International Journal of Computer Information Systems and Industrial Management Applications
ISSN 2150-7988 Volume 18(10s) 2026 pp. 91-101
https://doi.org/10.70917/ijcisim-2026-3569
Article

A SURVEY ON OPTIMIZING DATA AGGREGATION AND SCHEDULING STRATEGIES FOR EFFICIENT MULTI-HOP IOT COMMUNICATION

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Abstract: Internet of Things (IoT) has been raised as a fundamental component of making intelligent infrastructures of the next generation, whereby billions of devices can be interconnected to produce, share and process immense amounts of data. With the current development of the scale and complexity of the IoT networks, the development of efficient data aggregation, scheduling and routing mechanisms is critical to assure the reliability of the communication, low-energy consumption and responsiveness in real-time. The given survey is concerned with aggregation of data and optimization of the timeline of the deployment of multi-hop IoT networks, especially with the goal of enhancing Age of Information (AoI), minimizing consumption of power and ensuring data freshness. Energy efficient and clustering based aggregation strategies, trust based and secure routing mechanism, energy harvesting and resource allocation models, protocol level optimization and link scheduling techniques are all examined. The survey then proceeds to the IoT in the vehicular and industrial environments, where automated processes, operational safety and smart infrastructure require timely and reliable delivery of data. Various types of approaches are examined concerning reduction in latency, prolongation of network lifetime and reliability of its communication. New directions, such as adaptive AI-centered scheduling, cross-layer optimization and edge intelligence have been mentioned as some of the enablers of sustainable and reactive IoT communication. The survey further emphasizes the need to have context-sensitive, scalable and energy efficient architectures that have the potential to satisfy the dynamic requirements of the next-generation 6G-enabled IoT infrastructure and real-time intelligent applications.

Keywords: Age of Information, Edge Computing, Intelligent Systems, Internet of Things, Multi-hop Networks, Real-time Communication, Scheduling Optimization.

1. INTRODUCTION

The Internet of things is a network system that comprising of various sensors, devices and systems that interact with one another in order to gather, manipulate and transmit information. It is capable of monitoring, controlling and automate processes of the distributed environment in real time and has been applied in smart city, healthcare, industrial automation, agriculture and environmental monitoring environments. A hop can be defined in networking terms to mean a single transmission of data packets between two nodes that are not the end node of a communication path. With every hop of a router, gateway or sensor node a packet is forwarded, the packet has made one hop. Hop count is the total number of hops between a source and a destination and it has a direct impact on the latency, energy consumption and reliability of IoT networks. IoT networks can be classified as either single-hop or multi-hop communication. In single-hop communication, sensor nodes send data to a central sink or gateway, but in multi-hop communication, sensor nodes make use of multiple intermediate nodes before sending the data packets to a destination.

Multi-hop communication has a high coverage, more scalable, has less transmission power demands and offers greater reliability to a network, thereby making it appropriate in large-scale and resource-constrained IoT applications [1].

In order to enhance communication efficiency in the multi-hop settings, data aggregation techniques are used to consolidate information of multiple sensor nodes and hence, reduce redundancy, minimize transmission overhead and save energy. Aggregation processes like averaging, suppression, min-max processing and weighted fusion contribute to the increase of network lifetime and preservation of data accuracy [2]. Trust-based routing mechanisms evaluate the reliability of intermediate nodes by computing trust values based on factors such as packet forwarding behavior, residual energy and historical interactions. These trust values are then used to select secure and dependable routing paths, thereby preventing malicious or selfish nodes from participating in multi-hop data transmission and enhancing overall communication reliability [3].

Besides security and energy efficiency, real-time IoT applications require the maintenance of the information freshness. AoI is a timeliness metric that measures the amount of time since the latest update was dispatched at the source [4]. In contrast to existing delay measures, AoI provides a direct measurement of data freshness, which is especially relevant to application types that are time-sensitive, including industrial monitoring, vehicular network and smart grid. Scheduling optimization also adds to these mechanisms in terms of providing intelligent resource utilization strategies, routing paths and transmission time slot allocation to minimize delay, energy consumption and network load balancing [5]. Hence, trust-aware routing, AoI based optimization, data aggregation and adaptive scheduling have to be integrated to ensure a reliable, energy efficient and scalable multi-hop communication in IoT.

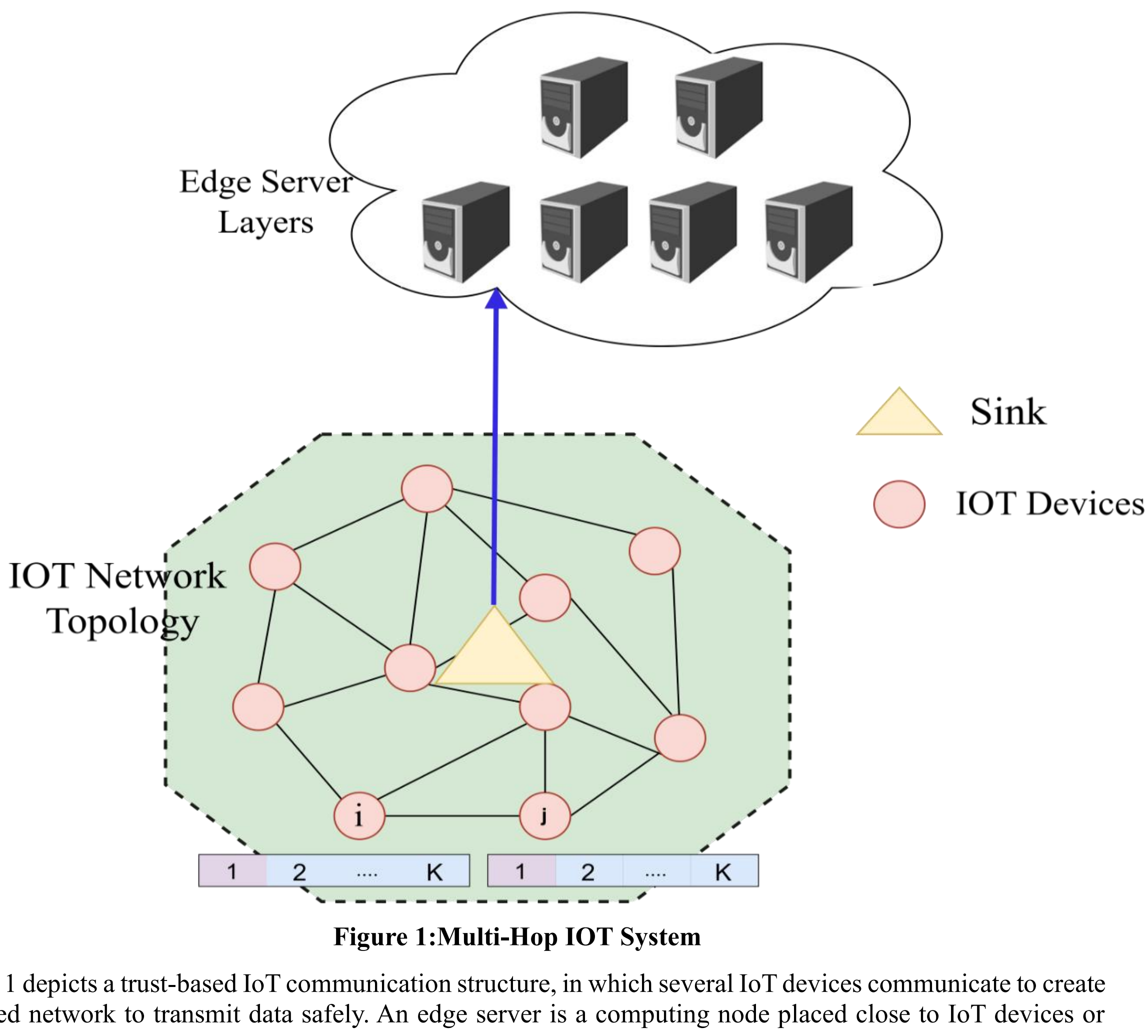

Figure 1:Multi-Hop IOT System

Figure 1 depicts a trust-based IoT communication structure, in which several IoT devices communicate to create a decentralized network to transmit data safely. An edge server is a computing node placed close to IoT devices or users to process data locally instead of sending everything to distant cloud servers. It reduces latency, improves response time, and saves bandwidth by handling time-sensitive tasks near the data source. Every node measures the nodes it is connected with based on trust values to determine a trustworthy intermediate node (highlighted triangle) to transmit data. The chosen trusted node transmits the aggregated data to the cloud infrastructure to be stored and processed upwards. This will enhance safe data transfer, reduce the risks of maliciousness and provide a solid interaction in dynamic Internet of Things.

The rapid expansion of the IoT has resulted in massive volumes of data generated from large-scale sensor deployments, creating the need for efficient data aggregation, scheduling and routing mechanisms to ensure timely and reliable information delivery. Maintaining information freshness quantified as the AoI has become a critical aspect in optimizing real-time IoT communications within multi-hop networks. Various studies have proposed adaptive aggregation and scheduling strategies to minimize AoI in multi-hop IoT systems [6], as well as energy-efficient multi-UAV-assisted aggregation models for latency optimization [7]. Trust-based secure routing approaches have been used to enhance the reliability of multi-hop data aggregation in medical IoT environments [3], while optimal clustering-based aggregation schemes have been designed to improve energy efficiency in wireless sensor networks [9]. Efficient next-hop selection methods further contribute to reliable multi-hop data delivery [10].

Basic works on minimization of AoI in vehicular networks [11] have motivated further models. Multi-hop strategies that are energy efficient have also been proposed to extend the network lifetime that has been demonstrated in medical IoT systems [12] and LoRaWAN-based pipeline supervision [13]. Thread-based mesh networks performance analyses have shown to be scalable in the IoT-based lighting systems [14]. The further methods have maximized the energy allocation in heterogeneous WSNs to the IoT-enabled smart grids [15] and proposed link scheduling to collect data in the multihop backscatter networks [16]. Self-scheduling routing algorithms have been implemented to prolong network lifetime with SDN operation [17] and network reliability has been tested in a large-scale maritime IoT system [18]. Energy-balanced and low-power routing schemes with smarter optimization algorithms have been used to increase the efficiency of multi-hop routing [19], which was supported by energy-efficient LoRa-based multi-hop communication protocols [20]. The adaptability of IoT systems is enhanced through the use of AoI aware models that support efficient and timely data collection under dynamic network conditions [21] with better genetic algorithm to optimize the network functioning schedule [22] and [23] analyzed the role of AoI in improving short-term energy forecasting, highlighting how timely data updates enhance decision-making in IoT-enabled energy systems

Further development in the multi-hop IoT networks has laid more emphasis on safe and trust-conscious communication protocols in order to have credible data aggregation and pathing in the changing network situations. Trust-based routing protocols have been implemented to improve the reliability of communication in other uses like power grid monitoring and industrial IoT whereby safe information transfer and defense against rogue nodes are mandatory [24], [29]. Also, AoI-based transmission models and decisions made by trust enhance data freshness without affecting the trustful multi-hop communication [28]. Intelligent trust-driven optimization is increasingly being used to support routing performance and resilience to internal attacks, further demonstrated by secure trust-aware routing schemes and the ant colony optimization-based schemes, which are becoming part of the future of multi-hop IoT communication systems [30, 31].

Trust mechanisms are required to allow an entity to have a trusted IoT communication. Hasan et al. [25] developed a context-sensitive trust prediction system in order to optimize the routing of opportunistic IoT systems. A social approach offered by Muhammad et al. [26] aims to ensure that devices cooperate to provide improved network performance and security. Trust assessment and management are necessary to have proper and safe IoT networks. Messina et al. [27] applied the trust patterns as means of research simulating multifaceted trustworthiness, which is effective in the decision-making process of the IoT systems. The Alghofaili and Rassam [32] developed a real-time detection of threats of trust in the form of a deep LSTM and performed it in the development of a dynamic model of attack detection. Trust-based optimization reporting was proposed by Khan et al. [33] to prevent black holes attacks in low-power network IoT, whereas Ghaleb and Azzedin [34, 35] offered trust-aware fog computing architecture to enhance the scalability and reasonableness in the context of the IoT. All of these researches point to the significance of integrating trust modeling and detection frameworks to overcome resilient and efficient Internet of Things communication.

Despite these improvements, achieving sustainable, low-latency and context-aware communication within dynamic IoT environments continues to be a complex and evolving research priority. This survey is organized as follows. Chapter 2 reviews data aggregation and scheduling optimization techniques in multi-hop IoT networks. Chapter 3 discusses and analyzes these approaches based on energy efficiency, latency, scalability and AoI. Chapter 4 presents a comparative performance analysis of existing IoT techniques. Outlines of the survey and future research directions are presented in the last chapter.

2. LITERATURE REVIEW

This chapter reviews existing research on IoT data aggregation, scheduling and optimization techniques across diverse network environments. It is organized into six key subsections covering multi-hop aggregation and scheduling optimization, energy-efficient clustering methods, secure and trust-based routing, energy harvesting and resource allocation models, network protocols and performance evaluation and vehicular and industrial IoT applications. Each subsection highlights how different methodologies enhance data freshness, energy efficiency, scalability and reliability in IoT systems, while also identifying existing challenges and research gaps.

2.1 Data Aggregation and Scheduling Optimization in Multi-Hop IoT Networks

Recent research on data aggregation and scheduling optimization in multi-hop IoT networks has focused on improving transmission efficiency, energy conservation and data freshness through adaptive and optimization-based approaches. More recently, Wu, Qu and Khabbaz [6] developed a joint data aggregation and scheduling framework that explicitly optimized information freshness, measured by the AoI, in multi-hop IoT networks. The work balanced aggregation efficiency with scheduling delays to minimize AoI, but challenges remained in handling dynamic traffic, real-world interference and energy constraints. Overall, existing studies demonstrate that while aggregation and scheduling significantly enhance IoT performance, achieving a balance between energy efficiency, delay and freshness in dynamic multi-hop environments remains a key open problem, motivating further optimization and adaptive strategies.

Amodu et al. [21] presented a comprehensive survey on age-aware UAV-assisted data collection in IoT and WSN environments, highlighting UAV trajectory planning, AoI-aware strategies and energy-efficient data collection approaches. The research discusses key performance metrics such as AoI, latency, energy consumption and coverage efficiency, emphasizing the role of AoI in ensuring timely and reliable data delivery. However, the work is primarily theoretical in nature, lacking experimental validation and detailed practical implementation aspects. Shakhov and Sokolova [28] developed data aggregation approach of environmental monitoring systems on the basis of IoT that uses probabilistic clustering as a tool of reducing the quantity of duplicate transmissions and augmenting the network lifetime. Though this approach is immensely efficient in terms of energy consumption and accuracy in aggregation, it makes certain that the case of stationary sensor nodes is taken into consideration but not that of mobility, AOI and real-time planning. To enhance the security and stability of the packet forwarding, Muzammal et al. [29] proposed a trust- and mobility-compatible secure routing protocol of RPL-based IoT networks. Although it was also shown that the improved delivery and strength of the packet had been achieved, the focus of the work is larger on the routing security without referring to data aggregation, energy efficiency or a schedule based on the AoI.

2.2 Energy-Efficient and Clustering-Based Aggregation Techniques

Energy-efficient and clustering-based methods play a vital role in extending the lifetime and sustainability of IoT networks by minimizing power consumption through optimized routing, aggregation and communication strategies. Lu et al. [7] proposed a multi-agent learning-based data aggregation scheduling approach for multi-channel WSNs, improving energy efficiency by optimizing communication and reducing redundant transmissions. Badiger and Ganashree [9] introduced an optimal clustering-based data aggregation scheme that enhances energy efficiency through effective cluster-head selection and data consolidation. Batta et al. [11] presented a distributed multi-hop intra-clustering approach based on two-hop neighborhood connectivity, which reduces transmission distance and improves communication reliability in IoT networks. Wang et al. [18] developed a low-power energy-balanced clustering routing scheme using an improved salp swarm algorithm combined with multi-hop transmission, achieving better load balancing and prolonged network lifetime. In low-power wide-area IoT scenarios, Leenders et al. [19] proposed a LoRa-based energy-efficient multi-hop communication protocol, where relay selection and preamble sampling techniques significantly reduce energy consumption in large-scale deployments. Additionally, these approaches demonstrate that integrating energy-aware clustering, intelligent routing and efficient communication mechanisms can significantly enhance network lifetime, scalability and overall system performance in IoT environments.

2.3 Secure and Trust-Based Routing Approaches in IoT

Recent studies on secure and trust-based routing approaches in IoT have focused on enhancing the reliability, confidentiality and integrity of data transmission in sensitive multi-hop environments such as healthcare and industrial monitoring. To address mobility challenges, the Trust and Mobility-Based Protocol for Secure Routing in IoT, Muzammal et.al [29] introduced mobility-aware trust metrics that adapt to dynamic node behavior and mitigate routing attacks such as blackhole and rank manipulation, though it still faces limitations in energy efficiency and computational overhead in large-scale networks. Similarly, Sharmin et al. [30] designed a secure trust-aware routing protocol based on ant colony optimization, where computed trust values guide path selection to improve packet delivery and resilience against internal attacks; however, the complexity of Ant Colony Optimization (ACO) limits its practicality for resource-constrained IoT devices. Overall, these trust-oriented approaches demonstrate that embedding trust computation and secure validation mechanisms into routing and aggregation processes significantly enhances reliability and protection against malicious behavior. Nevertheless, these methods often overlook joint optimization with data freshness, scheduling and aggregation, leaving open challenges in achieving balanced trade-offs between security, energy efficiency and timely data delivery in large-scale multi-hop IoT networks.

2.4 Energy Harvesting and Resource Allocation Models

Extending existing research on energy harvesting and resource allocation, Bankov et al. [15] addressed energy-efficient resource allocation in wireless energy-harvesting sensor networks by jointly optimizing transmission power and time scheduling to maximize network energy efficiency. This approach demonstrated significant improvements in the utilization of harvested energy and communication reliability. However, the model assumed idealized energy harvesting conditions and did not account for stochastic fluctuations in energy availability, limiting its applicability in dynamic IoT environments. Similarly, Wang et al. [18] focused on sensor placement and resource allocation by jointly optimizing power, bandwidth and sensor deployment for energy-harvesting IoT networks to minimize estimation error. While this enhanced network performance, the approach assumed stable energy harvesting and overlooked long-term battery degradation and real-time scheduling requirements. In summary, these studies highlight that energy harvesting and resource allocation are critical for sustaining IoT communications, yet existing models often rely on simplified energy dynamics and fail to integrate multi-hop scheduling, stochastic energy behavior and adaptive decision-making. Consequently, achieving truly sustainable and autonomous IoT operations remains a significant challenge, motivating further research into integrated energy-aware scheduling and adaptive resource allocation strategies that can dynamically respond to variable network conditions and energy constraints.

2.5 Network Protocols, Link Scheduling and Performance Evaluation

Recent advancements in network protocols, link scheduling and performance evaluation have focused on enhancing the efficiency, reliability and scalability of IoT communication systems under diverse network conditions. Liu et al. [14] proposed a link status based multipath scheduling scheme that improves bandwidth utilization and throughput by adaptively distributing traffic across multiple potential next hop routes, though it increases computational complexity and requires accurate link status information. In emerging domains, Gu et al. [17] examined maritime IoT performance optimization, addressing connectivity disruptions and link variability in oceanic communication systems through adaptive protocol design and scheduling models, though the research faced constraints in large scale validation and energy modeling.

In related researches have utilized genetic algorithm based link scheduling to optimize transmission slot allocation and minimize latency in dense IoT networks, achieving improved resource utilization but often at the cost of increased computational complexity Hong et al. [31]. Additionally, Ghantasala et al. [24] integrated data compression and aggregation techniques into scheduling frameworks to reduce bandwidth usage and delay but tend to overlook the tradeoffs between compression efficiency and processing overhead. Altogether, these studies underscore that while protocol level and scheduling improvements substantially enhance IoT performance, most existing methods still struggle to jointly optimize throughput, delay, energy consumption and adaptability, particularly in heterogeneous and large-scale multi-hop IoT networks, where dynamic link conditions and real-time responsiveness remain critical challenges.

2.6 Vehicular and Industrial IoT Applications

Recent research on vehicular and industrial IoT applications has emphasized integrating data aggregation and timeliness-aware communication strategies to enhance real-time responsiveness, reliability and efficiency in dynamic environments such as smart grids, autonomous systems and vehicular networks. Shakhov and Sokolova [28] proposed a data aggregation framework for industrial IoT monitoring systems, where probabilistic clustering and predictive status updates help reduce information staleness under short-packet transmissions, though the approach assumes relatively stable traffic patterns. In vehicular and autonomous systems, in smart grid IoT networks, Elmonser et al. [22] investigated dynamic multi-hop communication strategies to improve energy distribution efficiency, though performance degradation was observed under heavy congestion. Overall, despite notable advancements, existing approaches remain constrained by static assumptions, limited scalability and insufficient cross domain adaptability, highlighting the need for unified, context-aware aggregation frameworks that jointly address timeliness, energy efficiency and communication reliability across heterogeneous IoT ecosystems.

Accurate node localization is critical for efficient multi-hop IoT networks. Wang et al. [36] proposed a multi objective DV-Hop algorithm based on NSGA-II, improving localization accuracy and network performance in IoT environments. Wang et al. [37] proposed the use of a localization algorithm based on multi-hop with path tortuosity correction and hierarchical extension of the anchor to increase the localization accuracy of wireless sensor networks. Rehman et al. [38] proposed an LSTM-optimized DV-Hop localization framework to improve node positioning accuracy by mitigating multi-hop localization errors in wireless sensor networks.

3. Comparative Analysis and Critical Insights

This section discusses recent advancements in IoT data aggregation, focusing on methods that enhance data freshness, energy efficiency, security and scalability. It examines six key areas AoI optimization, energy efficient clustering, trust-based routing, energy harvesting, optimization algorithms and protocol design to highlight how each contributes to improving network performance. Together, these approaches provide a comprehensive understanding of how intelligent optimization ensures reliable and sustainable IoT communication.

3.1 Age of Information Based Optimization Methods

AoI-based optimization methods aim to improve data freshness and timeliness in IoT environments, which is critical for real-time decision-making and control. Wu et al. [6] proposed a data aggregation and scheduling framework that jointly optimizes transmission delay and information freshness in multi-hop IoT networks by prioritizing packets based on the generation time and importance, thereby significantly reducing end-to-end latency while maintaining balanced energy consumption across nodes. Energy-efficient scheduling strategies that indirectly support data freshness improvement were explored by Lu et al. [7], who designed adaptive transmission policies for multi-UAV-enabled IoT systems to improve energy utilization while sustaining timely data collection. Recent advancements have extended AoI-aware aggregation to industrial IoT environments, where Shakhov and Sokolova [28] demonstrated that adaptive data transmission combined with probabilistic clustering significantly improves information timeliness and energy efficiency in dynamic monitoring systems. Overall, these studies confirm that AoI-centric optimization goes beyond existing delay minimization by directly managing the age of information, thereby enabling greater efficiency, reliability and real-time responsiveness in diverse IoT applications.

Haseeb et al. [39] is a variety of energy-aware multi-hop routing algorithm of the IoT-based WSNs, where the information is divided into several shares and sent using various routes to increase security. Decision on routing is done based on residual energy, hop count and distance that enhance network lifetime and trustworthy data delivery. The approach was compared in terms of energy consumption, packet delivery ratio, end-to-end delay and network lifetime but it comes with increased computational and routing overheads. Kamal and Tariq [40] introduced a lightweight security and data provenance scheme for multi-hop IoT communication using hash chains and lightweight authentication. The method ensures data integrity and source verification at a low computational and communication cost. Performance was assessed in terms of energy consumption, latency and overhead, while a limitation of the scheme is its weaker confidentiality compared to encryption-heavy methods.

3.2 Energy-Efficient and Clustering-Based Methods

Energy-efficient and clustering-based methods play a vital role in extending the lifetime and sustainability of IoT networks by minimizing power consumption through optimized routing, data aggregation and communication strategies. Lu et al. [7] proposed an energy-aware data aggregation and scheduling model that balances transmission load among sensor nodes using intelligent coordination mechanisms, thereby reducing redundant transmissions and conserving node energy. Badiger and Ganashree [9] introduced an optimal clustering-based data aggregation scheme that enhances energy efficiency through effective cluster-head selection and intra-cluster communication management. Batta et al. [11] presented a distributed multi-hop intra-clustering approach based on two-hop neighborhood connectivity, which reduces transmission distance and packet loss, resulting in improved network lifetime.

To address energy imbalance in heterogeneous IoT environments, Elmonser et al. [23] proposed a dynamic multi-hop communication framework for IoT-enabled smart grids, enabling efficient energy distribution across sensor nodes. Wang et al. [18] developed a low-power, energy-balanced clustering routing scheme based on an improved Salp Swarm Algorithm (SSA) combined with multi-hop transmission, achieving enhanced load balancing and prolonged network lifetime. In low-power wide-area IoT scenarios, Leenders et al. [19] emphasized LoRa-based energy-efficient multi-hop communication, where relay selection and preamble sampling significantly reduce battery depletion in large-scale deployments. Furthermore, Ghantasala et al. [24] proposed a hybrid data aggregation algorithm integrating clustering and adaptive routing to minimize energy consumption further and improve communication reliability in wireless sensor networks.

Overall, these researches demonstrate that integrating clustering techniques with optimization-driven routing and multi-hop communication mechanisms effectively minimizes energy consumption, balances load among sensor nodes and extends network lifetime, making these approaches essential for sustainable and scalable IoT systems.

3.3 Trust and Security-Based Routing Methods

Trust and security-based routing methods in IoT networks aim to ensure reliable data aggregation and secure communication by integrating trust evaluation, authentication and intrusion detection into routing decisions. These methods address a major challenge in IoT systems—the vulnerability of resource-constrained nodes to malicious attacks, false data injection and selfish behavior during data transmission. Sunithanandhini et al. [8] proposed a trust-based secure routing approach for multi-hop medical IoT networks, where node trustworthiness is evaluated using behavioral metrics to isolate malicious nodes while maintaining aggregation efficiency. Similarly, Muzammal et al. [29] introduced a trust and mobility-aware secure routing protocol for RPL-based IoT networks, enhancing routing reliability under dynamic conditions. Sharmin et al. [30] developed a secure trust-aware ACO-based routing scheme that improves packet delivery and resilience against internal attacks. Together, these trust-oriented approaches demonstrate that embedding trust computation and secure validation mechanisms into routing decisions significantly enhances communication reliability and protection against internal and external threats in multi-hop IoT networks.

3.4 Energy Harvesting and Resource Allocation Methods

Energy harvesting and resource allocation methods focus on prolonging network lifetime and optimizing energy utilization in IoT systems by enabling sensor nodes to harvest, store and intelligently manage energy from ambient sources. These techniques address the inherent limitation of finite battery capacity in conventional IoT devices by incorporating sustainable power management and adaptive scheduling mechanisms. Bankov et al. [15] proposed an energy-efficient resource allocation framework for energy harvesting–enabled IoT devices by jointly optimizing transmission power and time scheduling, significantly improving energy utilization and communication reliability. Further advancements were presented by Elmonser et al. [22], who introduced a dynamic multi-hop energy distribution and resource allocation strategy for heterogeneous IoT-enabled smart grid networks, balancing energy consumption and communication performance under varying network conditions. Overall, these studies demonstrate that integrating energy harvesting with intelligent resource allocation strategies enables sustainable, self-powered IoT networks, enhancing performance, reliability and longevity, particularly in large-scale deployments where battery replacement is impractical.

3.5 Scheduling and Optimization Algorithm–Based Methods

Scheduling and optimization algorithm–based methods form a crucial foundation for enhancing efficiency, scalability and responsiveness in IoT data aggregation systems. These methods use metaheuristic, stochastic and evolutionary optimization techniques to intelligently coordinate data transmission, optimize energy consumption and ensure timely data delivery across heterogeneous sensor networks. Unlike existing fixed scheduling or static routing schemes, optimization-driven approaches can dynamically adapt to varying traffic loads, node failures and changing channel conditions.

Recently, Hong et al. [31] proposed an enhanced swarm intelligence–based optimization algorithm for link scheduling in wireless sensor networks, where transmission schedules are dynamically optimized to reduce interference and delay while improving throughput and energy efficiency. The results demonstrated that intelligent optimization significantly outperforms static scheduling approaches in dense multi-hop IoT deployments. Similarly, Leenders et al. [19] applied optimization principles in multi-hop LoRa-based IoT networks, where relay selection and transmission timing are adaptively optimized to reduce power consumption and improve scalability.

Furthermore, Ghantasala et al. [24] introduced an optimization-driven routing and aggregation framework that jointly considers clustering and data forwarding to enhance network lifetime and reliability. Overall, these researches demonstrates that optimization-based scheduling enables IoT networks to self-adapt to resource constraints and environmental dynamics, thereby achieving improved energy efficiency, lower latency and higher reliability in large-scale industrial, vehicular and smart city IoT applications.

3.6 Protocol Design and Network Performance Evaluation Methods

Protocol design and network performance evaluation methods focus on developing robust, adaptive and energy-efficient communication architectures to improve scalability and reliability in IoT systems. Multi-hop and mesh-based IoT networking approaches have been widely studied to address challenges such as dynamic topology changes, congestion and routing efficiency. For instance, Gu et al. [17] evaluated a multi-hop IoT network deployed on large ships, highlighting the impact of link variability and connectivity disruptions in maritime environments while emphasizing the need for adaptive scheduling and protocol optimization. Cooperative self-scheduling and SDN-enabled routing mechanisms were shown to significantly enhance routing efficiency, reduce latency and improve network lifetime, as demonstrated by Dhandapani et al. [16]. In addition, hybrid and hierarchical data aggregation strategies have been proposed to minimize packet redundancy, reduce congestion and improve energy efficiency in large-scale IoT and WSN environments (Wu et al. [6], Badiger &Ganashree [9]). Overall, these researches confirm that integrating intelligent protocol design with rigorous network performance evaluation is essential for achieving scalable, reliable and high-performance IoT communication frameworks suitable for heterogeneous and large-scale deployments.

4. COMPARISON OF RESULTS

This section presents a comparative analysis of six advanced IoT data aggregation techniques evaluated based on key performance indicators such as network lifetime, energy consumption, average delay, throughput and AoI. The main objective is to examine how various methods, including adaptive multi-hop scheduling, clustering-based aggregation, UAV-assisted collection and hybrid energy-efficient routing enhance system performance. Through this comparison, the research highlights the effectiveness of intelligent aggregation and routing strategies in improving energy efficiency, data timeliness and overall network reliability in IoT environments.

Author(s) Details	Method / Technique	Network Lifetime ↑	Energy Consumption ↓	Average Delay ↓	Throughput ↑	AoI (Freshness) ↓
Wu et al., [6]	Adaptive multi-hop scheduling	+22%	–18%	–15%	+12%	–20%
Amodu et al., [21]	Energy-efficient UAV-assisted data aggregation	+25%	–25%	–12%	+15%	–10%
Badiger &Ganashree, [9]	Optimal clustering-based aggregation	+28%	–30%	–10%	+9%	–14%
Elmonser et al., [22]	Dynamic multi-hop routing for smart grids	+19%	–23%	–8%	+11%	–7%
Wang et al., [18]	Improved SSA-based clustering	+33%	–33%	–18%	+14%	–12%
Ghantasala et al., [24]	Hybrid energy-efficient aggregation with routing	+26%	–28%	–10%	+10%	–9%

Table: 1 Comparative analysis

The above comparative performance analysis of six state-of-the-art IoT data aggregation techniques reveals distinct advancements in enhancing energy efficiency, network lifetime and data freshness across multi-hop and clustered communication frameworks. The percentage values are reported based on the performance improvements claimed in the respective research. Wang et al. [18] achieved the most substantial improvement, recording a 33% increase in network lifetime and a 33% reduction in energy consumption through an Improved SSA-based clustering scheme. The approach also reduced delay by 18%, improved throughput by 14% and decreased AoI by 12%, demonstrating effective overall performance optimization. Similarly, Wu et al. [6] proposed an adaptive multi-hop scheduling mechanism aimed at optimizing information freshness in real-time IoT networks. This approach resulted in a 20% reduction in AoI, a 15% decrease in delay and a 12% increase in throughput, demonstrating strong applicability in time-sensitive monitoring systems. Amodu et al. [21] adopted an energy-efficient UAV-assisted aggregation strategy, which enhanced data collection coverage and reduced overall power consumption by 25%, contributing to a 25% gain in network lifetime and 15% improvement in throughput.

Further, Badiger and Ganashree [9] utilized an optimal clustering-based data aggregation technique that emphasized load distribution and intra-cluster communication efficiency. The model delivered a 28% enhancement in network lifetime and a 30% reduction in energy consumption, confirming the robustness of clustering mechanisms for large-scale sensor deployments. Elmonser et al. [22] designed a dynamic multi-hop routing protocol for IoT-enabled smart grids, focusing on adaptive path selection and balanced energy utilization, achieving 23% lower energy consumption and 11% higher throughput. Lastly, Ghantasala et al. [24] introduced a hybrid energy-efficient aggregation algorithm integrating clustering with adaptive routing to improve communication reliability, achieving a 26% increase in network lifetime and a 9% reduction in AoI. Overall, these results underscore that hybrid clustering and adaptive multi-hop scheduling approaches offer the most effective trade-offs between energy conservation and information timeliness.

5. CONCLUSION

The comprehensive review of multi-hop IoT data aggregation frameworks highlights significant advancements in energy efficiency, scalability and information freshness, achieved through adaptive scheduling, clustering and optimization-based routing techniques. Integration of AoI based scheduling with energy-aware clustering effectively reduces latency, while intelligent optimization algorithms such as SSA, PSO and GA help balance energy consumption and extend network lifetime. UAV-assisted data aggregation and hybrid routing further improve throughput and minimize redundancy, supporting large-scale deployments in industrial, vehicular and smart-grid IoT applications. Despite these achievements, challenges remain in real-time adaptability under dynamic energy conditions, heterogeneous network configurations and ensuring scalability and interoperability. Trust-based security and energy harvesting mechanisms enhance reliability, yet further work is needed to address these challenges comprehensively. The survey highlights the growing need for context-sensitive, scalable and energy-efficient architectures capable of addressing the dynamic requirements of next-generation 6G-enabled IoT systems. Future research may focus on developing intelligent and adaptive frameworks that integrate AoI-aware scheduling, trust-based security, energy harvesting and cross-layer optimization. Additionally, incorporating edge intelligence and AI-driven decision-making mechanisms can further enhance real-time responsiveness, reliability and sustainability in large-scale multi-hop IoT environments.

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