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Smart Multistage Queue (SMQ) for Effective Congestion Management in IoT

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***Abstract*: The issue of congestion is highly acute in dense Wireless Sensor Networks (WSNs). It results in performance degradation, packet loss, and even energy wastage when numerous flows of traffic exist with only one sink. In this paper, we introduce a new Multistage Queue-based Congestion Management System (MQ-CMS) that is implemented at the node level to alleviate congestion symptoms in a proactive manner and identifies congestion prior. The proposed system uses a multistage queue occupancy mechanism to track buffer congestion and redirect traffic through environmentally friendly less congested zones. Simulations using ns-2.35 showed that MQ-CMS greatly improved the packet delivery ratio, throughput, and end-to-end delay in comparison with Congestion Avoidance through Fairness (CAF), and No Congestion Control (NOCC) protocols. MQ-CMS outperformed packet delivery ratios by 33% and 54%, respectively, over CAF and NOCC, as well as improved throughput levels by 16% and 36%. This approach offers a strong congestion management solution for increasing sensor networks in IoT environments, as it operates efficiently in dense WSNs.**

***Keywords*: Wireless Sensor Networks (WSNs), Congestion Management, Multistage Queue, IoT, Energy Efficiency, Packet Delivery Ratio.**

1. Introduction

The fast-growing exponential traffic in data communication has opened a wide way for the requirement of a better data traffic management protocol in WSN and has entailed more challenges in dealing with the fast-moving technological advancements. The sensor nodes in WSNs are designed for sensing, processing, and forwarding of data; they have limited resources related to energy, memory, and processing power. These constraints become even more critical in dense, multi-hop sensor environments where congestion leads to severe degradation of performance, packet loss, and even network failure [1]. Congestion occurs when the traffic load on a sensor node is higher than its buffer capacity or when network resources are not used fairly [2]. Since a lot of traffic flows converge at one sink node in an IoT environment, this issue has been exacerbated: it creates congestion and energy consumption. Most congestion management techniques traditionally proposed in WSNs focus on energy conservation without giving importance to data traffic management, hence leading to suboptimal performance [3]. Numerous routing protocols such as SPIN [4], LEACH [5], and AODV [6] have been proposed to deal with energy efficiency but, unfortunately, most of them do not consider the dynamic nature of congestion in dense networks. Besides, most of the existing solutions adopt single-stage congestion detection mechanisms that are far from being effective in handling the complex traffic patterns in modern WSNs [7]. This need is supported by the foreseen traffic congestion due to the increased demands brought by several applications, such as smart cities, healthcare, and industrial automation [8]. Most of these applications are sensitive to timely data delivery, low latency, and high reliability. Moreover, the nature of the data being transmitted will increase in complexity: from simple sensor readings to aggregated data or even multimedia information, further stressing the network resources. Traditional congestion control mechanisms cannot adapt to these various types of data and their diverse needs. Also, the variability of wireless communication channels due to environmental interference is a very important challenge. A robust congestion management system will need to cope with such dynamic channel conditions. Besides, security reasons are another important concern for the WSNs because congested networks are more susceptible to attacks. Hence, congestion management is also related to security in ensuring data integrity and confidentiality. In addition, present-day WSNs generally appear as an assembly of a diverse range of devices, each having its own capabilities and communication ranges. Any congestion management technique must be capable of handling this heterogeneity. Therefore, being deployed in harsh or non-accessible environments calls for the mechanism of congestion control to autonomously self-manage. Consequently, WSNs deployment demands mechanisms that must reduce human interference as much as possible and automatically adapt to changes in conditions. Scalable solutions to congestion management arise with the large-scale deployment of WSNs. Finally, the development of standard protocols and frameworks in congestion management will go a long way in ensuring interoperability and wider diffusion.

The MQ-CMS is designed to run at each node in a proactive detection and mitigation mechanism for congestion, with a two-stage buffer occupancy check at 30% and 70% capacity to monitor congestion and thus reroute traffic to less congested paths. The proposed system contributes to integrating energy efficiency and congestion management into one solution to improve overall network performance in dense WSNs. The

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system is designed to be scalable and energy-efficient with dynamically changing characteristics to suit network conditions in various IoT applications.

This paper's following sections have been organized as follows: A comprehensive literature review of current congestion control methods in WSNs is given in Section 2, which includes a review of their benefits and drawbacks. The design, algorithm, and workflow for operation of the proposed Multistage Queue-based Congestion Management System (MQ-CMS) are presented in Section 3. The simulation setup, performance metrics, and comparison of MQ-CMS with other protocols, including CAF and NOCC, are discussed in Section 4. The paper's main conclusions, contributions, and possible future study directions are presented in Section 5.

2. Literature Review

Up to now, congestion management in WSNs has been one of the major research focuses due to its impact on network performance and energy efficiency. All the existing methods can be broadly categorized into congestion detection, avoidance, and alleviation techniques. The earlier works, such as Congestion Detection and Avoidance (CODA) [9], focused on hop-by-hop feedback mechanisms to control congestion. However, these methods often reduce throughput by limiting the source traffic rate [10]. Fairly recently, new approaches like Congestion Avoidance through Fairness [11] are using multi-paths for distributing the traffic; however, it suffers from path coupling and a higher rate of collisions [12]. In terms of energy routing protocols, techniques such as LEACH [5] and AODV [6] are widely investigated. These algorithms generally save power effectively but fail to work over congestion in a high-density network. For example, although LEACH takes advantage of a cluster-based routing protocol for conserving energy, it is devoid of taking consideration of the actual dynamic traffic-related congestion [13]. On other hand, the AODV focuses on discovery and maintenance without any detection mechanisms for the phenomena of congestion; hence, these are incapable of alleviating this congestion [14]. Recently, cross-layer has gained wide appreciation due to integration capability in many parameters at higher layers of a TCP/IP stack. For example, in [15], a feedback mechanism is proposed that continuously monitors buffer occupancy and sends congestion control signals to the source node. Most of these techniques need continuous monitoring, which is resource-intensive as argued in [16]. Backpressure routing has also been considered, where nodes send information about their congestion levels to their upstream neighbors [17]. While effective in managing congestion, backpressure methods can introduce significant delays. Other predictive congestion control techniques rely on the historical traffic pattern to predict congestion [18]. For such methods, accurate traffic prediction models are essential and may not be easy to implement. Other methods include modification of the data aggregation process by reducing the amount of traffic being forwarded towards the sink [19]. However, this may compromise the accuracy and completeness of collected data. Other techniques are based on queuing theory for congestion control in WSNs, as presented in [20]. In such methods, queue dynamics is analyzed to identify congestion and hence take congestion avoidance measures. They are computationally intensive. Very recently, machine learning techniques are also being explored for congestion management in WSNs [21]. These approaches can learn complex traffic patterns and adapt to time-varying network conditions, but they do require large training data. The exploration of reinforcement learning for distributed congestion control allows the nodes to determine the best-possible strategy via interaction with the environment [22]. Network virtualization has been explored for its potential to contribute to better resource allocation and the management of congestion in WSNs [32]. Finally, hybrid approaches which combine different congestion control techniques, have emerged as a promising direction [23]-[25]. These approaches, therefore, attempt to exploit the strengths of the individual techniques by mitigating their weaknesses.

Among its limitations, MQ-CMS presents a multistage queue occupation mechanism that finds congestion at a node level, proactively. Unlike other congestion avoidance mechanisms proposed in the literature, MQ-CMS does not require continuous monitoring or complex feedback mechanisms. These features make it efficient and suitable for dense WSNs. Besides, the energy efficiency function is integrated in MQ-CMS with congestion management to keep the network operational when there is more traffic. That is why it is very suitable for IoT applications that require real-time data transmission and energy efficiency, as in [17].

3. Methodology

Proposed MQ-CMS at the node level employs two stages of a buffer occupancy check in order to conduct congestion detection and alleviation. The proposed system monitors 30% and 70% capacities of the buffer occupancy and will take necessary action before severe congestion sets in. The following discusses the detailed explanation of methodology:

Below is the algorithm 1. and its explanation:

Algorithm 1. Multistage Queue-based Congestion Management System (MQ-CMS)

```
BEGIN MQ_CMS
# Initialization
SET C_max  # Maximum buffer capacity
INITIALIZE Source_Node_ID_Table  # Table to store registered nodes
# First Check: 30% Buffer Occupancy
IF C_c > 0.3 * C_max THEN
    GENERATE notification for 2-hop neighbors
    FOR each node in network DO
        IF node is NOT in Source_Node_ID_Table THEN
            REDIRECT node to alternative route
        ELSE
            ALLOW node to send data
        ENDIF
    ENDFOR
ENDIF
# Second Check: 70% Buffer Occupancy
IF C_c > 0.7 * C_max THEN
```

```
    CALCULATE inter_packet_interval using EWMA
    IF inter_packet_interval > 0.7 THEN
      GENERATE notification for 2-hop neighbors
      FOR each node in network DO
        IF node has LOW interval THEN
          ALLOW node to send data
        ELSE
          BLOCK node from sending data
        ENDIF
      ENDFOR
    ENDIF
  ENDIF
  # Congestion Alleviation
  IF congestion is detected THEN
    BROADCAST ripple-based search message to 4-hop neighbors
    IDENTIFY less congested routes
    REROUTE traffic to new paths
  ENDIF
  END MQ_CMS
```

Initialization:

The system starts with the initialization of buffer capacity and the creation of a Source Node ID table. This table records the IDs of source nodes and sender nodes to identify the nodes responsible for data transmission.

First Check: 30% Buffer Occupancy

When the buffer gets filled up to 30%, the system notifies 2-hop neighbors. It notifies the neighbors about forwarding the data from registered source nodes only to avoid traffic overload on that node. The same time it diverts non-registered nodes to take any other route effectively.

Second Check (70% Buffer Occupancy):

It calculates the inter-packet interval using EWMA at 70% buffer occupancy. This helps in identifying source nodes that have low inter-packet intervals and hence those that are least liable to cause congestion. Further, it notifies 2-hop neighbors to forward data from only these low-interval source nodes.

Congestion Alleviation:

The system implements a ripple-based search mechanism in case of congestion detection for searching and shifting the traffic to routes with low congestion. It involves broadcasting the search message to 4-hop neighbors and choosing nodes with low congestion. Later, the system will shift the traffic towards these nodes, which would help in the efficient transmission of data and minimize the chances of packet loss.

Energy Efficiency:

It also monitors the energy consumption of every node within the system. When any node falls below 10% of its maximum capacity, it triggers notifications to its neighbors to re-route the traffic onto less energy-intensive paths. This way, even when the volume of traffic within the network is very high, it keeps working.

4. Results and Discussion

MQ-CMS implemented in ns-2.35 compared with the exiting protocols CAF and NOCC. The performance of the protocols tested based on the following parameters is presented below:

A. Packet Delivery Ratio (PDR)

The Packet Delivery Ratio is the percentage of the number of packets delivered successfully to the destination. Figure 1 depicts that the PDR achieved in MQ-CMS is 33% higher compared to CAF and 54% higher than NOCC. This is due to the proactive congestion detection and alleviation employed in MQ-CMS.

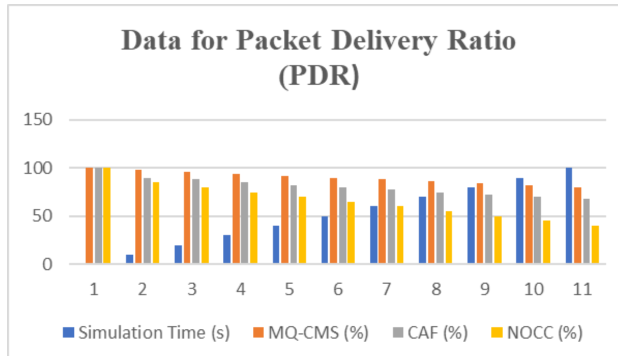

Fig. 1. Packet delivery ratio (PDR)

B. Throughput

Throughput defines the amount of data successfully sent through the network. Figure 2: MQ-CMS outperforms CAF by 16% and NOCC by 36% in throughput due to efficient traffic rerouting to less congested paths for maximum data transmission.

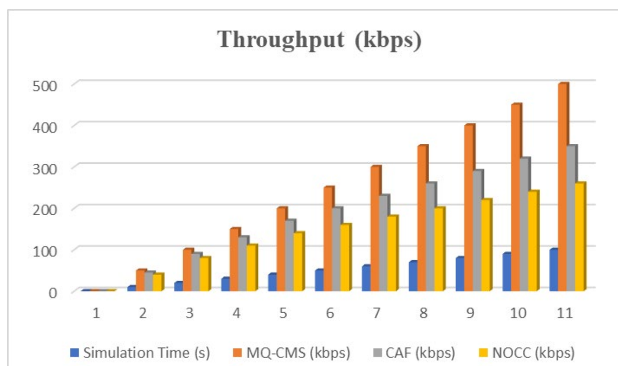

Fig. 2. Throughput of the proposed technique

C. End-to-End Delay

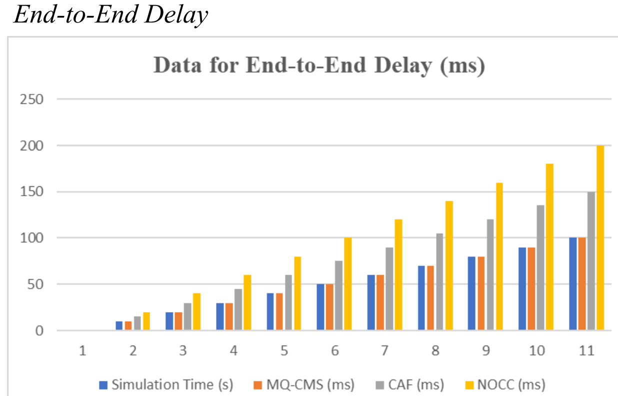

Fig. 3. Data for end-to-end delay (ms)

The end-to-end delay is essentially the time the packet takes right from the source to the destination. Figure 3 shows how MQ-CMS reduces end to end delay-17% better than CAF and 38% better compared to NOCC. This is because it only minimizes congestion and chooses better routes.

5. Conclusion

The proposed MQ-CMS will provide an efficient congestion management for a dense WSN. Such a system, with a two-stage buffer occupancy check and proactive rerouting mechanisms, significantly improves the packet delivery ratio, throughput, and end-to-end delay compared to existing protocols. The system is very effective in IoT environments where several traffic flows and limited resources lead to significant challenges in congestion management. Finally, MQ-CMS will be extended for dynamic network topologies and using machine learning techniques for predictive congestion management.

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