Revolutionising Healthcare Resource Management with IoT-Integrated Fault-Tolerant Digital Twin Technology

V Shreya Sivani, Vandana J, Sonali Mahesh Rane and Animesh Giri
Dept. of CSE, PES University Bangalore, India

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Abstract: Healthcare systems require reliable monitoring to prevent critical gaps caused by sensor failures, which can compromise patient outcomes and delay medical interventions. Continuous monitoring of vital signs is crucial for timely care, and the integration of advanced technologies has significantly improved accuracy and efficiency. However, traditional systems face challenges such as interruptions due to sensor failures. Digital twin technology, with its fault-tolerant architecture, addresses these issues by enabling real-time replication of sensor systems and ensuring uninterrupted operations. The proposed system achieves a Packet Delivery Ratio (PDR) of 95% for the primary sensor cluster, 80% for the coordinator, and 90% for the backup cluster, demonstrating robust performance even under fault conditions. This approach not only enhances reliability and data integrity but also has the potential to revolutionize resource management and operational efficiency in critical healthcare environments.This paper addresses these challenges by introducing a healthcare monitoring system that leverages digital twin technology.The system employs a dual-layered sensor mechanism where primary sensors continuously gather data, and backup sensors automatically activate in case of primary sensor failure, ensuring high availability and fault tolerance. Additionally, by integrating with cloud-based platforms, the system enables efficient data transmission and real-time monitoring, empowering healthcare professionals with timely access to critical patient information. Comprehensive performance evaluations demonstrate that the system maintains continuous data flow, achieving high reliability and low latency, even during sensor failures. This innovative approach not only transforms patient monitoring systems but also offers a scalable and dependable solution for hospital settings, ultimately contributing to enhanced patient care.

1 INTRODUCTION

In today's healthcare landscape, the integration of cutting-edge technology is critical to addressing the complexities of patient care, improving operational workflows, and ensuring patient safety. Delays or failures in continuous patient monitoring are a leading contributor to critical healthcare incidents, underscoring the need for robust monitoring systems. Traditional healthcare practices, while effective, often face limitations in continuously monitoring patients' vital signs, which can result in delays in detecting critical health issues. The need for a robust, real-time healthcare monitoring system is evident.

This work aims to develop a fault-tolerant digital twin system for continuous healthcare monitoring. One of the primary challenges in healthcare is the continuous, uninterrupted tracking of patient data, especially in environments where any sensor failure can lead to significant gaps in monitoring. Errors in data collection and transmission can impact the well-being of patients, making it essential to design systems that can reliably gather and process real-time health information.

This research introduces a digital twin-based healthcare monitoring network designed to be fault-tolerant, ensuring seamless data flow and reliable patient monitoring even during sensor failures. The proposed solution creates a virtual replica of the physical network, enabling continuous synchronization and data accuracy (Jacoby and Usländer, 2020).

The digital twin technology in this system allows for real-time mirroring of the healthcare network, providing healthcare professionals with a comprehensive view of the system's functionality and status. By continuously replicating the behavior of the physical sensors, the digital twin can simulate potential issues and analyze data trends, thereby enabling predictive analysis and ensuring continuous patient care. This capability allows for real-time data analysis and early

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intervention, thus minimizing the chances of critical health events going undetected (Erol et al., 2020).

The fault-tolerant nature of the system ensures that data collection is not interrupted, even if primary sensors fail. The proposed network autonomously switches to backup sensors when faults are detected, maintaining data integrity and system reliability. This approach minimizes downtime and ensures that vital patient information continues to be monitored and transmitted without interruption, which is essential for real-time healthcare monitoring applications (Zaiter and Hacini, 2020).

In healthcare settings, especially in critical environments like ICUs, a variety of IoT-enabled sensors are employed to monitor essential patient parameters. Key sensors include electrocardiogram (ECG) sensors for heart rate monitoring, pulse oximeters for tracking blood oxygen levels, blood pressure sensors, temperature sensors, and respiratory rate sensors. Each of these plays a vital role in collecting continuous patient data and transmitting it to a central monitoring system for real-time analysis. The integration of IoT ensures seamless connectivity and efficient data transmission across the network, allowing healthcare professionals to monitor patients remotely and in real time. To address the risk of sensor failure, the system incorporates redundant backup sensors. These backup sensors are kept in a standby mode and automatically activate if a primary sensor experiences a malfunction, ensuring uninterrupted monitoring and reliable data collection (Al-kahtani et al., 2022).

At the core of this healthcare network is a robust communication infrastructure designed to achieve high reliability and low latency, ensuring that data is reliably transmitted with minimal delay, even in the presence of faults. This combination of digital twin technology, fault-tolerant design, and efficient data handling forms a comprehensive solution for modern healthcare environments, supporting continuous and reliable patient monitoring.

This paper delves into the design and development of a fault-tolerant digital twin system tailored for healthcare environments. It explores the integration of digital twin technology with IoT-enabled sensors, focusing on ensuring uninterrupted patient monitoring despite sensor failures. The proposed system's architecture, implementation, and performance evaluation demonstrate its capability to maintain data integrity and reliability under fault conditions. Additionally, the paper highlights the potential of this approach to enhance resource management and operational efficiency in critical healthcare settings, paving the way for innovative advancements in real-time healthcare monitoring.

2 RELATED WORKS

Andreas P. Plageras et al. presented a framework that integrates Digital Twins and multi-access edge computing (MEC) for IIoT (Plageras and Psannis, 2022), showing improvements in latency, overhead, and energy consumption by utilizing edge resources efficiently. Similarly, Chi-Hung Hsiao et al. proposed an open-source framework to address integration issues in IIoT, highlighting the importance of choosing appropriate communication protocols for different types of data. However, these works lack redundancy mechanisms to handle critical failures, focusing primarily on improving communication and resource efficiency.

Mesmin Toundé Dandjinou et al. (Dandjinou et al., 2020) introduced the F-Hopcount protocol, which is a fault-tolerant routing mechanism designed for Wireless Sensor Networks (WSNs) that handles random node failures while maintaining high network performance. In (Jain et al., 2008), the Dual-Homed Routing (DHR) protocol is introduced, which enhances packet delivery by using redundant paths but incurs higher energy and bandwidth costs. The Informer Homed Routing (IHR) protocol proposed in (Qiu et al., 2013) improves DHR by reducing energy consumption through conditional activation of backup cluster-heads. However, both DHR and IHR focus on static backup paths, which might not be adaptable to dynamic network changes.

Younis et al. (Yu and Zhang, 2007) proposed a routing technique to combat random node failures, where sentry nodes monitor active nodes. While effective, this approach introduces extra traffic and resource wastage. The Dynamic Energy-aware Fault-Tolerant Routing (DEFTR) protocol (Haseeb et al., 2016) optimizes energy consumption by creating uniformly sized clusters and balancing routes, addressing energy depletion but lacking mechanisms to manage temporary node failures. The Distributed Fault-Tolerant Clustering Routing (DFCR) protocol focuses on energy efficiency and backup cluster heads but overlooks the impact of transient faults. Similarly, the Dynamic Fault-Tolerant Routing (DFTR) protocol (Chalhoub et al., 2017) utilizes transmission metrics and access delay to handle random node failures with minimal impact on network performance but does not prioritize redundancy mechanisms for critical failures.

While previous works have significantly advanced the fields of Digital Twin applications and fault-tolerant protocols, they often fail to address redundancy mechanisms comprehensively or focus solely on specific fault types. The proposed system bridges these gaps by integrating Digital Twin technology

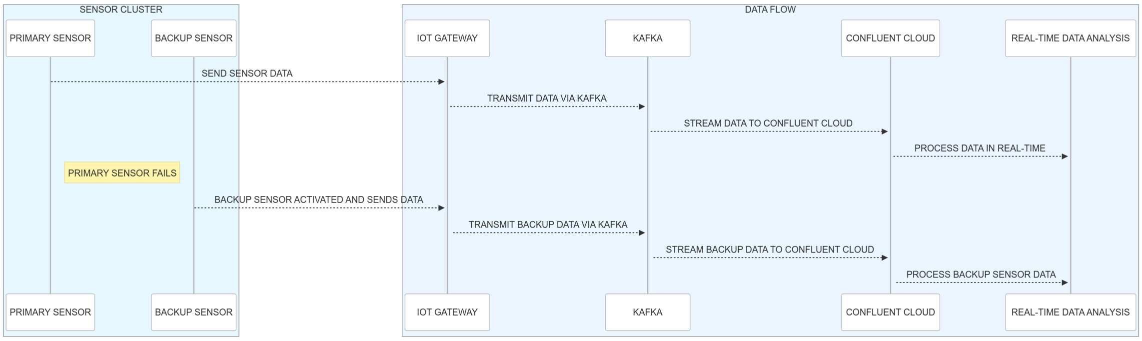

Figure 1: Sequence of Operations in the Digital Twin-Based Healthcare Monitoring System.

with a fault-tolerant architecture that ensures continuous healthcare monitoring. Unlike prior approaches, it emphasizes dynamic redundancy and seamless switching to backup sensors, thus providing a more robust solution for critical healthcare environments.

3 IMPLEMENTATION

The proposed healthcare monitoring system employs a digital twin architecture to ensure continuous and reliable data collection from patient wards. This approach provides a virtual representation of the physical sensor network, enabling real-time monitoring and rapid response to sensor failures. The system's dual-layered sensor network, comprising both primary and backup sensors, maintains data integrity even in the event of sensor downtime, as depicted in Figure 1,which shows the sequence of operations within the system.

3.1 Sensor Network Architecture

In the proposed implementation, primary sensors are deployed in patient rooms to monitor vital signs such as heart rate, blood pressure, and body temperature. These primary sensors continuously collect real-time data critical for effective patient care and timely medical intervention. The physical layer is designed for low-power, low-data-rate wireless communication, ensuring reliable data transmission across the network, even with constrained resources.

The coordinator sensor acts as the central hub of the network, receiving and aggregating data from all primary sensors. It compiles and processes incoming information for further analysis, serving as a critical point of data collection. Communication between the coordinator and the sensors is facilitated by ContikiMAC, a Medium Access Control (MAC) protocol that provides collision avoidance and efficient duty cycling, ensuring both reliability and energy efficiency.

The network layer employs IPv6, with uIP (a lightweight TCP/IP stack), which aids in efficient routing and addressing of data packets. The status of primary sensors is continuously monitored by the coordinator sensor using User Datagram Protocol (UDP), which is optimal for fast, lightweight, connectionless data transmissions. In case of primary sensor failures or inactivity, the coordinator sends activation messages to backup sensors using UDP, ensuring the network's integrity and functionality.

Figure 2 illustrates the architecture of the healthcare monitoring system. In each patient room, sensors—including ECG, pulse oximeter, blood pressure, temperature, and respiratory sensors—collect vital patient data and transmit it to an IoT gateway. This gateway forwards data to a digital twin platform, which performs real-time analysis and stores backup information. The digital twin not only simulates the patient's physiological conditions but also predicts potential health risks, enabling proactive care. Processed data is then sent to a central monitoring system, equipped with alert capabilities for immediate response, and stored in the cloud for secure, remote access by healthcare providers. This architecture ensures reliable, continuous monitoring and a rapid response to critical changes in patient health, enhancing patient care. Additionally, it facilitates seamless communication between healthcare providers and patients, promoting better health outcomes through timely interventions.

3.2 Fault Tolerance Through Backup Sensors

To mitigate potential failures of primary sensors, backup sensors are integrated into the system. While backup sensors are not actively functioning unless their primary counterparts fail, they constantly moni-

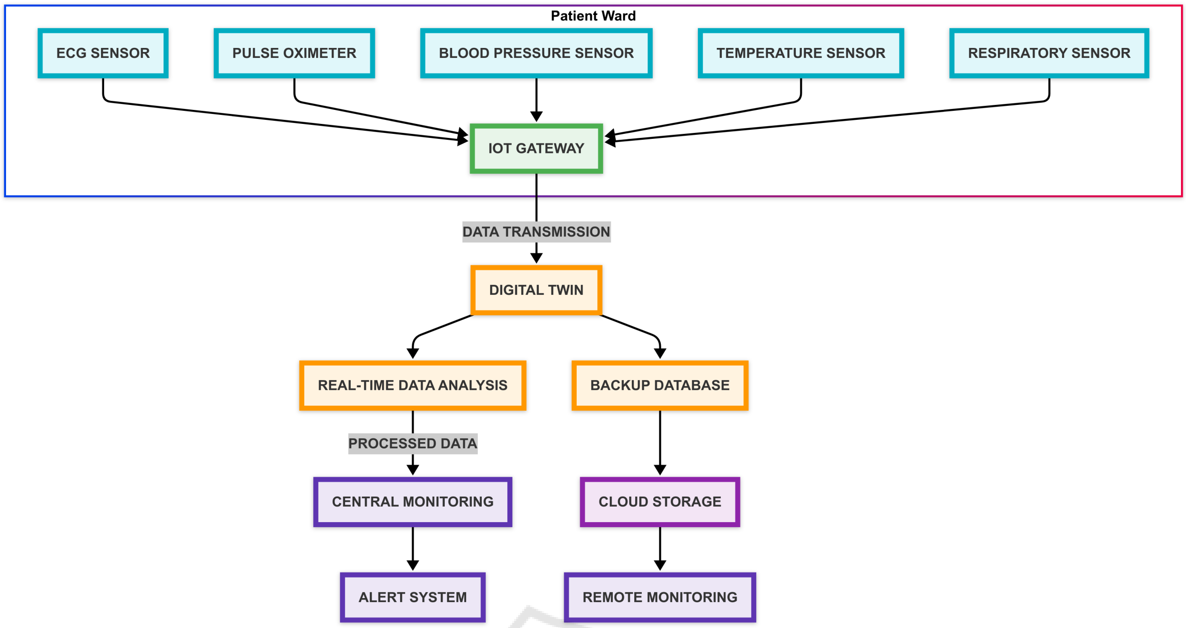

Figure 2: Digital-Twin based Healthcare Monitoring System.

tor the health and proper functionality of the primary nodes. In the event that a primary sensor fails to transmit data, the corresponding backup sensor is activated to ensure that data collection continues without interruption.

The ContikiMAC protocol plays a critical role in this process by enabling low-power operation and efficient data transmission. Its asynchronous duty cycling ensures that the sensors conserve energy during idle periods while maintaining readiness to respond to faults. Additionally, ContikiMAC's ability to rapidly wake up backup sensors and manage data retransmission ensures minimal latency and reliable fault recovery, thereby maintaining high availability and efficient operation of the system.

3.3 Digital Twin and Simulation Setup Using Contiki OS and Cooja

The Cooja simulator integrates seamlessly with Contiki OS, an open-source operating system tailored for resource-constrained Internet of Things (IoT) devices. This combination provides a robust platform for developing and testing large-scale IoT networks, supporting various networking protocols optimized for IoT applications.

In this project, a digital twin of the healthcare sensor network was implemented using Contiki OS, offering a virtual replica for real-time performance analysis, failure management, and robust data collection through simulation.

Cooja and Contiki OS are utilized to simulate client-server communication over the User Datagram Protocol (UDP). The `coordinator.c` file sets up a UDP server that listens for incoming packets on port `UDP_PORT 1234`. Upon receiving a message indicating an active sender, it sends activation commands to backup sensors. The `main.c` file serves as the sender, generating sensor data and toggling its active state to simulate faults.

The backup nodes, managed by `backup.c`, are activated upon receiving specific commands from the coordinator, ensuring continuous data collection even in the event of primary sensor failures. The backup nodes periodically check for active status and send data only when activated. This design guarantees the system's resilience by maintaining data integrity through backup sensors.

To enhance simulation realism, a backoff timer (`etimer`) introduces randomized delays before sending packets, reducing potential network congestion. The cluster of devices within the Cooja emulator, as shown in Figure 3, illustrates the arrangement of the primary, coordinator, and backup nodes in the simulation environment.

In addition, Figure 4 demonstrates the simulation of sensor data transmission and the activation of backup nodes, providing further insight into the dynamic operations of the system. The key simulation parameters are summarized in Table 1.

The algorithm presented below outlines a healthcare monitoring system that employs a dual-layered

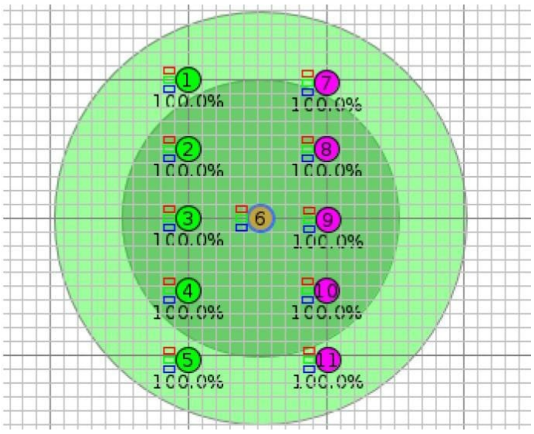

Figure 3: Cluster of devices with the Cooja emulator.

Table 1: Simulation Parameters.

Components	Specifications
Operating System	Ubuntu and Contiki OS
Simulator Version	Cooja
Radio Medium	Unit Disk Graph Medium (UDGM)
Inference Range	100 m
Transmission Range	150 m
Time of Simulation	300 seconds
Distribution	Linear
Number of Nodes (Primary)	5
Number of Nodes (Coordinator)	1
Number of Nodes (Backup)	5
Mote Type	Sky
RX Ratio	100%
TX Ratio	100%

sensor mechanism to ensure high availability and reliability in critical health data monitoring. In this system, primary sensors are deployed to continuously transmit critical health data (S2), while backup sensors initially operate at a lower priority, sending non-critical data (S1). The system continuously evaluates incoming values (vg), ensuring that critical parameters such as heart rate and oxygen levels are monitored in real time. In the event of a primary sensor failure, its corresponding backup sensor is activated, and its data is treated as critical (S2) to maintain uninterrupted health monitoring.

Once data is classified, S1 values are routed to a general monitoring queue for historical analysis, while S2 values are sent to an urgent monitoring queue, triggering real-time event detection and medical responses. By integrating this algorithm with Contiki OS in an IoT-based healthcare system, hospitals can ensure fault tolerance, efficient resource allocation, and continuous patient monitoring, preventing gaps in critical health assessments.

Data: Sensor data from primary and backup sensors.
Result: Real-time monitoring with prioritized sensor data handling.
S1 = Situation 1 (non-critical data from inactive backup sensors);
S2 = Situation 2 (critical data from active primary sensors and activated backup sensors);
vg = Value generated by a device;
Primary sensors: High priority (critical data, S2);
Backup sensors: Lower priority (initially non-critical data, S1);
Set Sensor Data Flow:;
Primary sensors: Send data as critical (S2);
Backup sensors: Initially send data as non-critical (S1);
while *monitoring is active* **do**
  Check device priority;
  Process data from primary sensors first (critical data, S2);
  If a primary sensor fails, activate the corresponding backup sensor and treat its data as critical (S2);
  for *each vg generated by a device* **do**
    Check if vg is non-critical (S1) or critical (S2);
    if *vg = S1 (non-critical data from inactive backup sensors)* **then**
      Route vg as non-critical data to a general monitoring queue;
      Archive data if it is only for historical reference;
    end
    else if *vg = S2 (critical data from active primary sensors or activated backup sensors)* **then**
      Route vg as critical data to the urgent monitoring queue;
      Trigger real-time processing for critical event response;
    end
    else
      Send vg directly to a central monitoring system for analysis and storage;
    end
  end
end

Algorithm 1: Healthcare Monitoring System with Dual-Layered Sensor Mechanism.

3.4 Data Management and Visualization

All sensor data, which includes temperature, ECG, and fault state statistics, is transmitted via a Kafka

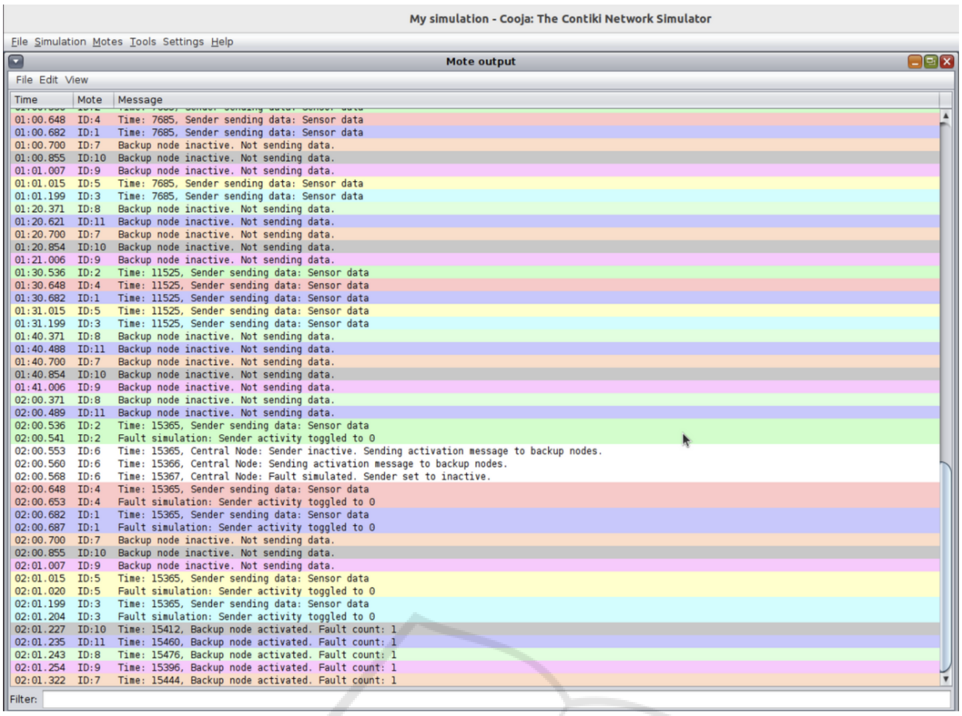

Figure 4: Output of the Simulation Showing Sensor Data Transmission and Backup Node Activation.

stream to the Confluent Cloud by the coordinator sensor. For real-time monitoring, a lightweight transport layer is essential; thus, data is transmitted via UDP over IPv6. Each data packet includes timestamp, partition, and offset for accurate tracking of the sensor behavior.

Data is processed quickly and categorized effectively within Confluent's Kafka, creating a robust platform for efficiently handling both live and historical data. The ContikiMAC protocol manages the radio duty cycle, allowing sensors to transmit data only when necessary while remaining idle otherwise. This setup ensures that critical events, such as sensor data transmission failures or node inactivity, are promptly captured and made readily available for further analysis and visualization, as demonstrated in Figure 5.

4 RESULT AND ANALYSIS

Achieving effective data transmission is vital in healthcare monitoring systems. The simulation results demonstrated the effectiveness of the energy-aware fault-tolerant mechanism and the Digital Twin in maintaining uninterrupted data flow. During the simulation, primary sensors were intentionally deactivated to test the response of backup sensors, which successfully activated and took over data transmission, ensuring no data loss. The Digital Twin provided real-time insights and optimizations, enhancing the system's fault tolerance and resource allocation.

4.1 Packet Delivery Ratio (PDR)

The Packet Delivery Ratio (PDR) measures the percentage of packets successfully delivered from the source to the destination within a network. A higher PDR indicates better network performance and reliability in terms of packet delivery.

$$\text{PDR} = \frac{\text{Number of packets successfully delivered}}{\text{Number of packets sent}} \tag{1}$$

Packet Delivery Ratio (PDR) is crucial in evaluating how reliably data is transmitted in the system. As illustrated in **Figure 6**, both the primary and backup clusters maintained a high PDR, confirming stable data reception from the IoT devices. This robust performance ensured effective data transmission even during failures, with the network remaining stable and allowing for the continued operation of the system across all clusters.

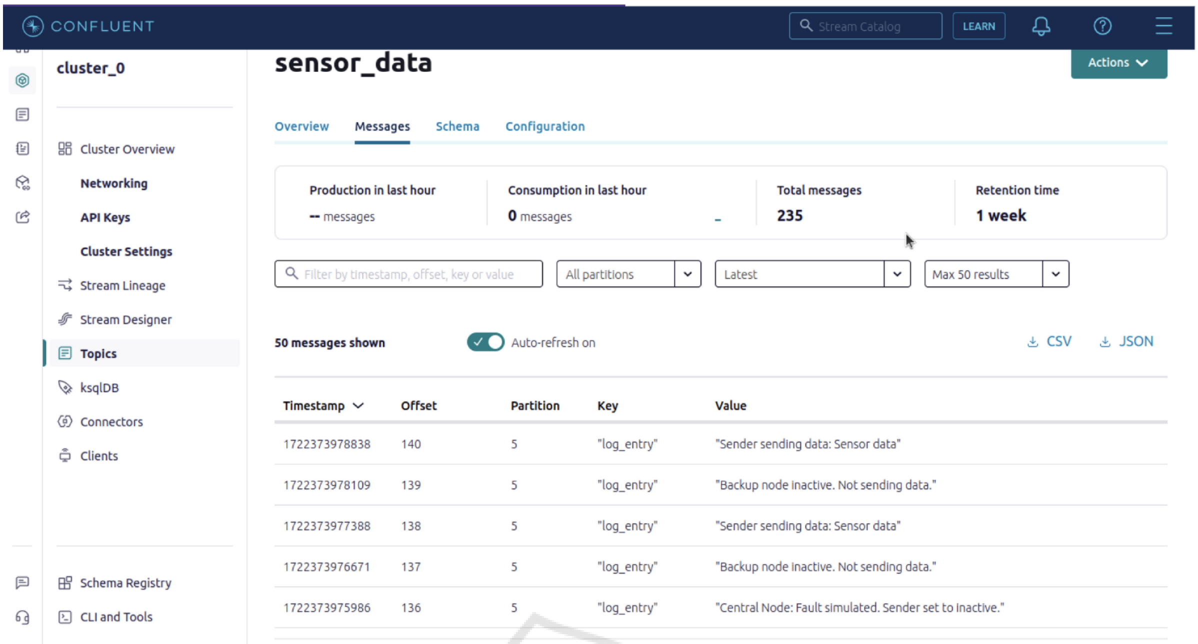

Figure 5: Sensor data in Confluent Kafka.

Figure 6: Packet Delivery Ratio.

4.2 Average Latency

Average Latency calculates the average time taken for a packet to travel from the source to the destination in a network. Lower average latency values indicate faster data transmission and better network responsiveness.

$$\text{Average Latency} = \frac{\text{Latency for all packets}}{\text{Number of packets}} \tag{2}$$

Latency is important for ensuring the system's timely responsiveness, particularly in healthcare scenarios where timely data transmission is critical. As illustrated in **Figure 7**, the primary cluster exhibits low latency, enabling swift decision-making and prompt updates on vital signs. This low latency guarantees reliable data monitoring even during primary sensor failures.

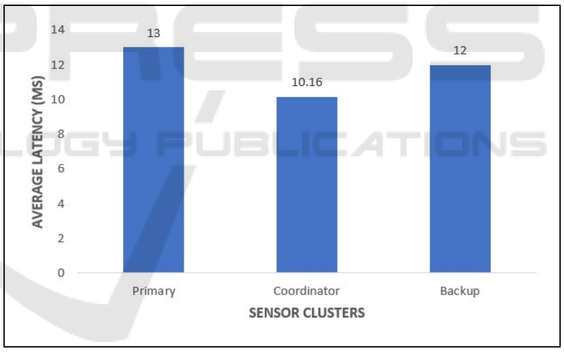

Figure 7: Average Latency.

4.3 Comparative Analysis and Significance

The improvements in both PDR and latency underscore the advantages of integrating the proposed fault-tolerant mechanism and Digital Twin in healthcare monitoring. By addressing critical gaps in existing systems, the proposed solution ensures uninterrupted and efficient monitoring, which is crucial in life-saving scenarios. The graphs and metrics are interpreted in the context of healthcare applications, where consistent, reliable data transmission directly impacts patient safety and care quality.

5 CONCLUSIONS

This research demonstrates the potential of combining backup sensor systems with Digital Twin technology to enhance the reliability and fault tolerance of patient monitoring systems in healthcare. The proposed system ensures continuous data transmission, even in the event of sensor failures, addressing one of the most critical requirements in healthcare monitoring.

By leveraging Digital Twin technology, real-time shadowing and analysis of sensor networks become feasible, enabling healthcare providers to maintain high-quality care with minimal delays. The predictive functionality incorporated into backup sensors further strengthens the system, reducing downtime and preserving service continuity.

The broader implications of this work suggest that such resilient and fault-tolerant systems can significantly transform critical care environments like ICUs. Continuous monitoring with minimal latency ensures that vital patient data—such as heart rate, oxygen levels, and blood pressure—is always available, enabling prompt decision-making and reducing the likelihood of adverse events. The system's ability to seamlessly activate backup sensors during primary sensor failures is particularly vital in ICUs, where every second can impact patient outcomes. By reducing intervention delays, this technology can support healthcare providers in responding to emergencies faster and more effectively, ultimately improving the quality of care and saving lives.

Furthermore, the scalability of this approach positions it as a viable solution for larger and more complex healthcare networks. As healthcare facilities grow in size and complexity, the ability to extend this system to accommodate an increasing number of patients, sensors, and data streams is essential. The modular design of the system ensures it can be adapted to different hospital settings, from single ICU units to entire hospital networks, while maintaining its core fault-tolerant capabilities. This scalability not only makes it suitable for large-scale deployments but also opens opportunities for integration into national healthcare infrastructures, where uninterrupted patient monitoring is critical.

This work provides evidence that incorporating predictive functionality into backup sensors, combined with real-time insights from Digital Twins, can contribute significantly to resilient healthcare systems. These systems are well-equipped to handle diverse operational challenges, ensuring continuity of care and advancing the field of digital healthcare.

6 FUTURE WORKS

Incorporating machine learning algorithms into the analysis of sensor data presents a significant opportunity for enhancing the healthcare monitoring system. Integrating models such as Long Short-Term Memory (LSTM) networks or Random Forests for predictive maintenance can enable the system to anticipate sensor failures with high accuracy. By analyzing historical and real-time data patterns, these models facilitate the prediction of potential issues before they occur, allowing for timely interventions and ensuring uninterrupted patient monitoring.

Moreover, integrating these machine learning models with hospital management systems can enable seamless data handling and improved decision-making across the healthcare infrastructure. This integration would ensure that predictive insights are efficiently relayed to healthcare personnel, enabling proactive maintenance and reducing operational disruptions. Collaborative efforts between data scientists and healthcare professionals are crucial for tailoring these solutions to the specific challenges of monitoring systems. Additionally, establishing robust validation processes through real-world testing in hospital environments will be critical to ensuring the reliability and efficacy of these algorithms in practical healthcare scenarios.

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