

Adaptation in IoT-Fog Data Transmission: SLR and Future Perspectives on Dynamic Frequency Control

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Abstract— The advancement of Internet of Things (IoT) and fog computing technologies has created significant opportunities for more efficient, faster, and proximity-based data management. However, IoT-Fog systems face considerable challenges related to device heterogeneity, traffic dynamics, and the complexity of network topologies that continuously change. This study conducts a Systematic Literature Review (SLR) of various research works covering dynamic scheduling, routing, context-aware data flow, offloading, and IoT-Fog systems without adaptive mechanisms. The findings indicate that most existing approaches still rely on relatively static topology assumptions, rendering them insufficiently adaptive to real-time changes in network conditions. One area identified as a research gap is dynamic frequency control, an adaptive mechanism capable of dynamically adjusting data transmission intensity based on network conditions. The main conclusion of this study emphasizes the necessity for developing adaptive systems that are topology-agnostic and supported by dynamic frequency control to maintain optimal performance even under significant topology changes. Such systems are anticipated to become a crucial foundation for future IoT-Fog applications, including smart cities, Industry 4.0, and intelligent healthcare services, which demand high reliability and low latency.

Keywords— Adaptive Systems; Context-Aware; Dynamic Scheduling; Fog Computing; Internet of Things (IoT); Offloading; Routing; Topology-Agnostic.

I. INTRODUCTION

Recent advancements in Internet of Things (IoT) and fog computing technologies have transformed data processing and transmission, especially in essential applications that demand real-time responsiveness and high energy efficiency. One of the biggest challenges with IoT-fog systems is developing adaptive mechanisms that can quickly respond to changing network loads, environmental conditions, and diverse application requirements. Adaptive systems in this ecosystem employ diverse methods, such as rapid detection of changes in data patterns to maintain analytic accuracy [1], fault-tolerant processing to ensure service reliability under node failures [2], and privacy-preserving schemes that safeguard data without imposing excessive computational overhead [3]. Moreover, the combination of lossless data compression techniques with fog computing has been proposed to facilitate the transmission of extensive data, such as EEG signals, thereby reducing latency and conserving bandwidth [4]. Improving the efficiency of data processing near the edge has also become an important trend to help IoT-fog systems work better [5].

Adaptive approaches continue to evolve, encompassing context-based risk management models, multivariate time-series prediction for more intelligent traffic control, and lightweight authentication schemes to secure data transmissions [6]–[9]. Research has also looked into how to improve system performance and resilience in changing conditions by combining collaborative computing, adaptive process migration, and security-based attribute identification at the fog layer [9–11]. The flexible use of blockchain technology

is being looked at more to make sure that data is accurate and transactions are safe in fog architectures [12]. To best distribute workloads across the edge, fog, and cloud layers, frameworks like the Adaptive Fog Computing Framework (AFCF) have been created to meet the needs of different workloads and applications [13].

There has also been a lot of research on dynamic resource allocation using differentiated service models, context-aware access control, and fog architecture designs that support real-time data analytics to improve the management of changing traffic loads [14]–[16]. Recent trends show a lot of interest in using acoustic emission (AE) technology to use acoustic data as a key source of information for keeping an eye on the condition of industrial equipment and infrastructure. AE has been incorporated into IoT-fog systems to facilitate predictive monitoring, prompt identification of structural damage, and swift decision-making in industrial maintenance contexts [17]–[23]. Combining AE with fog computing not only improves sensor-based monitoring, but it also creates new possibilities for processing large amounts of real-time data.

TABLE I. DISTRIBUTION OF ADAPTIVE APPROACHES IN 208 SCIENTIFIC ARTICLES

No	Approach	Number of Articles	Percentage (%)
1	AI-based Scheduling	80	38.46%
2	Dynamic Routing	29	13.94%
3	Context-Aware Transmission	64	30.77%
4	Offloading Server	26	12.50%
5	System Implementation (Other)	9	4.33%

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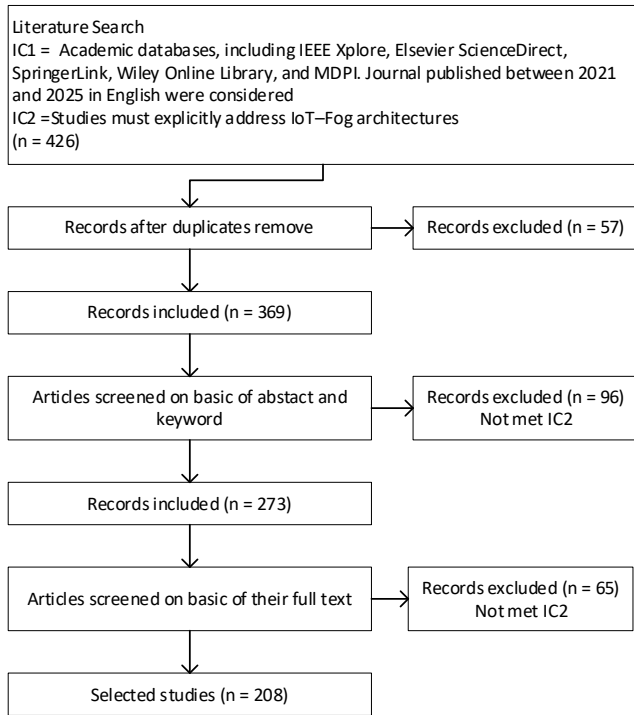


Figure 1. PRISMA Flow Diagram.

Dynamic frequency control is still largely unexplored as a particular adaptive strategy for controlling data transmission intensity in real-time, even though a variety of adaptive approaches have greatly improved the performance of IoT-fog systems. Dynamic frequency control has a lot of promise for maximizing resource utilization efficiency, decreasing latency, and stabilizing data flows—especially in situations with high data loads like AE data processing or other real-time applications. To achieve truly adaptive and scalable IoT-fog systems, dynamic frequency control may be a crucial mechanism, considering traffic dynamics, device conditions, and application requirements. Therefore, this study is particularly interested in the following research question:

RQ: How can dynamic frequency control be developed and systematically integrated into IoT-Fog architectures to enable adaptive, topology-agnostic, and lossless data transmission for real-time applications?

Based on this research gap, the current study intends to perform a thorough Systematic Literature Review (SLR) in order to define future research directions required to address the remaining challenges in the literature and to identify recent approaches related to dynamic frequency control in data transmissions within IoT-fog systems.

II. METHOD

This study was conducted using a Systematic Literature Review (SLR) approach to evaluate developments, trends, and research gaps related to adaptive data flow in IoT-Fog Computing systems, particularly in the context of single-server and single-link scenarios. The methodology comprised four main stages: literature search, article selection, data extraction, and synthesis analysis.

A. Literature Search Strategy

The literature search was performed across several leading academic databases, including IEEE Xplore, Elsevier ScienceDirect, SpringerLink, Wiley Online Library, and MDPI.

The search keywords were: IoT-Fog computing, adaptive data transmission, dynamic routing, AI-based scheduling, context-aware data flow, and acoustic emission monitoring. The search focused on journal articles and international conference proceedings published between 2021 and 2025 to ensure relevance and currency of the reviewed findings.

B. Inclusion and Exclusion Criteria

The inclusion criteria for this study comprised articles discussing IoT systems involving fog computing, exploring adaptive approaches at network, server, or data transmission levels, and focusing on system performance optimization metrics such as latency, throughput, bandwidth efficiency, or resource utilization. Additionally, only studies involving real-world scenarios or large-scale simulations were included in the analysis. Conversely, articles solely discussing cloud computing without fog involvement, studies focusing exclusively on security or encryption aspects without direct relation to data flow, non-English publications, and non-peer-reviewed papers such as editorials or opinion pieces were excluded from this review. The purpose of these inclusion and exclusion criteria was to ensure that only relevant, high-quality literature was analyzed within the context of this research.

C. Selection and Data Extraction

The systematic search initially identified 426 articles across major databases. To ensure methodological rigor, the following inclusion criteria were applied:

- IC1: Peer-reviewed journal articles published between 2021 and 2025 in English were considered.
- IC2: Studies must explicitly address IoT-Fog architectures.

Following the removal of duplicate records, 369 unique articles remained. Title and abstract screening was then performed according to IC1 and IC2, which further reduced the dataset to 273 articles. A subsequent full-text review excluded studies that did not fully satisfy the inclusion criteria, resulting in 208 articles being retained for final synthesis and analysis. This multi-stage selection process ensured that only relevant and high-quality studies were considered, thereby strengthening the validity and reproducibility of the review. The complete flow of article identification, screening, and inclusion is summarized in the PRISMA diagram presented in Figure 1.

The extracted data included: Adaptive methods implemented (e.g., offloading, AI-based scheduling, routing, context-aware transmission), System architectures reviewed (multi-server vs. single-server), Optimization focus (transmission frequency, data prioritization, communication paths), System performance evaluations (latency, throughput, bandwidth usage)

D. Synthesis Analysis

The selected articles were analyzed both qualitatively and quantitatively. The analysis involved categorizing articles into dominant adaptive approach groups, identifying their strengths, limitations, and relevance within single-server and single-link contexts. The data synthesis included comparisons among approaches, identification of key trends, areas of research that remain underexplored, and potential future research directions. The results of the analysis were visualized using diagrams, classification tables, and descriptive statistics to reinforce the research findings.

III. RESULTS AND DISCUSSION

This study systematically analyzes 208 scientific articles published between 2021 and 2025 to evaluate adaptive approaches in IoT-Fog Computing, particularly concerning data flow management. The review categorizes adaptive solutions into five main approaches: AI-based scheduling, dynamic routing, context-aware transmission, server offloading, and implementations based on specialized methods. The distribution of articles presented in Table I reflects current research trends, ranging from the use of artificial intelligence and dynamic routing to offloading strategies. This classification aids in mapping the contributions of each approach to system optimization and in identifying areas that require further research, serving as the foundation for the analysis in the State-of-the-Art section.

A. AI-based Scheduling

The literature highlights AI-based scheduling as a central mechanism in IoT-Fog environments, targeting energy efficiency, latency reduction, and resource optimization. Various techniques have been developed, ranging from latency-aware neural networks that balance scheduling efficiency with migration delays [24], to heuristic and metaheuristic methods (e.g., greedy, learning-based, hybrid, and nature-inspired approaches) that address heterogeneity and resource constraints [25]. Advanced approaches such as Deep Q-Learning (DQL) outperform traditional methods for delay-sensitive applications [26]–[28], while reinforcement learning integrated with fuzzy logic achieves notable improvements in latency and energy consumption [29], [30]. Evolutionary and swarm-based methods, including Genetic Algorithms (GA) [31]–[34], Particle Swarm Optimization (PSO), the Jellyfish Algorithm [35]–[37], and Simulated Annealing [38], further optimize task mapping and resource allocation.

Recent studies emphasize multi-objective optimization to ensure service quality across multiple parameters [39]–[42], with specialized solutions such as the Intelligent Salp Swarm for scientific workflows [43] and security-driven FUPE for SDN-IoT-Fog [44]. Hybrid AI that combines machine learning with classical algorithms [45]–[47], as well as resource-aware [48]–[51], security-aware [52]–[54], explainable AI (XAI) [55]–[57], and federated learning [58]–[60], has become increasingly important for scalability and data privacy.

Overall, AI-based scheduling consistently outperforms conventional methods [34], [47], [55], [61] and demonstrates significant progress in healthcare, smart cities, industry, and smart grids [66]–[70]. Nonetheless, challenges remain regarding scalability, computational overhead, and robustness in dynamic environments [62]–[65], and integrating these diverse methods into comprehensive frameworks remains a key research direction [71]–[103].

B. Dynamic Routing

Research on dynamic routing within the IoT-Fog ecosystem has become increasingly crucial for communication efficiency, latency reduction, and reliable data transmission [104]. Solutions such as FOG-RPL integrate energy management and load balancing [104], while DMRVR optimizes logistics routing based on Fog-VANET architectures [105]. Approaches leveraging fuzzy logic, trust management, and cognitive computing enhance routing reliability in dynamic environments [106], [107]. Service prioritization models [108], multiple RPL instances [109], and robust protocols like RSocket [110] have also been proposed. The integration of Software-Defined Networking (SDN) with machine learning supports

adaptive routing [111], while service-aware routing strengthens interoperability across service providers [112]. Advancements in dynamic routing span applications in autonomous vehicles [113], opportunistic and hybrid protocols [114], [115], as well as trust management mechanisms [116], [117]. The application of machine learning in dynamic routing optimizes both Quality of Service (QoS) and security [118]–[122], including improvements in energy efficiency [123]–[126]. Recent trends encompass Industrial IoT-Fog 5.0 [127], [128], big data-driven routing strategies [129], [130], and hybrid heuristic-ML methods [131], [132], although significant challenges related to scalability and security remain.

C. Context-Aware Transmission

Research on context-aware data flow in IoT-Fog systems has rapidly evolved to enhance system intelligence, efficiency, and adaptability [133]–[135]. Context-aware scheduling leverages environmental context, application priorities, and real-time network conditions to reduce latency for delay-sensitive applications [133]–[135]. Meanwhile, context-aware routing utilizes information such as node locations, traffic patterns, and trust levels to improve network stability and energy efficiency [136]–[138], with integration into Software-Defined Networking (SDN) enabling more dynamic communication control [139], [140]. In resource placement, user location context and workload characteristics are key factors in determining application deployment to enhance service performance and conserve bandwidth [141]–[143], aligning with Industry 4.0 demands [144]. Context-aware offloading has also emerged as a solution for deciding where processes should execute—at the edge, fog, or cloud—to achieve energy efficiency and low latency [145]–[147]. Additionally, context-based trust and reputation models support fog network security [148]–[150], including adaptive access control mechanisms [151]–[153]. Context-aware resource discovery facilitates efficient service lookup with low overhead [154]–[156], while machine learning integration enables predictive resource demand forecasting and anomaly detection [157]–[159]. Research has also focused on energy efficiency [160]–[162], big data analytics [163]–[165], and explainable models to improve system transparency [166]–[168]. These trends are expanding into specific applications such as smart transportation, healthcare, and industrial automation [169]–[173], as well as large-scale data processing using context-aware approaches [174]–[196].

D. Offloading Server

The literature on offloading in IoT-Fog systems has been rapidly expanding, driven by the need for real-time services, energy efficiency, and optimal data processing at the edge [197]–[200]. Energy-optimal offloading has gained significant attention, with strategies considering power consumption, latency, and network load to maintain service quality for delay-sensitive applications [197]–[200]. Dynamic collaborative offloading has also been extensively studied, leveraging cooperation among edge and fog nodes to adaptively distribute computational loads based on network conditions [201]–[203]. In the realm of optimization, approaches such as stochastic programming and multi-stage deferred acceptance have produced robust offloading solutions resilient to traffic uncertainties [202], [204]. Hybrid fog-cloud offloading enables the sharing of computational loads between fog and cloud layers, employing machine learning algorithms like Q-learning for autonomous decision-making [205], [206]. Adaptive offloading frameworks, such as FRATO, consider dynamic

parameters like traffic load and resource status to achieve efficient service provisioning [203], [207]. Integrating offloading with dynamic resource allocation has been shown to enhance resource utilization and reduce latency [208], [209]. Systematic reviews have identified significant progress alongside major challenges, including data security, communication overhead, and the limitations of edge resources [210], [211]. Recent research directions include predictive analytics-based approaches [212], [213], energy-efficient strategies [199], [214], and QoS-aware offloading [200], [215], with applications extending to big data analytics [216], [217] and edge intelligence [218]–[220]. Nevertheless, energy sustainability and scalability remain critical ongoing challenges [221], [222].

E. System Implementation (Other)

Research on IoT-Fog systems without adaptive schemes continues to make significant contributions, particularly in areas such as security, resource management, and network architecture. Fog security schemes support fine-grained data protection with energy efficiency benefits [223], while multi-level trust management enhances network reliability [224]. In smart building applications, fog-based systems enable rapid anomaly detection and response [225]. Fog architectures have demonstrated reductions in latency for industrial applications [226], and revocable privacy-preserving schemes facilitate dynamic access control [227]. Other studies have focused on stochastic traffic-based fog node planning [228], optimal deployment via Integer Linear Programming (ILP) [229], engineering fog systems [230], and link-aware energy-efficient mechanisms [231].

F. Comparative Quantitative Analysis of Adaptive Approaches

Table II presents a quantitative performance comparison of the five major adaptive IoT-Fog approaches. AI-based scheduling achieves the lowest latency (5–20 ms) and the highest throughput, yet at the cost of very high energy consumption due to intensive ML/DL processing. Dynamic routing provides balanced performance with medium latency and relatively high throughput, but its efficiency is dependent on the availability of multiple paths, and energy usage grows with the number of hops. Context-aware transmission demonstrates strong energy savings through data filtering, but this comes at the expense of data integrity, leading to higher latency (30–70 ms) and only moderate throughput. Offloading server strategies deliver high throughput and low-to-medium latency by distributing tasks to fog or cloud nodes, though this introduces high energy costs and dependency on infrastructure. Finally, the non-adaptive baseline shows the poorest performance, with latency exceeding 70 ms, low throughput, and only marginal energy efficiency, reflecting the absence of any adaptive optimization.

Overall, the table highlights a clear trade-off: none of the existing approaches can simultaneously guarantee low latency, high throughput, and energy efficiency, underscoring the need for a more topology-agnostic and lossless solution.

G. Topology-Agnostic Framework as Future Research Directions

The review highlights five adaptive IoT-Fog approaches: AI-based scheduling, dynamic routing, context-aware transmission, offloading, and the non-adaptive baseline. Each offers advantages but depends on specific topologies. AI-based scheduling reduces latency but incurs high computational cost;

dynamic routing requires multi-path availability; context-aware transmission saves energy but sacrifices integrity; offloading improves throughput but relies on multi-server setups; and the non-adaptive baseline, while simple, lacks adaptability.

This analysis underscores that the most suitable solution is a topology-agnostic framework. Unlike conventional approaches, it does not rely on network structure but instead adapts data flow frequency dynamically while preserving lossless transmission, maintaining lightweight computation, and ensuring scalability. Thus, topology-agnostic adaptive frequency control emerges as the answer to the limitations inherent in the five conventional approaches.

TABLE II. DISTRIBUTION OF ADAPTIVE APPROACHES IN 208 SCIENTIFIC ARTICLES

Approach	Average Latency (ms)	Throughput (kbps–Mbps)	Energy Consumption (relative)
AI-based Scheduling	5–20 (low)	High (>90% bandwidth utilization)	High (requires ML/DL, heavy computation)
Dynamic Routing	20–50 (medium)	Medium–High (depends on protocol)	Medium (energy varies with hops and route updates)
Context-Aware Transmission	30–70 (medium–high)	Medium (improved efficiency due to data filtering)	Low (saves bandwidth and energy)
Offloading Server	10–40 (low–medium)	High (depends on fog/cloud capacity)	High (edge devices save energy, but server load increases)
Non-adaptive Baseline	>70 (high)	Low (often bottlenecked)	Low–Medium (no optimization)

TABLE III. COMPARISON OF FIVE ADAPTIVE IoT-FOG APPROACHES ACROSS SEVEN PERFORMANCE CRITERIA.

Approach	A	B	C	D	E	F	G
AI-based Scheduling	3	4	2	5	3	2	3
Dynamic Routing	4	4	3	3	4	3	4
Context-Aware Transmission	3	2	4	3	3	5	4
Offloading Server	2	4	3	2	3	2	4
Non-adaptive Baseline	2	3	5	1	2	3	5
Proposed AFC (Topology-Agnostic)	5	5	4	5	5	4	5

A = Topology Compatibility
 B = Data Integrity
 C = Computational Load (low=5)
 D = Frequency Adaptivity
 E = Deployment Scalability
 F = Energy Efficiency
 G = Reproducibility

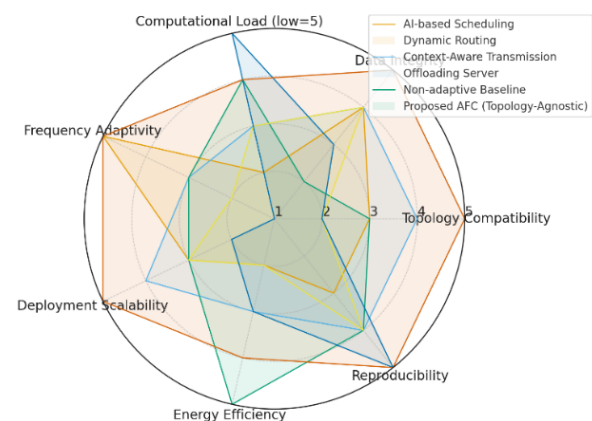


Figure 2. Radar chart of five adaptive IoT-Fog approaches across seven criteria, showing trade-offs and no single optimal solution.

The comparative quantitative analysis (Table III, Figure. 2) demonstrates that the topology-agnostic AFC occupies a dominant position in topology compatibility, data integrity, frequency adaptivity, deployment scalability, and reproducibility (score 5/5), while maintaining low computational load (4/5) through its rule-based logic. Compared with AI-based scheduling, AFC avoids the energy-hungry overhead of ML models (AI: load = 2/5, energy = 2/5) yet still preserves adaptive latency through frequency control. In contrast to context-aware transmission, which is energy-efficient (5/5) but compromises data integrity (2/5), AFC ensures full lossless transmission (5/5). Offloading improves throughput but remains constrained by topology compatibility (2/5) and energy efficiency (2/5). The non-adaptive baseline is easy to replicate (5/5) and imposes minimal computational load (5/5) but completely fails to adapt (1/5). These findings highlight the central trade-offs—ML-heavy versus reproducibility, and filtering-based versus integrity—positioning AFC as a lossless, lightweight, and deployment-friendly solution.

IV. CONCLUSION

The literature review shows that IoT-Fog systems have advanced considerably through AI-based scheduling, dynamic routing, context-aware data flow, and offloading, enabling data processing closer to the edge. While these innovations address latency, energy, security, and resource challenges, the dynamic and heterogeneous topology of IoT-Fog networks remains problematic, as mobility, traffic variation, and service dynamics cannot be managed by static approaches. This highlights the need for adaptive, topology-agnostic systems that autonomously adjust to changing conditions, ensuring service performance, lower latency, and efficient resource use. Such systems are essential for future IoT-Fog architectures, particularly in critical domains such as smart cities, Industry 4.0, and healthcare.

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