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IOT-Based Integrated Asset Tracking And Predictive Maintenance Framework For Modern Healthcare Environments

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Abstract
Modern healthcare facilities face significant operational challenges due to the mismanagement of critical medical assets, leading to substantial financial losses and compromised patient care. While various Real-Time Location Systems (RTLS) using RFID, BLE, and Wi-Fi have been proposed, they often suffer from signal interference, lack of room-level precision, and a passive approach to maintenance. This paper proposes a multi-modal IoT ecosystem that fuses BLE proximity sensing with Infrared (IR) correction to achieve granular accuracy. Furthermore, it integrates an AI-driven predictive maintenance layer and a blockchain-based decentralized ledger to ensure data integrity and operational efficiency. The proposed framework transforms asset tracking from a passive inventory tool into a proactive management system.

Keywords: IoT, RFID, BLE, Predictive Maintenance, Blockchain, Hospital Asset Tracking, Healthcare 4.0.

1. Introduction

The global healthcare ecosystem is undergoing a major digital transformation driven by the integration of advanced communication technologies, data analytics, and automation. Within this transformation, the concept of Healthcare 4.0 has emerged as a paradigm that combines the Internet of Things (IoT), artificial intelligence, cloud computing, and cyber-physical systems to enhance the efficiency and quality of healthcare services. One of the most significant challenges within this evolving ecosystem is the efficient management of hospital assets, which include a wide range of portable medical equipment such as infusion pumps, ventilators, ultrasound scanners, patient monitors, and wheelchairs.

In large tertiary hospitals, thousands of medical devices circulate continuously across departments such as intensive care units (ICUs), emergency rooms, surgical theaters, and diagnostic laboratories [1]. Due to the highly dynamic nature of hospital environments, equipment frequently becomes misplaced, underutilized, or unavailable during critical situations. Studies have shown that clinical staff may spend 21–30 minutes per shift searching for essential equipment, which significantly reduces productivity and increases operational costs. These inefficiencies not only affect hospital resource utilization but also have a direct impact on patient care and clinical response time.

Traditional asset management systems in hospitals often rely on manual logging, barcode scanning, or periodic inventory checks, which provide only intermittent information about equipment location and status [2]. Such approaches create fragmented information systems where asset visibility is limited to the moment of manual interaction. As a result, hospitals lack continuous situational awareness regarding device availability, utilization patterns, and operational condition. Real-Time Location Systems (RTLS) have emerged as a promising solution to address these limitations [3]. RTLS technologies typically employ wireless communication protocols such as RFID, Wi-Fi, Bluetooth Low Energy (BLE), and Ultra-Wideband (UWB) to continuously monitor the location of tagged assets within hospital premises. These systems enable healthcare administrators to track equipment movement, optimize resource allocation, and improve emergency response times [4]. However, despite their advantages, current RTLS implementations often suffer from several technical challenges.

One of the major limitations is the "last-meter localization problem." Hospital infrastructure frequently includes metallic equipment, thick concrete structures, and lead-shielded walls used in radiology departments, all of which interfere with wireless signal propagation. As a result, RSSI-based localization techniques used in BLE and Wi-Fi systems may produce inaccurate location estimates, particularly at the room level. In time-critical situations such as emergency procedures,

inaccurate equipment localization can lead to delays that directly affect patient outcomes.
Beyond localization accuracy, modern healthcare systems also require predictive asset management capabilities. Conventional tracking systems primarily focus on monitoring the location of devices but do not provide insights into their operational health or maintenance requirements. Consequently, hospitals often follow a reactive "break-fix" maintenance model, where equipment is serviced only after a malfunction occurs. This approach increases downtime and may lead to equipment failure during clinical procedures.
Recent advancements in IoT-enabled medical device monitoring [5] have demonstrated the potential of integrating embedded sensors and cloud-based analytics to improve healthcare workflow automation and operational transparency. Furthermore, as healthcare systems become increasingly digitized, concerns regarding data security, privacy, and regulatory compliance have become more prominent. Centralized data storage architectures commonly used in IoT platforms are vulnerable to unauthorized access, data tampering, and system failures. Given the strict regulatory frameworks governing healthcare infrastructure, ensuring the integrity and traceability of asset management data is essential.
To address these limitations, this paper proposes a multi-modal IoT-based asset tracking and predictive maintenance framework designed specifically for modern healthcare environments. The proposed system combines BLE proximity sensing with Infrared (IR) confirmation to achieve reliable room-level localization. In addition, an AI-based predictive maintenance module analyses device usage patterns to anticipate potential failures and schedule maintenance proactively. To ensure transparency and security of operational data, the system integrates a blockchain-based distributed ledger, enabling immutable record keeping for asset movement, servicing, and operational history. The remainder of this paper presents the existing research landscape, the proposed methodology, and the system architecture that supports this intelligent asset management framework.

2. Literature Review

Healthcare asset tracking has been widely investigated in recent years due to the growing need for efficient hospital resource management. Existing research primarily focuses on improving localization accuracy, reducing implementation costs, and integrating tracking systems with hospital information infrastructures.
Radio Frequency Identification (RFID) technology has traditionally been one of the most widely adopted approaches for asset tracking in healthcare environments. Passive RFID systems operate through electromagnetic coupling between RFID tags and readers placed at designated checkpoints. Studies have demonstrated that specialized RFID gate structures can achieve detection accuracies as high as 99.8% in controlled environments, particularly for inventory tracking applications. However, RFID systems are typically limited by their reliance on line-of-sight communication [8] and predefined scanning zones, which restrict their ability to provide continuous asset monitoring across large hospital spaces.
To overcome these limitations, researchers have explored wireless localization techniques based on Bluetooth Low Energy (BLE) and Wi-Fi fingerprinting [9]. These systems estimate device location by measuring the Received Signal Strength Indicator (RSSI) from multiple wireless access points or beacons. BLE-based solutions have gained popularity due to their low power consumption, affordability, and compatibility with mobile devices such as smartphones. Despite these advantages, RSSI-based localization methods often suffer from multipath signal propagation, environmental noise, and signal attenuation, particularly in complex indoor environments such as hospitals.
Another promising approach is the use of Ultra-Wideband (UWB) technology, which offers centimetre-level localization accuracy by measuring time-of-flight signals between transmitters and receivers. UWB systems have demonstrated high reliability in real-time tracking applications [10]. However, their deployment requires specialized hardware infrastructure and significant installation costs, which limits their scalability in large healthcare facilities.
Beyond location tracking, recent studies have explored the integration of IoT-enabled monitoring systems to collect operational data from medical devices. Energy monitoring systems and sensor-based usage tracking can provide insights into equipment performance and utilization patterns. However, these systems typically focus on monitoring device status rather than integrating predictive analytics for maintenance planning.
Recent studies have also explored the use of Internet of Things (IoT) technologies to automate clinical equipment monitoring and operational workflows. For example, an IoT-enabled automated dialyzer reprocessing system integrated multiple sensors such as flow, pressure, conductivity, and temperature sensors with an ESP32 microcontroller to standardize cleaning and disinfection cycles while enabling real-time cloud monitoring and automated alerts as shown in Fig.1 [11]. Such systems demonstrate the potential of IoT architectures to improve operational efficiency, data traceability, and regulatory compliance within healthcare environments.

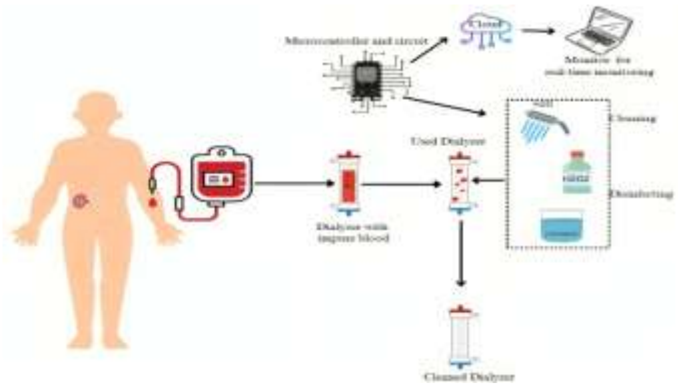

Fig.1: An example illustrating the real time cloud monitoring of IoT based dialyser reprocessing system.

Security and data integrity represent another critical area of concern in healthcare IoT systems. Traditional cloud-based asset management platforms rely on centralized databases that may be vulnerable to cyberattacks, unauthorized modifications, and single points of failure. Researchers have proposed blockchain-based architectures as a potential solution for secure healthcare data management [12-14]. Blockchain technology provides decentralized data storage with cryptographic verification, ensuring that records cannot be altered once they are recorded.

Despite these advancements, existing systems often address individual aspects of asset management, such as localization, monitoring, or security, without providing an integrated framework that combines these capabilities. The proposed methodology presented in this paper aims to bridge this gap by developing a hybrid IoT ecosystem that simultaneously addresses localization accuracy, predictive maintenance, and data security.

3. Proposed Methodology

The proposed framework introduces an integrated architecture designed to overcome the limitations of existing healthcare asset tracking systems. The methodology is structured into three primary functional modules: hybrid sensing, predictive maintenance intelligence, and decentralized security.

3.1. Multi-Modal Sensing Layer

The first component of the proposed system is a multi-modal sensing architecture that combines BLE proximity sensing with Infrared (IR) confirmation to improve localization accuracy. BLE beacons attached to medical assets periodically broadcast signals containing unique device identifiers. Stationary gateways installed throughout the hospital environment receive these signals and estimate the proximity of each asset using RSSI measurements. While BLE provides continuous tracking capability, RSSI-based localization may produce inaccurate estimates due to signal reflection and environmental interference.

To address this issue, the proposed system introduces Infrared (IR) sensors positioned at room entry points. Unlike radio signals, infrared signals cannot penetrate solid obstacles such as walls or doors. Therefore, when a tagged asset passes through a doorway equipped with an IR sensor, the system obtains a definitive confirmation that the device has entered or exited a specific room. By combining BLE proximity estimation with IR-based confirmation events, the system can correct location inaccuracies and maintain accurate room-level tracking. This hybrid approach significantly reduces the localization errors commonly observed in wireless-only tracking systems.

3.2. AI-Driven Predictive Maintenance Logic

In addition to location tracking, the proposed system incorporates an AI-driven predictive maintenance module designed to monitor equipment usage patterns and anticipate potential device failures. Sensors and tracking tags continuously record data related to equipment movement, usage duration, and operational frequency. This data is transmitted to a cloud-based analytics engine that applies machine learning algorithms to estimate the Mean Time To Failure (MTTF) for each device. Based on historical usage patterns and maintenance records, the system can generate predictive alerts indicating when a device is approaching a potential failure state. Maintenance tasks can then be scheduled proactively during periods of low clinical demand, minimizing operational disruption. This predictive approach enables hospitals to transition from traditional reactive maintenance models to preventive maintenance strategies, improving equipment reliability and reducing unexpected downtime

3.3. Blockchain-Based Security and Compliance

To ensure secure and transparent management of asset tracking data, the proposed system integrates a blockchain-based distributed ledger. Each asset movement, maintenance event, and predictive alert generated by the system is recorded as a transaction within the blockchain network. These transactions are cryptographically validated and stored in immutable blocks that cannot be altered or deleted once recorded.

The use of blockchain technology provides several advantages for healthcare asset management:

• Tamper-proof audit trails for equipment usage and maintenance history
• Improved regulatory compliance with healthcare standards such as HIPAA
• Enhanced data transparency and accountability across hospital departments

This decentralized approach eliminates the vulnerabilities associated with centralized databases and ensures that asset tracking records remain secure and verifiable.

Fig.2. System Architecture of the Proposed IoT-Based Healthcare Asset Tracking Framework.

The layered architecture of the proposed IoT-based asset tracking and predictive maintenance framework designed for modern healthcare environments as shown in Fig.2. The system is structured into four functional blocks that enable efficient sensing, communication, data processing, and application-level monitoring. At the Asset Layer (Block 1), medical equipment such as ventilators, mobile monitors, infusion pumps, and surgical kits are equipped with hybrid tracking tags containing technologies such as BLE, RFID, and infrared identifiers. These tags continuously broadcast signals that uniquely identify each asset and allow real-time monitoring of equipment movement within the hospital environment.

The Perception/Communication Layer (Block 2) consists of wireless readers and IoT gateways deployed across hospital wards and corridors. These devices capture signals transmitted by asset tags and relay the collected data through communication protocols such as Wi-Fi, BLE, or RFID networks. This layer acts as the bridge between physical sensing devices and the cloud infrastructure, enabling seamless data transmission and real-time monitoring.

The Processing Layer (Block 3) represents the cloud-based intelligence of the system. In this layer, the collected asset data is processed using data analytics engines and AI-driven predictive maintenance algorithms. The system analyzes equipment usage patterns, movement frequency, and operational duration to estimate potential equipment failures and schedule maintenance proactively. A centralized database stores operational records, while location intelligence algorithms compute accurate asset positions within the hospital environment.

Finally, the Application Layer (Block 4) provides a user interface for healthcare staff and administrators. Through staff dashboards, mobile applications, and geofencing alert systems, users can visualize hospital floor maps, receive real-time asset notifications, and access predictive maintenance schedules. This layer enables efficient decision-making and operational transparency within hospital infrastructure.

Together, these four layers create a comprehensive ecosystem that integrates sensing, communication, analytics, and user interaction to enable intelligent asset management in healthcare facilities.

4. System Architecture and Implementation

The proposed IoT-based healthcare asset tracking framework follows a layered architecture designed to ensure scalability, reliability, and seamless integration with existing hospital information systems. This architecture consists of four primary layers: the Asset Layer, Perception/Communication Layer, Processing Layer, and Application Layer, each responsible for a specific set of functions that collectively enable real-time tracking, predictive maintenance, and secure asset management as given in Fig.2.

The Asset Layer forms the physical sensing foundation of the system and is responsible for collecting real-time data from medical assets within the hospital environment. In this layer, each medical device is equipped with a hybrid tracking tag that integrates multiple sensing technologies such as Bluetooth Low Energy (BLE), Infrared (IR), and optionally RFID identifiers. The BLE module continuously broadcasts low-power signals containing unique device identifiers, enabling nearby receivers to estimate the proximity of the asset using Received Signal Strength Indicator (RSSI) measurements. Infrared sensors are strategically installed at critical locations such as room entrances, storage areas, and departmental boundaries. Because infrared signals cannot penetrate walls or barriers, they provide a reliable confirmation when a tagged asset enters or exits a specific room. This combination of BLE proximity sensing and IR-based event detection improves localization accuracy and eliminates the ambiguity caused by signal reflection and multipath interference commonly found in wireless-only tracking systems.

The Perception/Communication serves as the communication backbone of the system, enabling data transmission between sensing devices and the centralized processing infrastructure. This layer utilizes a hybrid communication approach consisting of stationary IoT gateways and mobile gateways. Stationary gateways are deployed throughout the hospital corridors, wards, and equipment storage areas to continuously capture BLE signals from nearby assets. In addition, smartphones or handheld devices carried by healthcare staff can act as mobile BLE gateways, enabling flexible and scalable data collection without requiring extensive infrastructure deployment. These gateways aggregate sensor data and transmit it securely to cloud servers using standard communication protocols such as Wi-Fi, Ethernet, or cellular networks. Edge computing nodes may also be integrated at the gateway level to perform preliminary data filtering and reduce network latency.

The Processing Layer is responsible for analysing the large volume of data generated by the sensing infrastructure and transforming it into actionable insights. This layer typically operates within a cloud-based computing environment that hosts machine learning models, data analytics engines, and blockchain nodes. The AI-based predictive maintenance module processes historical and real-time equipment usage data to estimate parameters such as device utilization frequency, operational duration, and movement patterns. Using these parameters, predictive models estimate the Mean Time To Failure (MTTF) and generate alerts when a device approaches a potential malfunction threshold. At the same time, location data collected from BLE and IR sensors is processed using localization algorithms to generate accurate room-level asset positions. The blockchain component of the processing layer records critical events such as asset movement, maintenance activities, and system alerts, ensuring that all operational data is stored in an immutable and verifiable format.

The Application Layer represents the user interaction interface of the system and provides healthcare staff, biomedical engineers, and hospital administrators with access to real-time operational information. Through a centralized dashboard or mobile application, users can visualize the current location of medical assets on hospital floor maps, monitor equipment utilization statistics, and receive predictive maintenance notifications. Biomedical technicians can access maintenance schedules generated by the AI module, allowing them to perform servicing before equipment failures occur. In addition, hospital administrators can review blockchain-based audit records to verify equipment history, ensure regulatory compliance, and analyse long-term asset performance. By integrating visualization tools, predictive analytics, and secure data management within a unified interface, the application layer enables healthcare institutions to transform asset tracking from a simple inventory function into a strategic operational management tool.

Together, these four architectural layers create a comprehensive IoT ecosystem that supports real-time visibility, predictive maintenance, and secure data management within modern healthcare environments. The modular design of the architecture also allows hospitals to scale the system incrementally, integrate additional sensing technologies, and adapt the framework to different clinical workflows and infrastructure constraints. The edge computing framework used to support real-time data processing in the proposed IoT-based healthcare asset tracking system. The architecture consists of three primary layers: edge devices, edge nodes, and cloud infrastructure, which work collaboratively to ensure low-latency communication, efficient data processing, and scalable system performance.

At the edge device layer, various IoT-enabled devices such as medical equipment tags, smart sensors, monitoring systems, and connected infrastructure components continuously generate operational data. In the context of healthcare asset tracking, these devices include BLE-enabled asset tags, infrared sensors, and RFID modules attached to medical equipment. These devices collect information related to asset location, device usage, and environmental parameters.

The data generated by these edge devices is transmitted to edge nodes, which serve as intermediate processing units located closer to the data source. Edge nodes perform preliminary data filtering, aggregation, and local analytics before forwarding the information to the central cloud system. By performing computation at the edge, the system significantly reduces communication latency and network congestion while enabling faster response times for real-time asset monitoring and predictive maintenance alerts.

The cloud layer provides centralized storage, advanced analytics, and large-scale machine learning capabilities. In the proposed framework, the cloud hosts the predictive maintenance algorithms, blockchain-based data ledger, and system dashboards used by healthcare administrators. The cloud infrastructure also aggregates data from multiple edge nodes to provide hospital-wide asset visibility and long-term performance analysis. By integrating edge computing with IoT-based sensing infrastructure, the system ensures efficient data handling, reduced latency, and improved scalability, which are essential for real-time monitoring in modern healthcare environments

5. Conclusion

Efficient asset management remains a critical challenge for modern healthcare institutions, where the availability and reliability of medical equipment directly influence patient outcomes. Traditional asset tracking systems provide limited functionality and often fail to address the complexities of dynamic hospital environments. This paper presented a comprehensive IoT-based framework that integrates hybrid sensing, predictive analytics, and blockchain-based security for intelligent healthcare asset management. By combining BLE proximity sensing with IR-based location correction, the proposed system achieves improved room-level localization accuracy. The integration of AI-driven predictive maintenance enables proactive equipment servicing, reducing downtime and enhancing operational efficiency. Additionally, the use of blockchain technology ensures secure and transparent data management, addressing critical concerns related to healthcare compliance and data integrity. Future research will focus on incorporating 5G-enabled edge computing architectures to further reduce system latency and support high-density medical environments such as surgical suites and emergency care units.

6. References

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