, X. Artificial intelligence biosensors: Challenges and prospects. *Biosens. Bioelectron.* **2020**, *165*, 112412. [CrossRef]
23. Zhang, Y.; Hu, Y.; Jiang, N.; Yetisen, A.K. Wearable artificial intelligence biosensor networks. *Biosens. Bioelectron.* **2023**, *219*, 114825. [CrossRef]
24. Kim, J.; Campbell, A.S.; de Ávila, B.E.F.; Wang, J. Wearable biosensors for healthcare monitoring. *Nat. Biotechnol.* **2019**, *37*, 389–406. [CrossRef]
25. Prasad, A.S.; Kavanashree, N. ECG monitoring system using AD8232 sensor. In Proceedings of the International Conference on Communication and Electronics Systems (ICCES), Coimbatore, India, 17–19 July 2019; pp. 976–980.
26. Moreno Escobar, J.J.; Morales Matamoros, O.; Tejeida Padilla, R.; Chanona Hernandez, L.; Posadas Duran, J.P.F.; Perez Martinez, A.K.; Lina Reyes, I.; Quintana Espinosa, H. Biomedical signal acquisition using sensors under the paradigm of parallel computing. *Sensors* **2020**, *20*, 6991. [CrossRef] [PubMed]
27. Contardi, U.A.; Morikawa, M.; Brunelli, B.; Thomaz, D.V. Max30102 photometric biosensor coupled to esp32-webserver capabilities for continuous point of care oxygen saturation and heartrate monitoring. *Eng. Proc.* **2021**, *16*, 9.
28. Valenti, S.; Volpes, G.; Parisi, A.; Peri, D.; Lee, J.; Faes, L.; Busacca, A.; Pernice, R. Wearable Multisensor Ring-Shaped Probe for Assessing Stress and Blood Oxygenation: Design and Preliminary Measurements. *Biosensors* **2023**, *13*, 460. [CrossRef] [PubMed]
29. Siam, A.I.; Almaiah, M.A.; Al-Zahrani, A.; Elazm, A.A.; El Banby, G.M.; El-Shafai, W.; El-Samie, F.E.A.; El-Bahnasawy, N.A. Secure health monitoring communication systems based on IoT and cloud computing for medical emergency applications. *Comput. Intell. Neurosci.* **2021**, *2021*, 8016525. [CrossRef]
30. Engineers, L.M. Interfacing MAX30102 Pulse Oximeter and Heart Rate Sensor with Arduino. Available online: https://lastminuteengineers.com/max30102-pulse-oximeter-heart-rate-sensor-arduino-tutorial/ (accessed on 8 December 2023).
31. Oğur, N.B.; Al-Hubaishi, M.; Çeken, C. IoT data analytics architecture for smart healthcare using RFID and WSN. *ETRI J.* **2022**, *44*, 135–146. [CrossRef]
32. Priyanka, A.; Parimala, M.; Sudheer, K.; Kaluri, R.; Lakshmanna, K.; Reddy, M.P.K. BIG data based on healthcare analysis using IOT devices. In *IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Bristol, UK, 2017; Volume 263, p. 042059.
33. Chavva, S.R.; Sangam, R.S. An energy-efficient multi-hop routing protocol for health monitoring in wireless body area networks. *Netw. Model. Anal. Health Inform. Bioinform.* **2019**, *8*, 1–10. [CrossRef]
34. Akbar, M.S.; Hussain, Z.; Sheng, M.; Shankaran, R. Wireless body area sensor networks: Survey of mac and routing protocols for patient monitoring under ieee 802.15. 4 and ieee 802.15. 6. *Sensors* **2022**, *22*, 8279. [CrossRef]
35. Tronci, E.M.; Nagabuko, S.; Hieda, H.; Feng, M.Q. Long-Range Low-Power Multi-Hop Wireless Sensor Network for Monitoring the Vibration Response of Long-Span Bridges. *Sensors* **2022**, *22*, 3916. [CrossRef]
36. Mohanty, R.K.; Sahoo, S.P.; Kabat, M.R. Sustainable remote patient monitoring in wireless body area network with Multi-hop routing and scheduling: A four-fold objective based optimization approach. *Wirel. Netw.* **2023**, *29*, 2337–2351. [CrossRef]
37. Khalifeh, A.; Mazunga, F.; Nechibvute, A.; Nyambo, B.M. Microcontroller Unit-Based Wireless Sensor Network Nodes: A Review. *Sensors* **2022**, *22*, 8937. [CrossRef] [PubMed]

38. Alahi, M.E.E.; Sukkuea, A.; Tina, F.W.; Nag, A.; Kurdthongmee, W.; Suwannarat, K.; Mukhopadhyay, S.C. Integration of IoT-Enabled Technologies and Artificial Intelligence (AI) for Smart City Scenario: Recent Advancements and Future Trends. *Sensors* **2023**, *23*, 5206. [CrossRef] [PubMed]
39. Al-Kofahi, M.M.; Al-Shorman, M.Y.; Al-Kofahi, O.M. Toward energy efficient microcontrollers and Internet-of-Things systems. *Comput. Electr. Eng.* **2019**, *79*, 106457. [CrossRef]
40. Lee, E.; Seo, Y.D.; Oh, S.R.; Kim, Y.G. A Survey on Standards for Interoperability and Security in the Internet of Things. *IEEE Commun. Surv. Tutor.* **2021**, *23*, 1020–1047. [CrossRef]
41. Di Martino, B.; Rak, M.; Ficco, M.; Esposito, A.; Maisto, S.A.; Nacchia, S. Internet of things reference architectures, security and interoperability: A survey. *Internet Things* **2018**, *1*, 99–112. [CrossRef]
42. Shah, Q.A.; Shafi, I.; Ahmad, J.; Alfarhood, S.; Safran, M.; Ashraf, I. A Meta Modeling-Based Interoperability and Integration Testing Platform for IoT Systems. *Sensors* **2023**, *23*, 8730. [CrossRef] [PubMed]
43. Taherdoost, H. Security and Internet of Things: Benefits, Challenges, and Future Perspectives. *Electronics* **2023**, *12*, 1901. [CrossRef]
44. Sadek, I.; Codjo, J.; Rehman, S.U.; Abdulrazak, B. Security and privacy in the Internet of Things healthcare systems: Toward a robust solution in real-life deployment. *Comput. Methods Programs Biomed. Update* **2022**, *2*, 100071. [CrossRef]
45. Obaid, O.I.; Salman, S.A.B. Security and Privacy in IoT-based Healthcare Systems: A Review. *Mesopotamian J. Comput. Sci.* **2022**, *2022*, 29–40. [CrossRef]
46. Kanellopoulos, D.; Sharma, V.K.; Panagiotakopoulos, T.; Kameas, A. Networking Architectures and Protocols for IoT Applications in Smart Cities: Recent Developments and Perspectives. *Electronics* **2023**, *12*, 2490. [CrossRef]
47. Kim, T.; Yoo, S.; Kim, Y. Edge/Fog Computing Technologies for IoT Infrastructure. *Sensors* **2021**, *21*, 3001. [CrossRef] [PubMed]
48. Bukhari, A.; Hussain, F.K.; Hussain, O.K. Fog node discovery and selection: A Systematic literature review. *Future Gener. Comput. Syst.* **2022**, *135*, 114–128. [CrossRef]
49. Raza, R.S.; Qadir, A.M. Dynamic Routing Protocol in The Internet of Things (IoT). *Passer J. Basic Appl. Sci.* **2022**, *4*, 80–91. [CrossRef]
50. Paganelli, A.I.; Mondéjar, A.G.; da Silva, A.C.; Silva-Calpa, G.; Teixeira, M.F.; Carvalho, F.; Raposo, A.; Endler, M. Real-time data analysis in health monitoring systems: A comprehensive systematic literature review. *J. Biomed. Inform.* **2022**, *127*, 104009. [CrossRef] [PubMed]
51. Verma, D.; Singh, K.R.; Yadav, A.K.; Nayak, V.; Singh, J.; Solanki, P.R.; Singh, R.P. Internet of things (IoT) in nano-integrated wearable biosensor devices for healthcare applications. *Biosens. Bioelectron. X* **2022**, *11*, 100153. [CrossRef]
52. Kokabi, M.; Tahir, M.N.; Singh, D.; Javanmard, M. Advancing Healthcare: Synergizing Biosensors and Machine Learning for Early Cancer Diagnosis. *Biosensors* **2023**, *13*, 884. [CrossRef]
53. Dehghani, A.; Ghalamfarsa, F.; Bidgoly, A.J.; Mollarasouli, F. Recent Advances and Challenges in Internet of Things (IoT)-based Smartphone Biosensors for Covid-19 and Zika Viruses Detection: A Review. *IEEE Sensors J.* **2023**, *23*, 24123–24134. [CrossRef]
54. Mrabet, H.; Belguith, S.; Alhomoud, A.; Jemai, A. A survey of IoT security based on a layered architecture of sensing and data analysis. *Sensors* **2020**, *20*, 3625. [CrossRef]
55. Khan, A.U.; Khan, M.E.; Hasan, M.; Zakri, W.; Alhazmi, W.; Islam, T. An Efficient Wireless Sensor Network Based on the ESP-MESH Protocol for Indoor and Outdoor Air Quality Monitoring. *Sustainability* **2022**, *14*, 16630. [CrossRef]
56. Islam, M.R.; Kabir, M.M.; Mridha, M.F.; Alfarhood, S.; Safran, M.; Che, D. Deep Learning-Based IoT System for Remote Monitoring and Early Detection of Health Issues in Real-Time. *Sensors* **2023**, *23*, 5204. [CrossRef]
57. Heaney, J.; Buick, J.; Hadi, M.U.; Soin, N. Internet of Things-based ECG and vitals healthcare monitoring system. *Micromachines* **2022**, *13*, 2153. [CrossRef]
58. Anan, S.R.; Hossain, M.A.; Milky, M.Z.; Khan, M.M.; Masud, M.; Aljahdali, S. Research and development of an iot-based remote asthma patient monitoring system. *J. Healthc. Eng.* **2021**, *2021*, 2192913. [CrossRef]
59. Dini, M.Z.; Rakhmatsyah, A.; Wardana, A.A. Detection of Oxygen Levels (SpO2) and Heart Rate Using a Pulse Oximeter for Classification of Hypoxemia Based on Fuzzy Logic. *J. Ilm. Tek. Elektro Komput. Dan Inform.* **2022**, *8*, 17–26. [CrossRef]
60. Jincheng, Z.; Yanfei, L.; Boyuan, Z.; Kai, W. Design and implementation of wearable oxygen saturation monitoring system. In Proceedings of the IEEE International Conference on Electrical Engineering and Mechatronics Technology (ICEEMT), Qingdao, China, 2–4 July 2021; pp. 71–74.
61. Famá, F.; Faria, J.N.; Portugal, D. An IoT-based interoperable architecture for wireless biomonitoring of patients with sensor patches. *Internet Things* **2022**, *19*, 100547. [CrossRef]
62. Akkaş, M.A.; Sokullu, R.; Çetin, H.E. Healthcare and patient monitoring using IoT. *Internet Things* **2020**, *11*, 100173. [CrossRef]
63. Phan, D.T.; Nguyen, C.H.; Nguyen, T.D.P.; Tran, L.H.; Park, S.; Choi, J.; Lee, B.i.; Oh, J. A flexible, wearable, and wireless biosensor patch with internet of medical things applications. *Biosensors* **2022**, *12*, 139. [CrossRef] [PubMed]
64. Prabhu, S.N.; Gooneratne, C.P.; Hoang, K.A.; Mukhopadhyay, S.C. IoT-associated impedimetric biosensing for point-of-care monitoring of kidney health. *IEEE Sensors J.* **2020**, *21*, 14320–14329. [CrossRef]
65. Liu, Y.; Tong, K.F.; Qiu, X.; Liu, Y.; Ding, X. Wireless Mesh Networks in IoT networks. In Proceedings of the International Workshop on Electromagnetics: Applications and Student Innovation Competition, London, UK, 30 May–1 June 2017; pp. 183–185. [CrossRef]
66. Maakar, M.S.K. Implementing Wireless Mesh Network Topology between Multiple Wi-Fi Powered Nodes for IoT Systems. *Int. Res. J. Eng. Technol.* **2020**, *7*, 1242–1244.

67. Cilfone, A.; Davoli, L.; Belli, L.; Ferrari, G. Wireless mesh networking: An IoT-oriented perspective survey on relevant technologies. *Future Internet* **2019**, *11*, 99. [CrossRef]
68. Bellalta, B.; Bononi, L.; Bruno, R.; Kassler, A. Next generation IEEE 802.11 Wireless Local Area Networks: Current status, future directions and open challenges. *Comput. Commun.* **2016**, *75*, 1–25. [CrossRef]
69. Biswas, D.; Barai, S.; Sau, B. A WiFi-based self-organizing multi-hop sensor network for Internet of Things. In Proceedings of the International Conference on Innovative Trends in Information Technology (ICITIIT), Kottayam, India, 11–12 February 2021; pp. 1–6.
70. Nourildean, S.W.; Hassib, M.D.; Mohammed, Y.A. AD-Hoc Routing Protocols in WSN-WiFi based IoT in Smart Home. In Proceedings of the 15th International Conference on Developments in eSystems Engineering (DeSE), Baghdad, Iraq, 9–12 January 2023; pp. 82–87. [CrossRef]
71. Xu, X.; Yuan, D.; Wan, J. An Enhanced Routing Protocol for ZigBee/IEEE 802.15.4 Wireless Networks. In Proceedings of the 2nd International Conference on Future Generation Communication and Networking, Sanya, China, 13–15 December 2008; Volume 1, pp. 294–298. [CrossRef]
72. Midda, S.; Koner, R. Application of Low Cost Energy Efficient ZigBee Network Protocol To Develop A Cyber-Physical Intelligent System For Monitoring Mine Slope Health. In Proceedings of the OPJU International Technology Conference on Emerging Technologies for Sustainable Development (OTCON), Raigarh, India, 8–10 February 2022; pp. 1–6. [CrossRef]
73. Kumar, A.; Sharma, A.; Grewal, K. Resolving the paradox between IEEE 802.15.4 and Zigbee. In Proceedings of the International Conference on Reliability Optimization and Information Technology (ICROIT), Haryana, India, 6–8 February 2014; pp. 484–486. [CrossRef]
74. Ramya, C.M.; Shanmugaraj, M.; Prabakaran, R. Study on ZigBee technology. In Proceedings of the 3rd International Conference on Electronics Computer Technology, Kanyakumari, India, 8–10 April 2011; Volume 6, pp. 297–301. [CrossRef]
75. Unwala, I.; Taqvi, Z.; Lu, J. Thread: An IoT Protocol. In Proceedings of the IEEE Green Technologies Conference (GreenTech), Austin, TX, USA, 4–6 April 2018; pp. 161–167. [CrossRef]
76. Unwala, I.; Taqvi, Z.; Lu, J. IoT Security: ZWave and Thread. In Proceedings of the IEEE Green Technologies Conference (GreenTech), Austin, TX, USA, 4–6 April 2018; pp. 176–182. [CrossRef]
77. Khattak, S.B.A.; Nasralla, M.M.; Farman, H.; Choudhury, N. Performance Evaluation of an IEEE 802.15. 4-Based Thread Network for Efficient Internet of Things Communications in Smart Cities. *Appl. Sci.* **2023**, *13*, 7745. [CrossRef]
78. Ghori, M.R.; Wan, T.C.; Sodhy, G.C. Bluetooth low energy mesh networks: Survey of communication and security protocols. *Sensors* **2020**, *20*, 3590. [CrossRef] [PubMed]
79. Darroudi, S.M.; Gomez, C. Bluetooth Low Energy Mesh Networks: A Survey. *Sensors* **2017**, *17*, 1467. [CrossRef] [PubMed]
80. Natgunanathan, I.; Fernando, N.; Loke, S.W.; Weerasuriya, C. Bluetooth Low Energy Mesh: Applications, Considerations and Current State-of-the-Art. *Sensors* **2023**, *23*, 1826. [CrossRef] [PubMed]
81. Dvinge, R.T.E.; Stalmach, A.; Nalpantidis, L. Connection-based Bluetooth mesh network as a low energy solution for off-grid data networks. In Proceedings of the 8th International Conference on Modern Circuits and Systems Technologies (MOCAST), Thessaloniki, Greece, 13–15 May 2019; pp. 1–6.
82. Shibasaki, Y.; Iwamura, K.; Sato, K. A Communication-Efficient Secure Routing Protocol for IoT Networks. *Sensors* **2022**, *22*, 7503. [CrossRef]
83. Sahoo, A.; Kumar Tripathy, A. On routing algorithms in the internet of vehicles: A survey. *Connect. Sci.* **2023**, *35*, 2272583. [CrossRef]
84. Okafor, K.C.; Adebisi, B.; Anoh, K. Lightweight multi-hop routing protocol for resource optimisation in edge computing networks. *Internet Things* **2023**, *22*, 100758. [CrossRef]
85. Kotian, R.; Exarchakos, G.; Stavros, S.; Liotta, A. Impact of transmission power control in multi-hop networks. *Future Gener. Comput. Syst.* **2017**, *75*, 94–107. [CrossRef]
86. Musaddiq, A.; Olsson, T.; Ahlgren, F. Reinforcement-Learning-Based Routing and Resource Management for Internet of Things Environments: Theoretical Perspective and Challenges. *Sensors* **2023**, *23*, 8263. [CrossRef]
87. Srivastava, D.; Kumar, A.; Mishra, A.; Arya, V.; Almomani, A.; Hsu, C.H.; Santaniello, D. Performance Optimization of Multi-Hop Routing Protocols With Clustering-Based Hybrid Networking Architecture in Mobile Adhoc Cloud Networks. *Int. J. Cloud Appl. Comput.* **2022**, *12*, 1–15. [CrossRef]
88. Begum, B.A.; Nandury, S.V. Data aggregation protocols for WSN and IoT applications–A comprehensive survey. *J. King Saud-Univ.-Comput. Inf. Sci.* **2023**, *35*, 651–681. [CrossRef]
89. Pourghebleh, B.; Navimipour, N.J. Data aggregation mechanisms in the Internet of things: A systematic review of the literature and recommendations for future research. *J. Netw. Comput. Appl.* **2017**, *97*, 23–34. [CrossRef]
90. Badiger, V.S.; Ganashree, T. Data aggregation scheme for IOT based wireless sensor network through optimal clustering method. *Meas. Sensors* **2022**, *24*, 100538. [CrossRef]
91. Ahmed, A.; Abdullah, S.; Bukhsh, M.; Ahmad, I.; Mushtaq, Z. An Energy-Efficient Data Aggregation Mechanism for IoT Secured by Blockchain. *IEEE Access* **2022**, *10*, 11404–11419. [CrossRef]
92. Bodkhe, U.; Tanwar, S. Network management schemes for IoT environment towards 6G: A comprehensive review. *Microprocess. Microsyst.* **2023**, *103*, 104928. [CrossRef]

93. Fortino, G.; Guerrieri, A.; Pace, P.; Savaglio, C.; Spezzano, G. Iot platforms and security: An analysis of the leading industrial/commercial solutions. *Sensors* **2022**, *22*, 2196. [CrossRef]
94. Pallavi Sethi, S.R.S. Internet of Things: Architectures, Protocols, and Applications. *J. Electr. Comput. Eng.* **2017**, *25*, 9324035. [CrossRef]
95. Mugerwa, D.; Nam, Y.; Choi, H.; Shin, Y.; Lee, E. Implicit Overhearing Node-Based Multi-Hop Communication Scheme in IoT LoRa Networks. *Sensors* **2023**, *23*, 3874. [CrossRef]
96. Bomgni, A.B.; Ali, H.M.; Shuaib, M.; Mtopi Chebu, Y. Multihop Uplink Communication Approach Based on Layer Clustering in LoRa Networks for Emerging IoT Applications. *Mob. Inf. Syst.* **2023**, *2023*, 5828671. [CrossRef]
97. Ergun, K.; Ayoub, R.; Mercati, P.; Rosing, T.Š. Dynamic Reliability Management of Multigateway IoT Edge Computing Systems. *IEEE Internet Things J.* **2022**, *10*, 3864–3889. [CrossRef]
98. Abdul-Qawy, A.S.H.; Alduais, N.A.M.; Saad, A.M.H.; Taher, M.A.A.; Nasser, A.B.; Saleh, S.A.M.; Khatri, N. An enhanced energy efficient protocol for large-scale IoT-based heterogeneous WSNs. *Sci. Afr.* **2023**, *21*, e01807. [CrossRef]
99. Kalaivaani, P.; Krishnamoorthi, R. Design and implementation of low power bio signal sensors for wireless body sensing network applications. *Microprocess. Microsyst.* **2020**, *79*, 103271. [CrossRef]
100. Zanelli, F.; Castelli-Dezza, F.; Tarsitano, D.; Mauri, M.; Bacci, M.L.; Diana, G. Design and field validation of a low power wireless sensor node for structural health monitoring. *Sensors* **2021**, *21*, 1050. [CrossRef] [PubMed]
101. Nguyen, N.T.; Le, T.T.; Nguyen, H.H.; Voznak, M. Energy-efficient clustering multi-hop routing protocol in a UWSN. *Sensors* **2021**, *21*, 627. [CrossRef] [PubMed]
102. Del-Valle-Soto, C.; Velázquez, R.; Valdivia, L.J.; Giannoccaro, N.I.; Visconti, P. An energy model using sleeping algorithms for wireless sensor networks under proactive and reactive protocols: A performance evaluation. *Energies* **2020**, *13*, 3024. [CrossRef]
103. Basili, F.; Parrino, S.; Peruzzi, G.; Pozzebon, A. IoT Multi-Hop Facilities via LoRa Modulation and LoRa WanProtocol within Thin Linear Networks. In Proceedings of the IEEE Sensors Applications Symposium (SAS), Sundsvall, Sweden, 23–25 August 2021; pp. 1–6. [CrossRef]
104. Bayılmış, C.; Ebleme, M.A.; Çavuşoğlu, Ü.; Küçük, K.; Sevin, A. A survey on communication protocols and performance evaluations for Internet of Things. *Digit. Commun. Netw.* **2022**, *8*, 1094–1104. [CrossRef]
105. Coito, T.; Firme, B.; Martins, M.S.E.; Vieira, S.M.; Figueiredo, J.; Sousa, J.M.C. Intelligent Sensors for Real-Time Decision-Making. *Automation* **2021**, *2*, 62–82. [CrossRef]
106. Eyada, M.M.; Saber, W.; El Genidy, M.M.; Amer, F. Performance Evaluation of IoT Data Management Using MongoDB Versus MySQL Databases in Different Cloud Environments. *IEEE Access* **2020**, *8*, 110656–110668. [CrossRef]
107. Adi, E.; Anwar, A.; Baig, Z.; Zeadally, S. Machine learning and data analytics for the IoT. *Neural Comput. Appl.* **2020**, *32*, 16205–16233. [CrossRef]
108. Gerodimos, A.; Maglaras, L.; Ferrag, M.A.; Ayres, N.; Kantzavelou, I. IoT: Communication protocols and security threats. *Internet Things-Cyber-Phys. Syst.* **2023**, *3*, 1–13. [CrossRef]
109. Gu, J.; Park, M.; Lee, S.; Kang, H.; Kim, B. Evaluation of a Multi-Hop Wireless Internet-of-Things Network on Large Ships. *J. Mar. Sci. Eng.* **2023**, *11*, 2243. [CrossRef]
110. Ishak, M.; Rahman, R.; Mahmud, T. Integrating Cloud Computing in E-healthcare: System Design, Implementation and Significance in Context of Developing Countries. In Proceedings of the 5th International Conference on Electrical Engineering and Information Communication Technology (ICEEICT), Mirpur, Dhaka, 18–20 November 2021; pp. 1–6. [CrossRef]
111. Morais, D.; Pinto, F.G.; Pires, I.M.; Garcia, N.M.; Gouveia, A.J. The influence of cloud computing on the healthcare industry: A review of applications, opportunities, and challenges for the CIO. *Procedia Comput. Sci.* **2022**, *203*, 714–720. [CrossRef]
112. Sahu, M.L.; Atulkar, M.; Ahirwal, M.K.; Ahamad, A. Cloud-Based Remote Patient Monitoring System with Abnormality Detection and Alert Notification. *Mob. Netw. Appl.* **2022**, *27*, 1894–1909. [CrossRef]
113. Nayak, M.; Barman, A. A Real-Time Cloud-Based Healthcare Monitoring System. In *Computational Intelligence and Applications for Pandemics and Healthcare*; IGI Global: Hershey, PA, USA, 2022; pp. 229–247.
114. Shahzad, A.; Lee, Y.S.; Lee, M.; Kim, Y.G.; Xiong, N. Real-time cloud-based health tracking and monitoring system in designed boundary for cardiology patients. *J. Sensors* **2018**, *2018*, 3202787. [CrossRef]
115. Simeone, A.; Caggiano, A.; Boun, L.; Grant, R. Cloud-based platform for intelligent healthcare monitoring and risk prevention in hazardous manufacturing contexts. *Procedia CIRP* **2021**, *99*, 50–56. [CrossRef]
116. Kang, M.; Park, E.; Cho, B.H.; Lee, K.S. Recent patient health monitoring platforms incorporating internet of things-enabled smart devices. *Int. Neurourol. J.* **2018**, *22*, S76. [CrossRef] [PubMed]
117. Ali, O.; Shrestha, A.; Soar, J.; Wamba, S.F. Cloud computing-enabled healthcare opportunities, issues, and applications: A systematic review. *Int. J. Inf. Manag.* **2018**, *43*, 146–158. [CrossRef]
118. Gupta, U.; Sharma, R. A Study of Cloud Based Solution for Data Analytics in Healthcare. In Proceedings of the 6th International Conference on Information Systems and Computer Networks (ISCON), Mathura, India, 3–4 March 2023; pp. 1–6. [CrossRef]
119. Gholamhosseini, L.; Behmanesh, A.; Nasiri, S.; Ehsanzadeh, S.J.; Sadoughi, F. Cloud-Based Internet of Things in Healthcare Applications: A Systematic Literature Review. *Front. Health Inform.* **2023**, *12*, 145. [CrossRef]
120. Banimfreg, B.H. A comprehensive review and conceptual framework for cloud computing adoption in bioinformatics. *Healthc. Anal.* **2023**, *3*, 100190. [CrossRef]

121. Ghosh, A.; Raha, A.; Mukherjee, A. Energy-efficient IoT-health monitoring system using approximate computing. *Internet Things* **2020**, *9*, 100166. [CrossRef]
122. Upadhyay, S.; Kumar, M.; Upadhyay, A.; Verma, S.; Kaur, M.K.; Khurma, R.A.; Castillo, P.A. Challenges and Limitation Analysis of an IoT-Dependent System for Deployment in Smart Healthcare Using Communication Standards Features. *Sensors* **2023**, *23*, 5155. [CrossRef]
123. Khan, M.Z.; Alhazmi, O.H.; Javed, M.A.; Ghandorh, H.; Aloufi, K.S. Reliable Internet of Things: Challenges and future trends. *Electronics* **2021**, *10*, 2377. [CrossRef]
124. Pons, M.; Valenzuela, E.; Rodríguez, B.; Nolazco-Flores, J.A.; Del-Valle-Soto, C. Utilization of 5G Technologies in IoT Applications: Current Limitations by Interference and Network Optimization Difficulties—A Review. *Sensors* **2023**, *23*, 3876. [CrossRef] [PubMed]
125. Shaheen, Q.; Shiraz, M.; Aziz Butt, S.; Gani, A.; Khan, M.A. An analytical survey of wsns integration with cloud and fog computing. *Electronics* **2021**, *10*, 2625. [CrossRef]
126. Katsikas, S.; Gkioulos, V. Security, privacy, and trustworthiness of sensor networks and internet of things. *Sensors* **2020**, *20*, 3846. [CrossRef] [PubMed]
127. Gardašević, G.; Katzis, K.; Bajić, D.; Berbakov, L. Emerging wireless sensor networks and Internet of Things technologies—Foundations of smart healthcare. *Sensors* **2020**, *20*, 3619. [CrossRef] [PubMed]
128. Sagar, A.K.; Banda, L.; Sahana, S.; Singh, K.; Singh, B.K. Optimizing quality of service for sensor enabled Internet of healthcare systems. *Neurosci. Inform.* **2021**, *1*, 100010. [CrossRef]
129. Hussein, L.F.; Abass, I.A.M.; Aissa, A.B.; Hashim, A.H.A.; Alzahrani, A.A.; Alharithi, F.S. A comprehensive cost performance analysis for a QoS-based scheme in network mobility (NEMO). *Alex. Eng. J.* **2023**, *76*, 349–360. [CrossRef]
130. Waleed, M.; Kamal, T.; Um, T.W.; Hafeez, A.; Habib, B.; Skouby, K.E. Unlocking Insights in IoT-Based Patient Monitoring: Methods for Encompassing Large-Data Challenges. *Sensors* **2023**, *23*, 6760. [CrossRef]
131. Devi, D.H.; Duraisamy, K.; Armghan, A.; Alsharari, M.; Aliqab, K.; Sorathiya, V.; Das, S.; Rashid, N. 5g technology in healthcare and wearable devices: A review. *Sensors* **2023**, *23*, 2519. [CrossRef]
132. Palanisamy, P.; Padmanabhan, A.; Ramasamy, A.; Subramaniam, S. Remote Patient Activity Monitoring System by Integrating IoT Sensors and Artificial Intelligence Techniques. *Sensors* **2023**, *23*, 5869. [CrossRef] [PubMed]
133. Saeed, H.; Malik, H.; Bashir, U.; Ahmad, A.; Riaz, S.; Ilyas, M.; Bukhari, W.A.; Khan, M.I.A. Blockchain technology in healthcare: A systematic review. *PLoS ONE* **2022**, *17*, e0266462. [CrossRef] [PubMed]
134. Taherdoost, H. Privacy and Security of Blockchain in Healthcare: Applications, Challenges, and Future Perspectives. *Sci* **2023**, *5*, 41. [CrossRef]
135. Rundo, L.; Pirrone, R.; Vitabile, S.; Sala, E.; Gambino, O. Recent advances of HCI in decision-making tasks for optimized clinical workflows and precision medicine. *J. Biomed. Inform.* **2020**, *108*, 103479. [CrossRef]
136. Bartlett, R.; Boyle, J.A.; Simons Smith, J.; Khan, N.; Robinson, T.; Ramaswamy, R. Evaluating human-centred design for public health: A case study on developing a healthcare app with refugee communities. *Res. Involv. Engagem.* **2021**, *7*, 1–13. [CrossRef]