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**CHAPTER 7****CONCLUSION AND FUTURE WORK****7.1 CONCLUSION**

Wireless Sensor Networks (WSNs) handle various types of data packets in real-time (RT) applications. Due to bandwidth constraints in WSNs, prioritizing certain real-time data over others is crucial to prevent network overload with data of similar importance. Several methods have been developed in recent decades to regulate congestion based on the priority of RT packet flow. Congestion can occur when RT packets are mixed with Non-RT (NRT) packets; hence both types must be managed effectively. The Difference of Differential Rate Control (DDRC) algorithm was developed as a solution, and it takes as input the differential rate fluctuation between the sink node and the specified node. This algorithm was implemented to determine the rate of given node using global priority while considering differentials in traffic volume between the sink and the node in question. The Weighted Priority Differential Rate Control (WPDDRC) algorithm was developed to enable differential rate control for each node based on the relative importance of each traffic class. Here, the relative importance of different traffic classes was rebalanced by assigning higher priority to real-time data across the entire network. This careful balancing of traffic classes ensured practical connectivity among various nodes. However, this method has led to high packet loss and delays attributed to increased queue lengths. Therefore, this research has developed different control algorithms to overcome congestion and other related problems in Wireless Sensor Networks (WSNs).

In addressing congestion and buffer overflow in Wireless Sensor Networks (WSNs), the first stage of this work proposed WPDDRC with an adaptive queuing system known as the PRC algorithm. In the PRC technique, packets from all child nodes were aggregated in descending order of relevance and priority, and two distinct virtual queues were considered within a single physical queue. Congestion was monitored by assessing the state of these virtual queues, ensuring that incoming packets were acknowledged. When congestion was detected, the transmission rate of each virtual queue in the child nodes was adjusted dynamically to expedite packet delivery. This approach allowed for prioritization based on the relative importance of different traffic types and the current

queue conditions, effectively reducing packet loss and delays associated with buffer overflow in WSNs.

In the next stage of the study, the PRC-FBA method was developed by integrating concepts of prioritized traffic types and equitable bandwidth distribution. Initially, the Signal-to-Interference-plus-Noise Ratio (SINR) model was employed to address bandwidth distribution issues in WSNs, aiming to balance node and network efficiency. Subsequently, a novel bandwidth utility factor was introduced to optimize efficiency and fairness. This involved a combined computation of node connections and time slot allocations, formulated as a nonlinear programming challenge with a dual-part formulation. The approach adopted a 2-stage process: the primary phase focused on computing node relationships, while the secondary phase involved allocating time slots to maximize utility. As a result, WSNs were able to enhance their efficiency and achieve more equitable distribution of bandwidth.

In this third phase of the study, the PRCDA-FBA approach was introduced, leveraging robust data aggregation mechanisms to maximize equitable energy usage across all participating nodes. By employing adaptive network coding and data aggregation techniques, the approach effectively reduced network latency and energy consumption while enhancing overall throughput. Specifically, Random Linear Network Coding (RLNC) was employed for network coding, where each node's typical data packet transmission rate in a single communication cycle was defined by its transmission frequency. The strategy advocated that sensor nodes transmit only one packet per transmission round. Prior to transmitting data to the next hop, network coding paths were combined to optimize channel utilization and minimize packet redundancy. An adaptive approach was activated during congestion, integrating network coding with node data transmission to reduce packet drop rates. Additionally, a machine learning method was utilized to accurately forecast bandwidth consumption, aiding in preventing packet transmissions along paths where capacity was already in use. This approach aimed to minimize the need for retransmissions.

In the fourth stage of research, EPRCDA-FBA is introduced to mitigate the effects of spatial and temporal variability in energy resources through cooperative transmission power regulation and network-wide route adjustments. The primary objective is to

enhance Quality of Service (QoS) for delay-constrained data delivery while reducing energy consumption in nodes with limited energy resources, thereby extending the network's lifespan. This algorithm employs a priority-based rate control method that considers the remaining power at each node. Initially, a prediction model is used to estimate potential power savings by reducing each node's broadcasts without significantly compromising packet delivery ratios. Subsequently, nodes prioritized for transmitting traffic classes of packets based on their energy availability to prevent energy-critical nodes from becoming overwhelmed. However, a key challenge of this method lies in integrating excess power considerations into the rate control strategy effectively. This ensures that nodes operate efficiently while maintaining optimal QoS and extending network longevity under variable energy conditions.

Finally, the developed congestion control methods for Wireless Sensor Networks (WSNs) were constructed and tested using a simulator. These methods include PRC, PRC-FBA, PRCDA-FBA, and EPRCDA-FBA. Based on experimental evidence, it is evident that the proposed EPRCDA-FBA congestion management algorithm outperformed previous methods such as PRC, PRC-FBA, and PRCDA-FBA. Performance metrics such as throughput, packet loss, end-to-end (E2E) delay, queue size, and source data transfer rate adjustment were used to evaluate service quality. EPRCDA-FBA demonstrated superior performance across these metrics, highlighting its effectiveness in improving network efficiency, reducing congestion, and enhancing overall quality of service in WSNs compared to existing methodologies.

The performance advantages of EPRCDA-FBA over other methods are highlighted by several key metrics in a simulation lasting 120 seconds. EPRCDA-FBA achieves a throughput that is 10.15% higher than PRCDA-FBA, 8.11% higher than PRC-FBA, and 4.2% higher than PRC methods. EPRCDA-FBA reduces packet loss by 17.3% compared to PRCDA-FBA, 10.5% compared to PRC-FBA, and 3.5% compared to PRC methods. EPRCDA-FBA exhibits a 9.5% shorter E2E latency than PRCDA-FBA, 7.5% lower than PRC-FBA, and 5% lower than PRC techniques overall. EPRCDA-FBA decreases the average queue size by 34.4% compared to PRCDA-FBA, 26% compared to PRC-FBA, and 15.4% compared to PRC methods. These improvements demonstrate that raising the minimum queue length can potentially further decrease packet loss and E2E latency.

Additionally, EPRCDA-FBA achieves a data rate 10.2% higher than PRCDA-FBA, 8% higher than PRC-FBA, and 4% higher than PRC methods. Overall, EPRCDA-FBA shows superior performance across multiple critical metrics, indicating its effectiveness in enhancing network throughput, reducing packet loss, minimizing latency, managing queue sizes, and maximizing data transfer rates in WSNs compared to alternative approaches.

In conclusion, the EPRCDA-FBA demonstrates superior efficiency compared to classical algorithms, as evidenced by simulation results. This developed approach not only offers a proficient solution to mitigate limitations in Wireless Sensor Networks (WSNs), but also ensures Quality of Service (QoS) requirements. By effectively modulating congestion control, EPRCDA-FBA facilitates timely data delivery, reduces energy consumption in critical nodes, and extends the overall network lifespan. The implementation of EPRCDA-FBA represents a significant advancement in optimizing WSN performance, addressing key challenges such as throughput enhancement, packet loss reduction, latency minimization, and efficient management of network resources. This contributes to more reliable and sustainable operation of WSNs in various applications, enhancing their effectiveness in real-world scenarios.

## **7.2 FUTURE WORK**

In future investigations, the impact of limited node mobility on throughput will be studied, focusing on how mobility affects data transmission rates. Additionally, future research will explore the effects of different traffic patterns on queue size, aiming to optimize queue management strategies under varying traffic conditions. Further studies will also concentrate on examining the influence of mobile sink nodes, the number of child nodes, and parent nodes on throughput, and exploring modified queue management strategies. Instead of a single tree topology, future work may consider implementing a number of clusters with cluster heads, which could potentially enhance network efficiency and scalability. These proposed enhancements will be validated through real-time testing to assess their practical applicability and performance in diverse operational scenarios.