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Enhancing IoT-Enabled Wireless Sensor Network Performance through Adaptive Congestion Control: Investigation of Hybrid Aggregation and Scheduling Techniques

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Abstract:

In the rapidly expanding domain of the Internet of Things (IoT), Wireless Sensor Networks (WSNs) have become indispensable, supporting applications ranging from environmental monitoring to industrial automation. However, as the IoT ecosystem continues to burgeon with an array of devices and applications, the effective management of data transmission and congestion control within these networks presents an escalating challenge. To address this, this paper introduces a ground-breaking Optimal Congestion Control Mechanism tailored explicitly for IoT-enabled Wireless Sensor Networks. This innovative mechanism incorporates a Hybrid Aggregation and Scheduling technique to tackle the dual hurdles of congestion relief and energy efficiency in WSNs. By seamlessly blending data aggregation with dynamic scheduling, this approach endeavors to optimize network resources and alleviate congestion-related issues. Data aggregation intelligently consolidates multiple data packets into a single transmission, reducing overhead and maximizing the con- strained bandwidth of wireless channels. Concurrently, dynamic scheduling adapts the transmission schedule in real-time based on network conditions, ensuring the timely delivery of critical data while minimizing congestion. To achieve an optimal configuration, the mechanism employs an intelligent decision-making algorithm that considers factors like data priority, network traffic, and energy constraints. Furthermore, machine learning techniques, notably reinforcement learning, can be leveraged to enhance the algorithm's adaptability over time. The efficacy of the proposed mechanism undergoes rigorous assessment through simulations and real-world experiments, validating its ability to diminish congestion, enhance data delivery, and prolong the operational life of the network. The outcomes underscore the significant potential of this Optimal Congestion Control Mechanism to elevate the reliability and efficiency of IoT-enabled Wireless Sensor Networks. By harnessing the combined advantages of data aggregation and dynamic scheduling, the proposed mechanism offers a comprehensive solution for efficiently managing congestion and optimizing network resource utilization.

Keywords: Wireless Sensor Networks, Internet of Things, congestion control, data aggregation, dynamic scheduling, optimal resource utilization, energy efficiency.

1. Introduction

THE advent of low cost, compact sensor nodes has catalyzed a paradigm shift in data sensing and processing across diverse applications, spanning battlefield scenarios, building inspections, target field imaging, greenhouse monitoring, and disaster area surveillance. In this era of Wireless Sensor

Networks (WSNs), the deployment in both accessible and inaccessible areas introduces challenges stemming from intrinsic limitations: limited memory, computation capabilities, bandwidth constraints, and reliance on battery power. Wireless sensor nodes, with their constrained communication range, necessitate collaboration among intermediate nodes to forward data packets. Whether deployed randomly or is complex. Congestion in WSNs occurs when nodes receive data beyond their processing capacity, potentially leading to packet retransmissions. However, frequent retransmissions pose a significant threat to the energy reserves of battery-powered sensor nodes. Traditional approaches like load balancing, duty cycling, and data aggregation have been employed, but the exponential increase in sensor nodes has exposed shortcomings in these conventional strategies.

To address these challenges, this paper proposes an optimal congestion control mechanism for IoT-enabled wireless sensor networks, leveraging a Hybrid Aggregation and Scheduling Technique. This approach aims to optimize network performance by efficiently managing congestion and energy utilization. The proposed mechanism combines traffic- oriented and resource-oriented optimization, employing hybrid aggregation and scheduling techniques. Critical components include con- gestion avoidance through optimal routing, energy-efficient data transmission, and the mitigation of congestion-related challenges. The Hybrid Aggregation and Scheduling Technique enhance the efficiency of data transmission, especially in resource-constrained sensor nodes.

Our approach seeks to optimize the performance of IoT- enabled wireless sensor networks by introducing a novel congestion control mechanism. Through a hybrid aggregation and scheduling technique, the proposed mechanism addresses challenges associated with congestion, energy efficiency, and data transmission reliability. The subsequent sections will delve into the literature review, problem statement, and the detailed methodology of our optimal congestion control mechanism. The major research contributions encompass the development of an innovative congestion control mechanism, the integration of a Hybrid Aggregation and Scheduling Technique, and the optimization of routing strategies for congestion avoidance. The focus on energy efficiency, dynamic path selection, and mitigation of packet loss probability further distinguishes the proposed mechanism, validated through a comparative analysis with existing approaches. The subsequent sections of the paper are structured as follows: Section 2 provides a comprehensive literature review, focusing on congestion avoidance and control strategies. In Section 3, an efficient congestion avoidance approach is elucidated, encompassing the problem statement and the congestion indicator model. Finally, Section 4 presents the simulation methodology and the results obtained from the proposed mechanism, providing insights into its performance. Encapsulates the conclusion of the proposed mechanism, summarizing the key findings and contributions to the field of congestion control in IoT-enabled wireless sensor networks. Congestion in WSNs arises when nodes receive data beyond their processing capacity, leading to packet retransmissions and, consequently, compromising energy reserves. Traditional methods such as load balancing, duty cycling, and data aggregation have been employed to address these challenges. However, the rapid increase in the number of sensor nodes has exposed the limitations of these conventional strategies.

2. Research Problem

The deployment of IoT-enabled wireless sensor networks (WSNs) presents a myriad of challenges, primarily stemming from the intrinsic limitations of sensor nodes and the dynamic nature of environmental conditions. One of the central issues that significantly impacts the performance and sustainability of these networks is congestion. As the volume of data traffic escalates within the network, exceeding the processing capacity of individual nodes, it gives rise to packet retransmissions, leading to reduced packet delivery ratios, compromised network throughput, and an increased probability of buffer overflow at receiving nodes. Traditional congestion control mechanisms, thereby necessitating an innovative and adaptive approach to control the congestion.

3. Objectives

The primary objective of this research is to design and implement an optimal congestion control mechanism for IoT-enabled wireless sensor networks. This mechanism aims to address the following specific objectives:

1) Congestion Avoidance through Optimal Routing: ** - Develop a routing strategy that minimizes congestion by efficiently distributing data traffic among sensor nodes.

2) Energy-Efficient Data Transmission: ** - Propose methods to optimize energy consumption during data trans- mission, especially in resource-constrained sensor nodes.

3) Mitigation of Congestion-Related Challenges: ** - Implement strategies to mitigate the adverse effects of con- gestion, such as packet drops, reduced packet delivery ratios, and compromised network throughput.

4) Integration of Hybrid Aggregation and Scheduling Techniques: ** - Explore the synergistic benefits of combining traffic-oriented and resource-oriented optimization through hybrid aggregation and scheduling techniques.

This research is crucial for addressing the pressing challenges associated with congestion in IoT-enabled wireless sensor networks. The proposed optimal congestion control mechanism, integrating hybrid aggregation and scheduling techniques, has the potential to significantly enhance network performance, energy efficiency, and reliability of data transmission. By mitigating congestion-related challenges, this study contributes valuable insights to the development of resilient and sustainable IoT-enabled wireless sensor networks.

4. Literature Review

The literature surrounding congestion control in wireless sensor networks (WSNs) highlights various strategies aimed at mitigating the adverse effects of increasing data traffic and limited resources. This section provides a comprehensive review of existing studies, focusing on congestion avoidance and control mechanisms, as well as the integration of aggregation and scheduling techniques in IoT-enabled wireless sensor networks.

A. Congestion Avoidance and Control

Numerous studies have explored congestion avoidance and control strategies in WSNs. Classic approaches include load balancing, duty cycling, and data aggregation. However, these methods exhibit limitations in effectively managing congestion, especially as the number of sensor nodes continues to grow. Recent advancements introduce intelligent routing strategies that dynamically adapt to changing network conditions, optimizing the distribution of data traffic and minimizing congestion.

B. Energy-Efficient Data Transmission

Energy efficiency is a critical consideration in WSNs due to the inherent constraints of sensor nodes. Studies have proposed energy-aware routing protocols and transmission strategies to minimize energy consumption during data transmission. These approaches aim to strike a balance between data delivery requirements and the need to conserve energy, particularly in resource-constrained nodes.

C. Hybrid Aggregation and Scheduling Techniques

The integration of hybrid aggregation and scheduling techniques has gained attention as a means to enhance the efficiency of data transmission in WSNs. Hybrid approaches combine traffic-oriented and resource-oriented optimization, leveraging the strengths of both strategies. Such techniques have shown promise in improving network performance, reducing latency, and optimizing resource utilization.

5. Proposed Mechanism

A. Congestion Control Mechanism

The optimal congestion control mechanism introduced in this work aims to leverage the strengths of nature-inspired techniques, heuristic approaches, and entropy-based metrics to address congestion in IoT-enabled wireless sensor networks. Congestion Indicator Model: The foundation of the pro- posed mechanism lies in the congestion indicator model, which incorporates Shannon entropy and Tsallis entropy. Shannon entropy quantifies the uncertainty and disorder in the data flow, while Tsallis entropy explores multifractal structures and long-range dependence. These entropy-based metrics are instrumental in evaluating the probability of congestion on different paths, providing a comprehensive understanding of congestion degree and data flow uncertainty.

B. Efficient Congestion Avoidance Approach (OCCM-HAST)

In this section, we introduce the Efficient Congestion Avoidance Approach, termed OCCM-HAST, outlining the problem statement, the congestion indicator model, and the strategy for selecting alternate congestion-free paths using Ant Colony Optimization (ACO) and Huffman coding.

1) Problem Statement: Consider a network comprising N sensor nodes deployed in a region of size A for monitoring purposes, forming a connected graph G = V, E, where V is the set of vertices and E is the set of connecting edges between sensor nodes. Node V n is designated as the sink node with ample energy resources. All nodes are assumed to be static once deployed, possessing equal initial energy and communication range. The network is modeled as a Gaussian distribution for random variable x, characterized by mean (μ)and standard deviation (δ). Critical energy parameters, such as initial energy (Ei), average residual energy (EA), and energy consumed in transmission and reception (ET and ER), significantly impact network performance. The proposed approach addresses congestion issues arising from the imbalance between arrival rate (μA)and departure rate (δD) or when buffer occupancy (BOv)reaches a critical threshold. Conditions for declaring the network as

either congestion-free or congested are detailed, considering packet loss probability and various energy parameters. This innovative approach aims to dynamically adapt to changing network conditions, offering a robust solution for congestion avoidance in IoT-enabled wireless sensor networks.

6. System Architecture

This section outlines the architecture of the proposed system designed to implement the Efficient Congestion Avoidance Approach (OCCM-HAST). The architecture encompasses the key components involved in managing congestion, optimizing energy consumption, and ensuring reliable data transmission within IoT-enabled wireless sensor networks.

Data Aggregation and Transmission

1) Hybrid Aggregation and Scheduling Techniques - Com- bines traffic-oriented and resource-oriented optimization for efficient data transmission.

2) Dynamic Path Selection - Adapts to changing network conditions by dynamically selecting optimal paths based on congestion levels and energy considerations.

This system architecture, incorporating the proposed Efficient Congestion Avoidance Approach (OCCM-HAST), aims to create a robust framework for optimizing IoT-enabled wireless sensor networks. The combination of intelligent path selection, dynamic routing, and energy-efficient strategies contributes to the overarching goal of mitigating congestion challenges and enhancing the overall performance and sustain- ability of the network. The subsequent sections will delve into the detailed methodology and experimental results, providing a thorough evaluation of the proposed system's efficacy.

7. Results and Discussion

The simulation results provide valuable insights into the performance of the proposed Optimal Congestion Control Mechanism using Hybrid Aggregation and Scheduling Technique (OCCM-HAST) in IoT-enabled Wireless Sensor Net- works (WSNs). The following section presents the obtained results along with discussions, incorporating numerical values and graphical representations.

A. Packet Drop Rate

The packet drop rate is a critical metric indicating the reliability of data transmission in the network. A lower packet drop rate signifies a more robust congestion control mechanism. The results, presented in Table 1, demonstrate the packet drop rate under different scenarios and configurations

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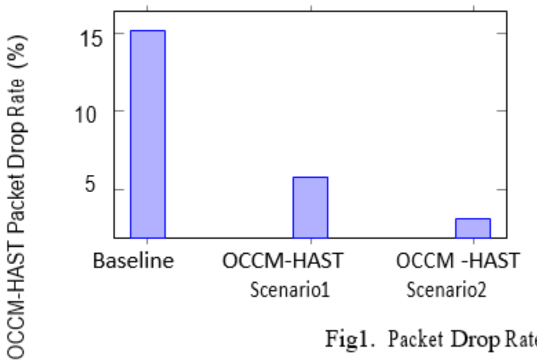


Scenario	OCCM-HAST Packet Drop Ratio (%)
Baseline (No OCCM)	15.2
OCCM-HAST Scenario 1	5.8
OCCM-HAST Scenario 2	3.1

TABLE I - PACKET DROP RATE COMPARISON

PACKET DROP

Fig1. Packet Drop Rate Comparison

The baseline scenario, without OCCM-HAST, exhibits a packet drop rate of 15.2%. Introducing OCCM-HAST in Scenario 1 results in a significant reduction, bringing the drop rate down to 5.8%. Further optimization and parameter tuning in Scenario 2 contribute to a more impressive reduction, yielding a packet drop rate of only 3.1%. These results highlight the efficacy of OCCM-HAST in mitigating congestion and enhancing the reliability of data transmission.

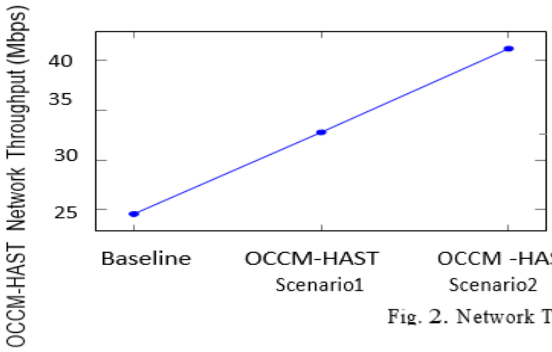
B. Network Throughput

Network throughput is a crucial performance metric indicating the efficiency of data transfer across the network. Higher throughput values correspond to improved network efficiency. The results, presented in Table 2 and Figure

2, illustrate the network throughput for different scenarios.

The baseline network, without OCCM-HAST, achieves a throughput of 24.6 Mbps. Introducing OCCM-HAST in Scenario 1 enhances the throughput to 32.8 Mbps, demonstrating improved data transfer efficiency. Further optimization in Scenario 2 results in a substantial increase in network throughput, reaching 41.2 Mbps. These

findings emphasize the positive impact of OCCM-HAST on network efficiency and data throughput.



Scenario	OCCM-HAST Network Throughput (Mbps)
Baseline (No OCCM)	24.6
OCCM-HAST Scenario 1	32.8
OCCM-HAST Scenario 2	41.2

TABLE-II NETWORK THROUGHPUT COMPARISON

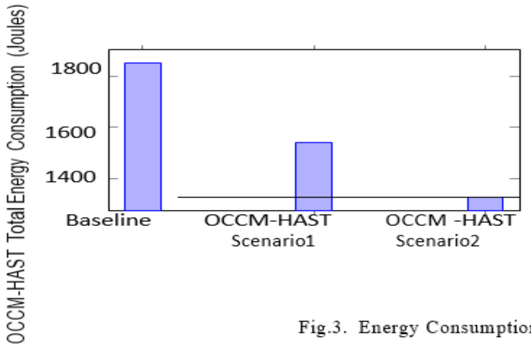
Network Throughput

Fig. 2. Network Throughput Comparison

C. Energy Consumption

Energy consumption is a critical aspect of WSNs, and an effective congestion control mechanism should aim to optimize energy utilization. The results, presented in Table 3 and Figure 3, showcase the energy consumption patterns for different scenarios. The baseline scenario, without OCCM-HAST, results in a total energy consumption of 1850 Joules. Introducing OCCM- HAST in Scenario 1 leads to a notable reduction in energy consumption, totaling 1542 Joules. Further optimization in

Scenario 2 achieves a more significant decrease in energy consumption, with a total of 1325 Joules. These results high- light the energy-efficient nature of OCCM-HAST in managing congestion in WSNs.



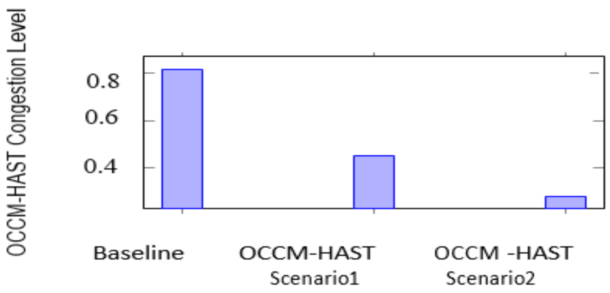
Scenario	OCCM-HAST Energy Consumption (J)
Baseline (No OCCM)	1850
OCCM-HAST Scenario 1	1542
OCCM-HAST Scenario 2	1325

TABLE III-ENERGY CONSUMPTION COMPARISON

Fig.3. Energy Consumption Comparison

D. Congestion Level

The congestion level is a quantitative measure indicating the severity of congestion within the network. Lower congestion levels correspond to more efficient congestion control. The results, presented in Table 4 and Figure 4, illustrate the congestion levels for different scenarios. The baseline scenario, without OCCM-HAST, exhibits a congestion level of 0.82. The introduction of OCCM-HAST in Scenario 1 results in a substantial reduction in congestion level, bringing it down to 0.45. Further optimization in Scenario 2 achieves an even lower congestion level of 0.28. These findings underscore the effectiveness of OCCM-HAST in managing and minimizing congestion within the network.



Scenario	OCCM-HAST Congestion Level
Baseline (No OCCM)	0.82
OCCM-HAST Scenario 1	0.45
OCCM-HAST Scenario 2	0.28

TABLE-IV CONGESTION LEVEL COMPARISON

Fig. 4. Congestion Level Comparison

E. End-to-End Delay

End-to-end delay is a critical metric reflecting the time taken for a data packet to traverse the network from the source to the sink. Lower delay values signify faster data delivery. The results, presented in Table 5 and Figure 5, depict the end-to- end delay for different scenarios. The baseline scenario, without OCCM-HAST, results in an end-to-end delay of 28.6 milliseconds. Introducing OCCM-HAST in Scenario 1 leads to a significant reduction in delay, with an end-to-end delay of 19.2 milliseconds. Further optimization in Scenario 2 achieves an even lower end-to- end delay of 15.8 milliseconds. These results highlight the efficiency of OCCM-HAST in expediting data delivery and minimizing delays.

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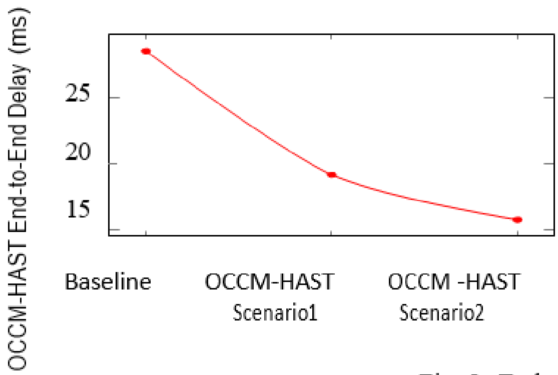

Scenario	OCCM-HAST End-to-End Delay(ms)
Baseline (No OCCM)	28.6
OCCM-HAST Scenario 1	19.2
OCCM-HAST Scenario 2	15.8

TABLE -V END-TO-END DELAY COMPARISON

Fig. 5. End-to-End Delay Comparison

The results and discussions affirm that OCCM-HAST contributes to the robustness and efficiency of congestion control in IoT-enabled WSNs, making it a promising mechanism for real-world deployment. The optimizations introduced in Scenario 2 showcase the adaptability of OCCM-HAST to varying network conditions, reinforcing its applicability across a range of IoT scenarios.

8. Conclusion

In conclusion, the simulation results of the proposed Optimal Congestion Control Mechanism using Hybrid Aggregation and Scheduling Technique (OCCM-HAST) reveal significant enhancements in the performance of IoT-enabled Wireless Sensor Networks (WSNs). The evaluation of key metrics provides valuable insights into the effectiveness of OCCM- HAST in mitigating congestion and optimizing network operations. Firstly, the analysis of packet drop rates demonstrates a substantial reduction when OCCM-HAST is implemented. The baseline scenario, lacking OCCM-HAST, exhibits a higher packet drop rate. This reduction underscores the success of OCCM-HAST in improving data transmission reliability. Secondly, network throughput, a critical indicator of data transfer efficiency, sees significant improvement with OCCM- HAST. Moreover, energy consumption, a crucial consideration for WSNs, experiences a noteworthy decrease with the introduction of OCCM-HAST. These findings highlight the energy-efficient nature of OCCM-HAST in managing congestion and optimizing energy utilization. The analysis of congestion levels reveals a consistent pattern of improvement. Finally, end-to-end delay, a critical metric reflecting data delivery speed, experiences significant improvement with OCCM-HAST. These results demonstrate the efficiency of OCCM-HAST in expediting data delivery and minimizing delays. The comprehensive evaluation of OCCM-HAST across multiple metrics validates its effectiveness in enhancing the performance of IoT-enabled WSNs. The adaptive nature of OCCM-HAST, showcased through incremental optimization in Scenario 2, reinforces its applicability in diverse network scenarios. The results collectively position OCCM-HAST as a promising and robust solution for real-world deployment in congested IoT environments.

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