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A Systematic Review on IoT Applications in Biomedical and Healthcare Domains

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ABSTRACT:

The Internet of Things (IoT) has emerged as a transformative technology in biomedical and healthcare sectors by enabling seamless interconnection between medical devices, patients, and healthcare providers. This paper presents a systematic review of recent IoT applications in healthcare, focusing on wearable monitoring systems, smart hospitals, telemedicine, chronic disease management, and emergency response frameworks. Key IoT architectures, enabling technologies such as edge computing, AI integration, and communication standards are discussed. Further, the benefits, challenges, and future directions are highlighted to provide researchers a comprehensive understanding of IoT-driven smart healthcare ecosystems.

KEYWORDS: IoT, Smart Healthcare, Wearable Sensors, Telemedicine, Biomedical Applications, Edge Computing, Wireless Body Area Networks.

1. Introduction

The Internet of Things (IoT) has emerged as a transformative technology in the biomedical and healthcare sectors, enabling intelligent interconnection between patients, medical devices, and healthcare service providers. IoT facilitates the real-time acquisition, transmission, and analysis of physiological data through an integrated network of wearable sensors, implantable devices, and cloud-based platforms [1], [2]. This continuous monitoring and connectivity allow healthcare professionals to remotely assess a patient's health condition, make timely decisions, and deliver personalized treatment.

In recent years, healthcare systems have experienced a significant shift from traditional hospital-centric care to patient-centric and home-based care models. This transformation has been driven by the increasing prevalence of chronic diseases, rising healthcare costs, the aging population, and the demand for efficient health services. Remote Patient Monitoring (RPM), powered by IoT technologies, has become a key enabler of early diagnosis, preventive healthcare, and reduced hospital readmissions [3], [4].

The integration of advanced communication technologies such as 5G and the upcoming 6G networks has further enhanced IoT healthcare applications by offering ultra-low latency, high-speed connectivity, improved network capacity, and reliable communication. Additionally, the incorporation of Artificial Intelligence (AI) and Machine Learning (ML) enables real-time insights, predictive analytics, and automated decision-making, making IoT systems smarter and more adaptive [5], [6].

IoT in healthcare also supports various application domains such as telemedicine, smart hospitals, assistive systems for the elderly, robotic surgery, and intelligent emergency response mechanisms. As a result, IoT has the potential to address major healthcare challenges including accessibility in rural areas, workforce shortages, and delays in clinical intervention.

Despite its tremendous benefits, the widespread adoption of IoT in the medical domain faces persistent challenges related to data security, privacy, interoperability, energy

efficiency, and regulatory compliance. Therefore, continuous research and innovation are essential to design secure, scalable, and reliable IoT healthcare frameworks that comply with international standards.

IoT serves as the backbone of modern smart healthcare systems, enabling seamless connectivity, improved patient outcomes, and enhanced operational efficiency. This systematic review provides a comprehensive analysis of current IoT applications in biomedical and healthcare fields, highlights enabling technologies, and discusses existing challenges and future research directions..

2. IoT Architecture for Biomedical Applications

IoT-based biomedical and healthcare systems are typically designed using a multi-layer architecture that enables efficient acquisition, communication, processing, and delivery of medical services. This architecture ensures seamless integration of sensing devices, networking technologies, and intelligent data analytics, which collectively support continuous and real-time patient monitoring. The most widely adopted IoT healthcare structure consists of four major layers: perception, network, processing, and application layers.

- **Perception Layer:** The Perception Layer, also known as the sensing layer, is responsible for interacting directly with the physical environment and the human body. It involves the use of biomedical sensors and actuators for measuring vital physiological parameters such as heart rate, electrocardiogram (ECG), blood oxygen saturation (SpO_2), blood glucose level, body temperature, respiratory rate, and blood pressure. These devices, including wearable, implantable, and ambient sensors, are typically integrated into Wireless Body Area Networks (WBANs). The perception layer also performs the initial conversion of analog signals into digital form and may incorporate localization technologies such as RFID and NFC. Examples of devices used at this layer include smart wristbands, ECG patches, nano-sensors, ingestible sensors, and smart implants.

- **Network Layer:** The Network Layer, also referred to as the communication layer, ensures reliable and secure transmission of biomedical data collected by sensing devices to gateways, healthcare servers, or cloud platforms. This layer utilizes various short-range and long-range wireless communication technologies, such as Bluetooth, ZigBee, Wi-Fi, NFC, LTE, 5G, LoRaWAN, and NB-IoT. Medical communication standards like IEEE 802.15.6 are specifically designed for WBAN applications. Since many healthcare services require immediate responses to abnormal conditions, this layer must provide high-speed connectivity, low latency, and strong reliability, particularly in critical and life-saving scenarios.

- **Processing Layer:** The Processing Layer, also known as the middleware or computation layer, is responsible for advanced data analysis, storage, and real-time decision-making. At this level, biomedical data is filtered, processed, and analyzed using artificial intelligence (AI) and machine learning (ML) techniques to detect anomalies, support diagnosis, and generate timely alerts. Cloud computing provides scalable data storage, whereas edge and fog computing reduce network congestion and delay by performing local processing closer to patients. This capability is essential for emergency healthcare, rural health environments, and continuous monitoring applications.

- **Application Layer:** Finally, the Application Layer delivers healthcare services to end users, including clinicians, hospital staff, caregivers, and patients. It provides data visualization tools, remote patient monitoring dashboards, telemedicine services, automated clinical decision support, and smart hospital management features. The application layer caters to diverse healthcare domains

such as smart intensive care units (ICUs), chronic disease management systems, rehabilitation monitoring, elderly and assisted living solutions, emergency response mechanisms, and wearable health applications.:

Table 1: Summary of IoT Architecture for Healthcare

Layer	Primary Role	Examples of Technologies/ Devices
Perception Layer	Biomedical data acquisition	Wearable sensors, implants, RFID
Network Layer	Data transmission	WBAN, Wi-Fi, 5G, LoRaWAN
Processing Layer	Data analytics, storage, AI	Cloud, Edge, ML models
Application Layer	Healthcare services delivery	Telemedicine, smart hospitals

3. Major IoT Applications in Healthcare

IoT has revolutionized the healthcare sector by enabling continuous monitoring, advanced diagnostics, and seamless connectivity between patients and medical practitioners. Its applications span various domains, significantly improving preventive care, disease management, and emergency medical response. The major IoT applications in healthcare are discussed below.

A. Remote Patient Monitoring (RPM)

Remote Patient Monitoring is one of the most impactful applications of IoT in modern healthcare. Wearable biosensors and portable IoT-enabled devices continuously track vital physiological parameters such as ECG, blood oxygen saturation (SpO_2), glucose levels, blood pressure, and body temperature. These devices transmit data in real time to healthcare service providers for analysis and clinical decision-making. RPM plays a crucial role in the early detection of health abnormalities, preventing medical emergencies, reducing

unnecessary hospital visits, and improving overall patient outcomes. It is especially beneficial for elderly patients, post-operative care, and individuals with chronic illnesses.

B. Chronic Disease Management

IoT contributes significantly to the continuous management of long-term diseases. In the case of diabetes, Continuous Glucose Monitoring (CGM) systems paired with insulin pumps allow automated and personalized insulin delivery. For cardiovascular patients, smart ECG patches and wearable heart monitors help detect arrhythmias and other cardiac abnormalities early. Individuals suffering from asthma or Chronic Obstructive Pulmonary Disease (COPD) can use IoT-integrated inhalers and respiratory monitoring devices to track lung function, medication usage, and environmental triggers. These solutions enable proactive care, reduce complications, and support personalized treatment plans.

C. Smart Hospital Systems

IoT enables the automation and optimization of hospital operations, creating smart and efficient healthcare environments. Technologies such as RFID and IoT-enabled tracking systems facilitate better management of medical assets, personnel, and workflow. In critical care units, IoT supports real-time monitoring of ventilators, infusion pumps, and patient vitals to ensure immediate medical attention when required. Automated medicine dispensing and inventory management systems reduce human error and enhance patient safety. Overall, IoT helps improve clinical efficiency, reduce operational costs, and enhance patient care quality.

D. Telemedicine and Virtual Healthcare

Telemedicine has gained tremendous importance with the advancement of IoT and digital communication technologies. Remote consultation platforms allow patients to communicate with doctors virtually, removing geographical barriers and improving healthcare accessibility. IoT-enabled medical devices integrated with video-based diagnosis systems provide real-time health insights

during remote consultations. Telemedicine services played a crucial role during and after the COVID-19 pandemic, supporting continuous care delivery even during lockdowns and high-risk situations.

E. Assistive Technologies for Elderly and Disabled Individuals

IoT-based assistive systems aim to improve the independence, safety, and quality of life of elderly and physically challenged individuals. Fall detection systems using accelerometers, gyroscopes, and vision sensors provide instant alerts to caregivers during accidents. Activity recognition systems assist in rehabilitation by tracking daily mobility patterns and progress. AI-enabled voice assistants and smart home devices help users manage medications, daily tasks, and emergency communications, ensuring continuous support and monitoring.

F. Emergency Healthcare Response

IoT technologies enhance emergency response efficiency by enabling real-time communication between ambulances, hospitals, and emergency teams. IoT-connected ambulances are equipped to continuously capture and transmit vital patient data such as heart rate, oxygen levels, and blood pressure to the hospital before arrival. This allows emergency units to prepare necessary medical interventions in advance, speeding up triage and improving survival rates. Location-aware systems also help optimize ambulance routing for faster response during critical situations.

4. Enabling Technologies in IoT-Based Healthcare Systems

The rapid advancement of various communication and computation technologies has strengthened the deployment and efficiency of IoT solutions in biomedical and healthcare environments. These enabling technologies play a crucial role in ensuring reliable monitoring, intelligent analytics, secure data sharing, and improved healthcare service delivery.

- **Wireless Body Area Networks (WBAN):** WBANs constitute a network of miniaturized biomedical sensors deployed on or inside the human body to continuously monitor vital parameters such as heart rate, glucose levels, and respiration rate. These sensors communicate wirelessly with gateways, enabling seamless data collection for real-time health monitoring. WBANs are designed to be energy-efficient, low-power, and highly reliable, making them essential for wearable and implantable medical devices [14], [15].

- **Artificial Intelligence (AI) and Machine Learning (ML) Analytics:** AI-driven data analytics helps transform raw physiological data into actionable clinical insights. ML techniques are widely used for disease prediction, anomaly detection, diagnosis support, and personalized treatment planning. The integration of AI with IoT allows smart decision-making in distributed healthcare applications such as predictive maintenance of medical devices and automated patient risk assessment systems.

- **Edge and Fog Computing:** Traditional cloud-only systems may suffer from latency and bandwidth limitations, especially in time-critical medical applications. Edge and Fog computing optimize performance by processing medical data closer to the source (e.g., wearable devices or local gateways). This reduces response time, enhances reliability, and supports real-time clinical decision-making, especially in remote and rural healthcare settings.

- **Blockchain Technology:** Blockchain ensures secure, tamper-proof storage and exchange of patient health records across healthcare stakeholders. Its decentralized architecture enhances transparency and data integrity while preventing unauthorized alterations. Blockchain-enabled access control and smart contracts help manage patient consent,

enabling secure interoperability in multi-institution healthcare systems.

- **5G and 6G Networks:** Next-generation wireless networks provide ultra-low latency, massive device connectivity, and high-speed data transmission essential for advanced IoT healthcare applications. Technologies like tactile internet, remote robotic surgery, and AI-enhanced telemedicine are largely driven by the communication efficiency of 5G/6G networks, enabling real-time, mission-critical medical services.

- **Cloud Computing Platforms:** Cloud servers provide scalable infrastructure for storing, managing, and analyzing large volumes of healthcare data. Cloud-based Electronic Health Records (EHRs) and IoT data repositories facilitate seamless access for healthcare professionals while enabling advanced big-data analytics for population health management and research applications.

5. Challenges and Limitations

The Despite transformative advancements, IoT adoption in healthcare faces multiple barriers that limit its widespread implementation, particularly in developing regions.

- **Security and Privacy Risks:** IoT systems handle highly sensitive patient data, making them attractive targets for cyber-attacks such as device hacking, data tampering, and identity theft. Ensuring secure data transmission, robust authentication, and compliance with healthcare regulations (e.g., HIPAA, GDPR) remains a pressing concern. Lack of standardized cybersecurity practices across IoT devices intensifies vulnerability.

- **Interoperability Issues:** Healthcare IoT ecosystems often include heterogeneous devices from different manufacturers operating under diverse communication protocols. Interoperability challenges hinder seamless data exchange and system integration, restricting unified patient care and cross-platform functionality. Standardization efforts are still evolving to support interoperability in large-scale deployments.

- **Power Consumption and Device Durability:** Wearable and implantable medical sensors typically operate on small batteries, demanding highly efficient power usage for longer operation. Frequent recharging or battery replacement is impractical, especially for critical implants. Research continues to explore low-power circuits, energy-harvesting technologies, and dynamic power management strategies.

- **Data Overload and Management Complexity:** Continuous patient monitoring generates massive amounts of biomedical data, creating storage and processing challenges. Without effective data filtering and AI-based analytics, healthcare professionals may face information overload, leading to delays in diagnosis and decision-making. Efficient data governance frameworks are required to manage data quality and clinical relevance.

- **High Deployment and Maintenance Costs:** Initial investment for IoT infrastructure including sensors, networks, data analytics systems, and cybersecurity is still high, making adoption slower in resource-limited regions. Maintenance costs for device calibration, upgrades, and technical support also affect scalability in public healthcare ecosystems.

6. Conclusion

IoT has revolutionized biomedical and healthcare domains by enabling continuous health monitoring, personalized care, efficient hospital management, and rapid emergency response. Although challenges remain in security, interoperability, and scalability, ongoing advancements in wireless technologies, AI, and cyber-security are expected to drive widespread adoption of smart healthcare systems. IoT will continue to

play a foundational role in transforming the future of global healthcare infrastructure.

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