Low-Latency Fog Computing for Healthcare IoT: Nature inspired Approaches to Resource Optimization

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Abstract: The swift incorporation of the Internet of Things (IoT) in healthcare has led to continuous data generation, demanding low-latency processing and optimal resource use. The central research problem is that conventional cloud computing, due to its centralized structure and high communication delay, fails to achieve the real-time requirements of critical healthcare applications. By bringing calculation closer to IoT devices, fog computing overcomes this constraint and supports time-sensitive applications like wearable health tracking, remote monitoring, and emergency treatment. With a focus on Artificial Intelligence (AI) and Machine Learning (ML) methodologies, this survey examines recent developments in fog-based resource management for healthcare IoT. It looks at techniques for load balancing, intelligent scheduling, task offloading, and dynamic provisioning in fog situations with limited resources. The comparative evaluation of state-of-the-art strategies reveals that AI-driven frameworks achieve significant improvements in latency reduction, energy efficiency, throughput, and overall Quality of Service (QoS). These findings highlight the growing relevance of intelligent solutions for addressing the complexity of decentralized fog systems. This work's main contribution is a structured classification of AI-enabled fog computing approaches tailored specifically for healthcare IoT applications. Beyond summarizing existing methods, the review identifies key research issues like scalability, energy-aware scheduling, and adaptive real-time processing that remain open for exploration. By aligning emerging AI-driven techniques with performance parameters, this study offers a comprehensive foundation for experimenters and professionals seeking to design next-generation healthcare frameworks that are both intelligent and resilient.

Keywords: Internet of Things (IoT) , Healthcare IoT (HIoT), Quality of Service (QoS), Artificial Intelligence (AI), Machine Learning (ML), Fog Computing Resource Management (FRM), Fog computing, Resource Allocation, Nature Inspired Algorithm.

I. INTRODUCTION

Often referred to as HIoT, the incorporation of the Internet of Things into healthcare, enables applications like remote monitoring, telemedicine, wearable-assisted diagnostics, and emergency response [1], [2]. These applications require ultra-low latency, reliability, and secure data handling. However, centralized cloud computing introduces bottlenecks such as latency, bandwidth constraints, privacy concerns, and service unreliability in mobile or rural scenarios [1], [15]. Such limitations underscore the inadequacy of traditional cloud models for real-time healthcare delivery.

Fog and edge computing address these issues by extending computation closer to data sources, thereby decreasing communication delays and enhancing scalability and service dependability [15], [26]. Despite these advantages, distributed

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environments bring new challenges in resource allocation. Efficient management of computational, storage, and network resources is necessary to ensure

QoS, energy efficiency, and data security [6], [19], [30]. Yet, many proposed mechanisms are simulation-driven and lack adaptability to heterogeneous healthcare settings, leaving a gap between theoretical approaches and practical implementations.

Existing research on IoT resource management provides valuable insights but often neglects healthcare-specific requirements such as strict privacy, life-critical reliability, and the energy limitations of wearable devices. Moreover, most studies rely on heuristic or meta-heuristic techniques, with limited exploration of hybrid, adaptive, or AI-driven solutions [6], [19]. The objective is to provide a comprehensive review while identifying research gaps and opportunities for practical, life-critical healthcare deployments [26], [30]. This survey focuses on resource allocation strategies designed for fog-edge-cloud healthcare systems, emphasizing underexplored directions including nature-inspired optimization and hybrid scheduling.

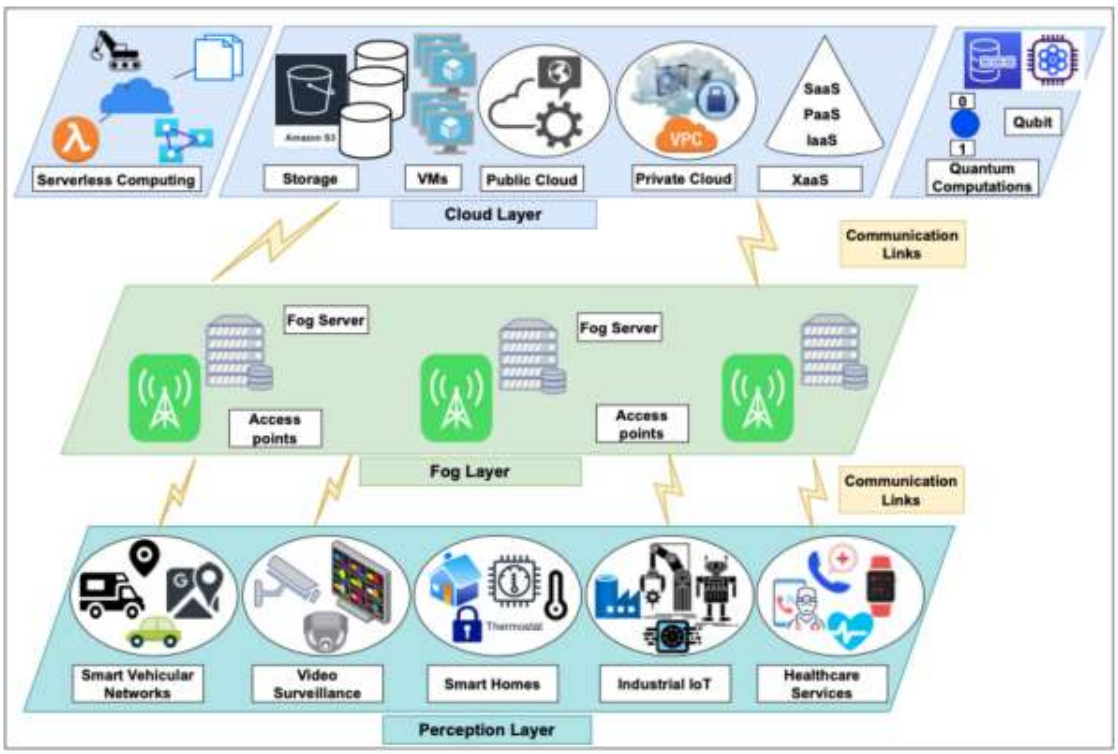

Fig. 1: Hierarchical Architecture for Fog-Assisted IoT Systems [9]

II. BACKGROUND THEORY

Due to large delays and centralized processing, typical cloud computing is unable to meet the low latency, dependability, and energy efficiency requirements of healthcare IoT applications including wearables, emergency response, and remote monitoring [5], [11], [21]. Fog and edge computing resolve these problems by allowing real-time analytics and effective resource use by moving computation closer to IoT devices. [2], [15], [26].

However, resource allocation and task scheduling remain major challenges due to device heterogeneity, dynamic workloads, and limited fog resources [6], [7], [18]. Recent works propose priority-based scheduling [1], service-oriented allocation [4], hybrid load balancing [10], and energy-aware strategies [24]. Security and privacy are equally critical, with solutions such as cognitive fog models and quantum-inspired frameworks being explored [8], [20], [25]. Artificial intelligence and nature-inspired algorithms offer adaptive optimization for scheduling and allocation, improving latency, scalability, and energy efficiency in healthcare fog environments [9], [17], [19]. Despite these advances, open challenges remain in efficient resource management, energy sustainability, security, and interoperability for large-scale healthcare IoT systems [22], [30], [24]. Managing healthcare IoT systems is highly complex, requiring an integrated balance of latency, scheduling efficiency, resource optimization, security, and energy constraints.

III. RESEARCH CHALLENGES

Despite extensive progress, multiple research gaps remain:

- **Latency and Real-Time Responsiveness** - Healthcare applications like critical patient monitoring require guaranteed low end-to-end delay; resource allocation must support ultra-fast scheduling and local processing to meet strict deadlines. [10], [14]. Ensuring latency-aware optimization remains a central challenge in real-time healthcare systems.
- **Service Placement and Load Balancing** - Deciding where to place services (edge, fog, cloud) and how to distribute workloads dynamically is crucial to minimize latency and avoid hotspots; inefficient placement leads to higher cost and poorer QoS. [13], [16], [19]. Dynamic and adaptive placement strategies are therefore vital for healthcare IoT.
- **Energy Efficiency and Sustainability** - Many devices and fog nodes are energy-constrained, so allocation strategies must reduce power consumption while maintaining performance for long-term, sustainable operation. [6], [24]
- **Security and Data Privacy** - Sensitive health data demands strong encryption, access control, and privacy-preserving allocation policies that do not unduly increase processing or latency. [20], [25]. Trustworthy solutions must protect data without compromising service efficiency.
- **Scalability and Resource Management** - As device counts grow, allocation frameworks must scale gracefully and manage CPU, memory, storage, and bandwidth without severe performance degradation. [7], [13], [30]. Robust scalability ensures reliability in large-scale healthcare deployments.
- **Interoperability and Standardization** - Heterogeneous devices, protocols, and vendor platforms require common interfaces and standards so allocation mechanisms can interoperate across systems and support seamless service migration. [4], [11].
- **Reliability and Fault Tolerance** - Faults in edge/fog nodes must be anticipated by allocation schemes that provide redundancy and fast recovery to maintain continuous healthcare services. [13], [31]. High fault tolerance is essential for mission-critical patient care applications.

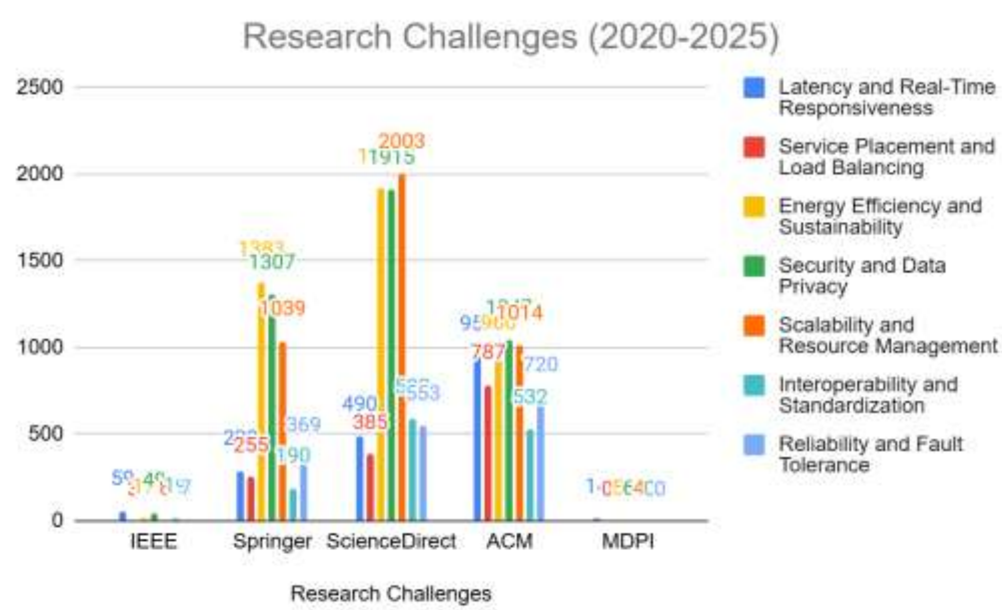

Fig 2. Research Challenges by Publishers (2020-2025)

Fig. 2 illustrates the distribution of key research challenges in healthcare IoT and fog/edge/cloud computing across major publishers (IEEE, Springer, ScienceDirect, ACM, MDPI) for 2020–2025. It shows that Energy Efficiency and Sustainability and Security and Data Privacy are the most dominant challenges, particularly in ScienceDirect and Springer. Meanwhile, Latency and Real-Time Responsiveness and Service Placement with Load Balancing are significant in ACM. Overall, the chart highlights varying research priorities depending on the publisher.

IV. LITERATURE CLASSIFICATION AND REVIEW

This section explains how we organized and compared the research papers we studied. We grouped them in different ways so it's easier to understand what each paper focused on. Below, we describe the categories and summarize the main ideas from the papers.

4.1 Resource Allocation Issues in Healthcare Systems

Resource allocation in healthcare-oriented fog, edge, and cloud systems faces several challenges due to the dynamic, life-critical, and heterogeneous nature of medical environments. Based on the reviewed literature, the major issues include:

1. **Latency and Real-Time Response Requirements:** Healthcare applications often demand immediate processing of patient data (e.g., during remote surgeries or emergency monitoring). Delays in allocating resources can lead to life-threatening consequences [3], [12], [22]. Reliable low-latency performance is thus an indispensable prerequisite for healthcare IoT systems.
2. **Energy Efficiency and Device Constraints:** Wearable devices and edge nodes in healthcare are often battery-powered. Efficient allocation strategies are required to minimize energy consumption while maintaining performance [20], [27]. Energy-aware allocation is essential to extend device life and support critical healthcare tasks.
3. **Heterogeneous Data and Devices:** Healthcare systems involve various sensors, imaging tools, and patient-monitoring devices. Allocating resources efficiently across these heterogeneous platforms is complex [4], [11], [23]. Seamless integration across diverse medical devices is vital for efficient and reliable healthcare service delivery.
4. **Privacy and Security Requirements:** Medical data is highly sensitive. Resource allocation must account for secure transmission, processing, and storage, especially when offloading to the cloud or edge layers [26].
5. **Dynamic and Unpredictable Workloads:** Patient conditions and emergency situations can change rapidly. This requires adaptive resource management systems that can reallocate computing power on the fly [28], [29].
6. **Other Issues:** Healthcare applications often face problems like scalability, Fog computing infrastructure (servers near hospitals, clinics, ambulances) requires high investment. Healthcare services require reliability for fault-tolerant allocation to handle node or network failures.

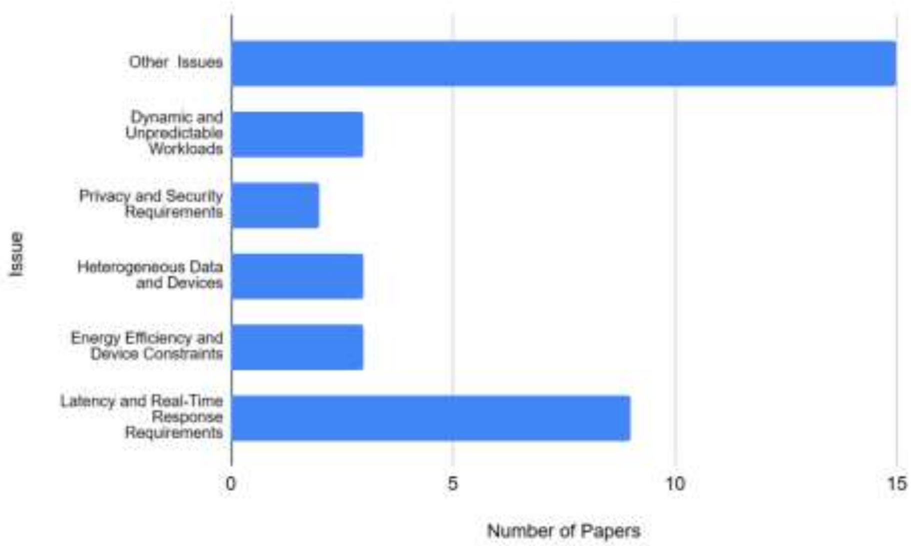

Fig. 3 Issue-Wise Analysis of Research Publications

This figure 3 shows the distribution of research papers across major issues in healthcare IoT and fog/edge computing. The highest number of papers address Other Issues, followed by Latency and Real-Time Response Requirements, which emerges as a significant research focus. Comparatively fewer papers deal with Energy Efficiency, Heterogeneous Data, Privacy, and Dynamic Workload Management, indicating these areas are less explored.

4.2 Comparison Table

This table presents a comparison of key research works that explicitly address latency in fog and edge computing environments using algorithmic approaches. Each paper proposes methods such as scheduling, load balancing, optimization, and resource migration to minimize task execution and communication delays in healthcare and IoT systems. The table highlights their core contributions, latency-handling strategies, and potential future research directions, offering insights into how different algorithms tackle low-latency requirements in real-time applications.

TABLE I:
COMPARISON TABLE OF LATENCY-FOCUSED ALGORITHMS IN HEALTHCARE IOT

Paper No.	Year	Algorithm / Method Used	Latency Handling Approach	Future Scope
J. Anand,et al.[1]	2025	Adaptive resource allocation and dynamic scheduling based on priorities	Prioritizes critical healthcare tasks and adaptively allocates edge resources to minimize response time	Extend to heterogeneous multi-edge & mobility-aware healthcare systems
Salman Khan,et al.[3]	2022	Optimization-based resource allocation (heuristic/metaheuristic)	Allocates fog resources optimally to reduce healthcare IoT data processing latency	Explore AI-driven methods for balancing energy–latency trade-offs
Di Zhao,et al.[4]	2025	Service-oriented resource allocation & task scheduling	controls Bluetooth and Wi-Fi cohabitation, lowering communication latency caused by interference.	Extend to multi-protocol IoT and heterogeneous smart healthcare devices
Ammar Awad Mutlag,et al.[10]	2023	Hybrid load balancing + scheduling (FRM model)	Balances workloads across fog nodes to reduce latency and improve QoS	Apply machine/deep learning for adaptive and real-time scheduling
Mohammed Jasim,et al.[13]	2024	Local load migration strategy	Migrates tasks across high-capacity fog nodes to reduce execution latency	Extend migration to mobile users and time-sensitive healthcare data
Mohammad Goudarzi,et al.[14]	2022	IoT application scheduling algorithms	Schedules IoT tasks closer to fog/edge nodes to minimize execution delay	Design scalable scheduling for massive IoT traffic and dynamic workloads

Farooq Hoseiny,et al.[16]	2020	QoS-aware & cost-efficient scheduling	Considers latency along with QoS and cost constraints in fog-cloud task placement	Extend with multi-objective optimization including energy & reliability
Giuseppe Faraci,et al.[17]	2020	UAV-assisted edge resource scheduling	Uses UAVs as mobile fog nodes to reduce IoT service latency	Optimize UAV trajectory & resource allocation for emergency healthcare
Zhendong Song,et al.[20]	2024	Quantum-inspired optimization	Improves wearable healthcare performance with secure, low-latency resource allocation	Extend to hybrid quantum-classical models for real-time IoT healthcare

Table 1 presents a comparative analysis of key research papers that explicitly address latency in healthcare IoT through different algorithms and methods. J. Anand et al. [1] focus on scheduling that is based on dynamic priorities and adaptive allocation to minimize response time in critical healthcare tasks, with future directions in multi-edge and mobility-aware systems. Salman Khan et al. [3] apply heuristic and metaheuristic optimization for fog resource allocation, highlighting the potential of AI-driven latency–energy trade-offs. Similarly, Di Zhao et al. [4] propose service-oriented scheduling to handle communication interference, with extensions suggested for heterogeneous devices. Approaches such as hybrid load balancing [10], local load migration [13], and IoT task scheduling [14] reduce execution delays by better distributing tasks. QoS-aware scheduling [16] and UAV-assisted resource allocation [17] further expand latency optimization to cost and mobility contexts. Finally, Zhendong Song et al. [20] employ quantum-inspired optimization, envisioning hybrid quantum-classical frameworks for real-time healthcare IoT.

V. CONCLUSION AND FUTURE WORK

The rapid growth of Healthcare IoT has created a strong demand for computing infrastructures that can ensure low latency, high reliability, and efficient resource utilization. Traditional cloud-based approaches, although powerful, are not able to meet the stringent requirements of real-time healthcare monitoring, emergency response, and wearable-driven applications due to high latency and bandwidth limitations. By moving computational resources closer to data sources, the fog and edge computing concepts have shown promise as remedies. However, they face threats like optimal resource allocation, dynamic task scheduling, energy efficiency, and security. The reviewed studies highlight advancements in adaptive scheduling [1], [3], AI-driven resource management [6], [9], [17], and hybrid fog–cloud collaboration models [11], [31], which collectively improve performance but still leave open issues for large-scale, heterogeneous healthcare environments.

Future research in fog-enabled healthcare IoT should focus on efficient resource optimization and allocation to minimize latency in real-time medical services. Nature-inspired techniques, including genetic algorithms, particle swarm optimization, and ant colony optimization, provide effective approaches by dynamically scheduling tasks and distributing workloads across fog nodes. These methods support near-optimal resource allocation, adapt to varying healthcare demands, and manage computational loads under limited resources. Integrating latency-aware scheduling with such optimization techniques can enhance scalability, reduce task delays, and improve system responsiveness, thereby ensuring reliable and timely delivery of critical healthcare applications.

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