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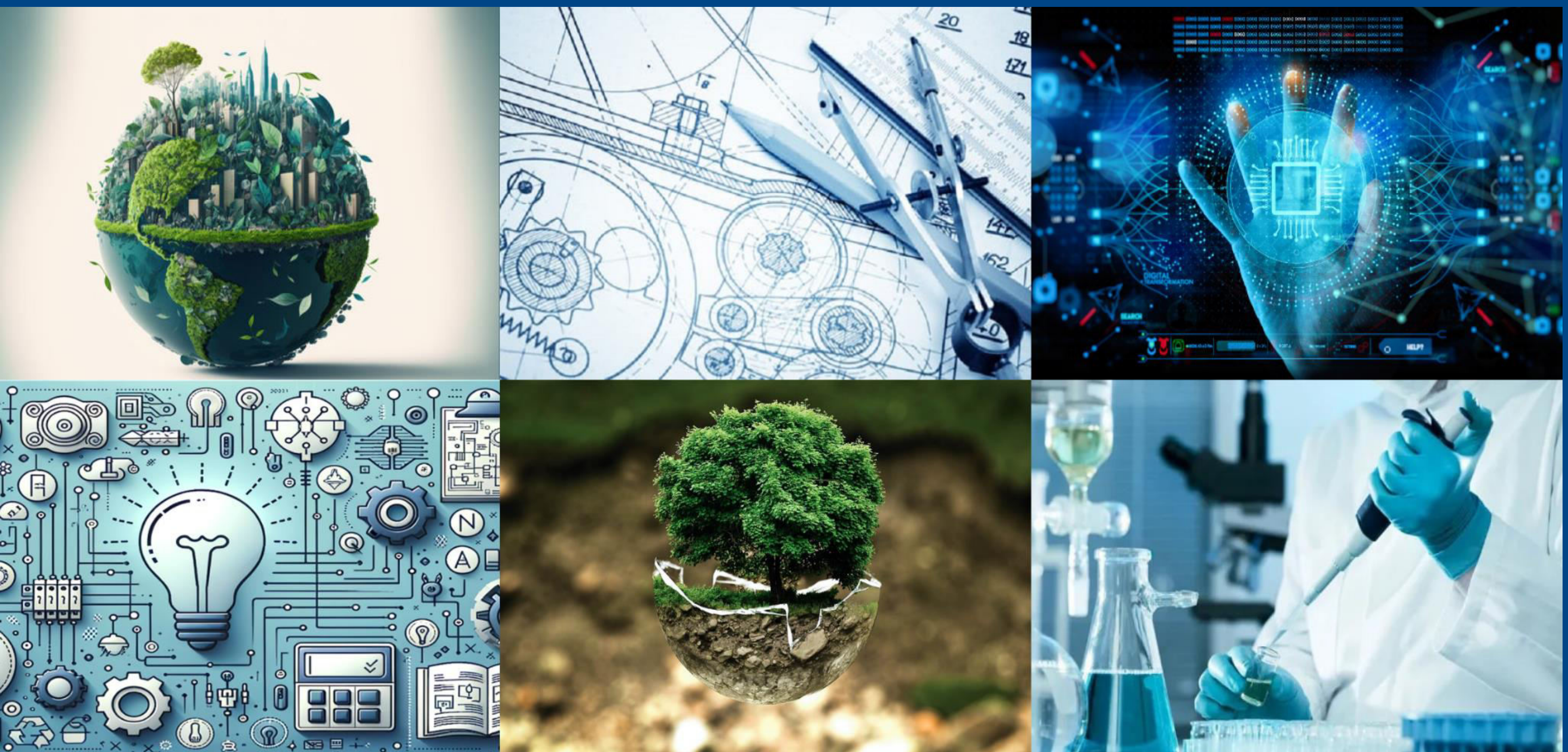

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# Water Wave Optimization Algorithm for Achieving Efficient Congestion Management and QoS Enhancement in Wireless Sensor Networks

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**ABSTRACT:** Wireless Sensor Networks (WSNs) face significant challenges related to congestion, energy constraints, and Quality of Service (QoS) degradation. Traditional congestion control mechanisms struggle to optimize performance without sacrificing network lifetime. This paper presents a novel congestion control strategy based on the Water Wave Optimization (WWO) algorithm, aimed at enhancing QoS parameters such as network throughput, residual energy, and packet loss rate. An objective function considering these critical parameters is formulated, and WWO is utilized to optimize data transmission routes dynamically. Extensive simulations show that the proposed WWO-based congestion control scheme outperforms existing methods, including Congestion Detection and Avoidance (CODA) and Particle Swarm Optimization (PSO), providing a substantial improvement in overall network performance and energy conservation.

**KEYWORDS:** Wireless Sensor Networks, Congestion Control, Quality of Service, Water Wave Optimization, Energy Efficiency, Packet Loss.

## I. INTRODUCTION

Wireless Sensor Networks (WSNs) have fundamentally transformed the landscape of data acquisition and monitoring across a wide array of domains, including but not limited to environmental surveillance, military operations, industrial automation, and smart city infrastructure development. A typical WSN is composed of a large number of spatially distributed, low-power sensor nodes endowed with capabilities for sensing, data processing, and wireless communication. These nodes collaboratively gather information about environmental conditions such as temperature, humidity, pressure, motion, or pollutants and transmit the collected data to a centralized sink or base station for further analysis and decision-making.

Despite their numerous advantages, WSNs are inherently constrained by several critical limitations. The sensor nodes generally operate on limited battery power, possess minimal computational resources, and have restricted communication bandwidth. These resource constraints impose significant challenges in maintaining network efficiency, reliability, and longevity. One of the most pressing issues affecting WSN performance is network congestion. Congestion in WSNs arises when the volume of data traffic exceeds the network's capacity to handle it, leading to buffer overflows, packet loss, increased end-to-end latency, and excessive energy consumption due to retransmissions. If left unaddressed, congestion can drastically degrade the Quality of Service (QoS) and shorten the operational lifetime of the network.

Traditional congestion control protocols, such as hop-by-hop flow control and end-to-end feedback mechanisms, have been proposed to mitigate these issues. However, many of these solutions fail to efficiently balance multiple conflicting objectives — such as maximizing network throughput, minimizing energy consumption, and reducing communication delays — especially under dynamic and unpredictable network conditions. Moreover, static or semi-dynamic approaches often lack the adaptability needed to respond effectively to sudden changes in network topology or traffic patterns.

In recent years, the research community has increasingly turned toward nature-inspired metaheuristic algorithms for solving complex optimization problems in WSNs. Algorithms such as Particle Swarm Optimization (PSO), Ant Colony

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Optimization (ACO), and Genetic Algorithms (GA) have demonstrated significant potential in areas such as routing, clustering, and energy management. However, these algorithms often suffer from certain drawbacks, including premature convergence to local optima, slow adaptation to dynamic environments, and suboptimal global search performance.

To address these challenges, this paper introduces a novel congestion control strategy based on the Water Wave Optimization (WWO) algorithm. WWO is a relatively recent metaheuristic inspired by the propagation, refraction, and breaking behaviours of natural water waves. It offers a unique mechanism for balancing exploration (global search) and exploitation (local search), making it highly suitable for highly dynamic and complex optimization landscapes such as those encountered in WSN routing and congestion management. By dynamically adapting routing paths and optimizing node scheduling decisions, the proposed WWO-based approach aims to mitigate congestion, minimize packet loss, reduce energy consumption, and ultimately enhance key QoS parameters such as throughput, delay, and network lifetime.

Through extensive simulation studies, the effectiveness of the proposed methodology is evaluated against conventional algorithms. The results demonstrate notable improvements in terms of congestion mitigation, energy efficiency, and QoS assurance, thereby highlighting the viability of WWO as a robust optimization framework for next-generation WSNs.

## II. RELATED WORK

**Various congestion control strategies have been proposed for WSNs:**

Congestion control in Wireless Sensor Networks (WSNs) is a critical aspect of ensuring reliable communication, energy efficiency, and overall network performance. A variety of congestion detection and avoidance strategies have been proposed in the literature, each addressing different aspects of congestion in sensor networks. These strategies range from traditional control mechanisms to advanced optimization algorithms inspired by nature.

**CODA (Congestion Detection and Avoidance)**

One of the earliest and most widely cited congestion control schemes for WSNs is CODA (Wan et al., 2003). CODA was one of the first algorithms to introduce event-driven congestion detection and avoidance mechanisms. It uses congestion notification in a hop-by-hop manner and incorporates an open-loop backpressure technique to mitigate congestion. The idea is to detect congestion at each sensor node and propagate the information upstream to the source node, which can then take corrective actions. CODA was designed to minimize packet loss by adjusting the transmission rate based on the network's congestion status. While this approach worked effectively in low-density networks, it struggled to scale efficiently in highly dynamic environments with fluctuating traffic patterns.

**Fusion: A Hybrid Congestion Control Approach**

Another early congestion control strategy, Fusion (Hull et al., 2002), combined multiple mechanisms, such as hop-by-hop flow control, source rate limiting, and prioritized Medium Access Control (MAC) protocols. Fusion aimed to address congestion by controlling data transmission at the source, regulating the flow of packets through the network, and prioritizing critical traffic. The combination of these techniques helped improve throughput while mitigating congestion. However, Fusion's reliance on static thresholds and centralized decision-making led to challenges in networks with high mobility or variable traffic loads, limiting its applicability in dynamic WSN scenarios.

**PSO-Based Routing**

In more recent years, Particle Swarm Optimization (PSO) has been employed to address routing challenges in WSNs. Rizvi et al. (2015) proposed a PSO-based approach for congestion control that seeks to find optimal routing paths by minimizing both energy consumption and end-to-end delay. The PSO algorithm, inspired by the social behaviour of birds flocking and fish schooling, is particularly well-suited for finding global optima in complex search spaces. However, while PSO has demonstrated improvements in routing efficiency over traditional methods, it suffers from the issue of premature convergence. This leads to suboptimal solutions, particularly in networks with complex topologies and high dynamics, where the algorithm may get stuck in local optima, limiting its ability to adapt to changing network conditions.

**ACO-Based Routing**

Similarly, Ant Colony Optimization (ACO) has been applied to routing and congestion control in WSNs. Saleem et al. (2011) utilized ACO to focus on distributed routing and congestion mitigation. ACO, inspired by the foraging behaviour of ants, relies on the concept of pheromone trails to guide packet routing decisions. The algorithm is particularly effective in finding paths with minimal energy consumption and delay. Despite its strengths, ACO encounters challenges in highly dense networks, where the number of possible routes increases dramatically. In such environments, the algorithm can suffer from scalability issues, and the pheromone updating process may become inefficient, leading to suboptimal routing decisions under high network load.

**Metaheuristic Approaches for Congestion Control**

In recent years, metaheuristic algorithms have gained significant attention due to their ability to handle the multi-objective optimization problems typical in WSNs. These approaches, which include PSO, Genetic Algorithms (GA), and ACO, provide a flexible framework for balancing multiple conflicting objectives such as throughput maximization, energy efficiency, and delay minimization. However, many of these algorithms face limitations, such as premature convergence, slow adaptation to changing conditions, and difficulty in managing highly dynamic and heterogeneous networks. This has led to a growing interest in newer optimization techniques that can overcome these challenges.

**Water Wave Optimization (WWO)**

Although metaheuristic algorithms have shown promise in improving congestion control and QoS in WSNs, there remains limited research on the application of the Water Wave Optimization (WWO) algorithm in this context. WWO is a relatively novel algorithm inspired by the natural behaviours of water waves, including phenomena such as wave propagation, refraction, and breaking. WWO has demonstrated significant potential in balancing exploration and exploitation during optimization, which makes it particularly suitable for complex and dynamic environments such as WSNs.

The WWO algorithm offers superior local and global search capabilities, allowing for dynamic adaptation to changing network conditions. Its ability to explore a wide search space while exploiting the most promising regions makes it well-suited for routing and congestion management in WSNs, where conditions such as network density, node mobility, and traffic patterns can change rapidly. Despite its advantages, the use of WWO in WSNs has not been extensively explored, making it an ideal candidate for addressing the congestion control and QoS challenges that still exist in current WSN protocols.

## III. PROBLEM STATEMENT

Wireless Sensor Networks (WSNs) are highly susceptible to congestion, particularly in dense deployments where the number of nodes and the volume of transmitted data can overwhelm network resources. Congestion in these networks can lead to several critical issues, including excessive packet loss, delayed data delivery, and the inefficient use of energy resources. In particular, the limited bandwidth and processing capabilities of sensor nodes exacerbate these issues, making it increasingly difficult to maintain a high level of Quality of Service (QoS). Furthermore, the network's energy consumption often becomes a key concern, as sensor nodes typically operate on limited battery power.

### 3.1 Challenges in Traditional Congestion Control Mechanisms

Conventional congestion control protocols, which were originally designed for traditional wireless networks, often fail to meet the specific requirements of WSNs. Several shortcomings of these protocols have been identified, particularly in the context of dynamic network conditions and resource constraints. These limitations include:

- **Lack of Adaptability to Dynamic Traffic Patterns**: Many traditional congestion control protocols do not account for the highly dynamic nature of traffic in WSNs. The volume and distribution of data traffic in a WSN can fluctuate drastically based on environmental factors, node mobility, and the type of sensing tasks. Static protocols that rely on predefined thresholds for congestion detection are often unable to effectively handle these changes, leading to either underutilization or overloading of network resources.
- **Energy Inefficiency**: Energy conservation is a critical concern in WSNs, as sensor nodes are typically powered by batteries that have limited lifespans. Many conventional congestion control strategies prioritize maximizing throughput and minimizing latency, often at the expense of energy efficiency. As a result, these protocols may

increase the number of retransmissions, leading to unnecessary energy consumption, which ultimately shortens the network's lifetime.

- **Failure to Adapt to Network Topology Changes**: WSNs are often subject to changes in topology due to node failures, mobility, or environmental factors. Traditional congestion control algorithms tend to assume a static or semi-static network topology, which makes them ineffective in handling such dynamic environments. These algorithms are often slow to adapt to changes in the network, resulting in suboptimal routing decisions, increased congestion, and degraded network performance.

### 3.2 Need for an Adaptive, Multi-Objective Optimization-Based Solution

To address the shortcomings of existing congestion control methods, an adaptive, multi-objective optimization-based routing mechanism is needed. Such a mechanism would need to dynamically adjust to changes in the network, optimize energy usage, and ensure the efficient delivery of data. The primary goals of this mechanism are to:

- **Reduce Packet Loss and Minimize Congestion**: The mechanism must actively monitor the network for signs of congestion and take immediate actions to reroute traffic or limit transmission rates to prevent packet loss. By intelligently managing traffic flow, the protocol can avoid network congestion and ensure that data is delivered reliably and in a timely manner.
- **Maintain High Throughput**: Despite congestion control measures, the mechanism must strive to maintain high throughput, ensuring that data is delivered efficiently and within acceptable timeframes. This involves balancing traffic loads across the network and optimizing routing paths to avoid bottlenecks.
- **Extend Network Lifetime**: Energy consumption is one of the most pressing issues in WSNs. The proposed solution must minimize energy wastage by optimizing routing paths, reducing unnecessary transmissions, and efficiently managing the use of the limited battery power of sensor nodes. By ensuring that nodes are used in an energy-efficient manner, the network lifetime can be extended significantly.

### 3.3 Proposed Solution: Water Wave Optimization (WWO)

The goal of this research is to address the gap in congestion control and QoS management by formulating a dynamic optimization problem and applying Water Wave Optimization (WWO). WWO, a nature-inspired metaheuristic, is well-suited for solving complex optimization problems in dynamic and resource-constrained environments like WSNs. By leveraging WWO's ability to balance exploration and exploitation, this research aims to develop an adaptive congestion control mechanism that can:

- **Dynamically adjust to changing traffic patterns** and energy states in the network.
- **Optimize routing paths** to reduce congestion, minimize packet loss, and enhance energy efficiency.
- **Improve QoS** parameters such as throughput, delay, and network lifetime.

In particular, WWO's unique characteristics, such as its ability to model wave propagation and refraction, make it particularly effective in navigating complex, non-linear search spaces like those encountered in WSNs. Through dynamic adaptation to evolving network conditions, WWO can offer a solution that is both flexible and efficient, addressing the challenges posed by traditional congestion control protocols.

### 3.4 Research Objectives

This research aims to:

- Formulate a multi-objective optimization problem that addresses the simultaneous challenges of congestion control, energy efficiency, and QoS enhancement.
- Develop and implement a WWO-based routing algorithm that dynamically adapts to changes in traffic patterns and network topology.
- Evaluate the performance of the proposed algorithm through extensive simulations to compare its effectiveness against traditional congestion control protocols in terms of packet loss, throughput, delay, energy consumption, and network lifetime.

Through this approach, we seek to contribute to the development of more efficient and robust congestion control solutions for WSNs, enabling better performance and longer operational lifetimes for sensor networks in a variety of application domains.

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## IV. PROPOSED METHODOLOGY

### 4.1 Objective Function

The multi-objective function, FFF, combines the following metrics:

$$F = \alpha \times \left(\frac{Throughput}{Throughput_{max}}\right) + \beta \times \left(\frac{Residual\_Energy}{Energy_{max}}\right) - \gamma \times \left(\frac{Packet\_Loss}{Loss_{max}}\right)$$

Where:
α,β,γ are weight coefficients.
$Throughput_{max}$, $Energy_{max}$ and $Loss_{max}$ are maximum values observed during network operation.
The aim is to maximize F.

### 4.2 Water Wave Optimization (WWO)

WWO is a metaheuristic inspired by the propagation of water waves.

**Key Processes:**
**Propagation**: Waves travel, exploring new areas.
**Refraction**: Waves adjust direction when encountering obstacles, improving local exploitation.
**Breaking**: New solution candidates are generated by simulating wave breaking, ensuring diversity.

**Algorithm Steps:**
Initialize a population of candidate routing paths.
Evaluate each path using the objective function.
Apply propagation, refraction, and breaking operations.
Update solutions based on fitness.
Repeat until the termination condition (iterations or convergence) is met.

### 4.3 WWO Routing in WSNs

In WSN routing:

- **Each wave** represents a collection of possible routes from the source to the destination.
- **Propagation** enables the exploration of new paths, helping the algorithm find better routes in the network.
- **Refraction** allows the paths to adjust when nodes face congestion or failure, ensuring continuous data flow.
- **Breaking** introduces diversity in the search process, preventing the algorithm from getting stuck in suboptimal paths and improving the chances of finding the best route.

## V. SIMULATION AND RESULTS

### 5.1 Simulation Setup

**Network Simulator 3**: The simulations were performed using NS-3 (Network Simulator 3), a tool suitable for modelling wireless networks. NS-3 allows detailed simulation of network protocols and is ideal for evaluating congestion control strategies in Wireless Sensor Networks (WSNs).

**Sensor Nodes**: The network consisted of 100 sensor nodes randomly placed in a 100m × 100m area. This setup represents a moderate WSN deployment where congestion and energy consumption are concerns. The nodes are responsible for sensing and transmitting data to a central sink node.
Each sensor node had an initial energy of 2 Joules, a typical value for battery-powered devices in WSNs. Energy consumption was tracked throughout the simulation to assess how well the congestion control mechanism conserved energy.

**Constant Bit Rate:** For the traffic model, Constant Bit Rate (CBR) was used, where nodes send data at a fixed rate. This allows the simulation to test the congestion control under steady traffic conditions. Each packet was 512 bytes, a common size in WSNs, balancing transmission efficiency and overhead.

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**MAC Layer:** The MAC Layer used for communication was IEEE 802.15.4, which is designed for low-power wireless communication, making it suitable for WSNs. The simulation was run for 500 seconds to observe the network's performance over time and evaluate the congestion control strategy under different conditions.

### 5.2 Performance Metrics

To evaluate the effectiveness of the proposed Water Wave Optimization (WWO)-based congestion control strategy in Wireless Sensor Networks (WSNs), we focus on four key performance metrics: Network Throughput, Packet Loss Rate, Average Residual Energy, and End-to-End Delay. These metrics help measure the efficiency and reliability of the routing protocol, ensuring it meets the challenges of congestion, energy consumption, and data delivery.

**Network Throughput** measures the total amount of data transmitted across the network in a given time period. High throughput is important for ensuring efficient data transfer, especially in real-time applications. The WWO-based protocol will be assessed based on how well it maintains throughput even when the network experiences congestion, and how it compares to traditional methods in handling data under different traffic conditions.

**Packet Loss Rate** refers to the percentage of packets that are not successfully delivered. Packet loss can occur due to network congestion or errors, and high loss rates degrade performance. A key goal of the WWO-based protocol is to minimize packet loss, ensuring reliable communication across the network. The packet loss rate will be compared with traditional congestion control schemes to measure the effectiveness of the WWO algorithm.

**Average Residual Energy** indicates the remaining energy of sensor nodes over time. Since WSNs typically rely on battery-powered nodes, energy efficiency is crucial for prolonging network lifetime. The WWO-based routing protocol will be evaluated based on its ability to conserve energy while maintaining performance. A higher average residual energy signifies that the network is operating more efficiently, extending the life of the sensor nodes.

**End-to-End Delay** measures the total time it takes for a packet to travel from the source to the destination. Low delay is essential for applications that require timely data delivery. The WWO-based protocol will be tested to ensure that it minimizes delay, even in congested network conditions, and will be compared with other protocols to assess its effectiveness in reducing latency. These four metrics provide a comprehensive view of the network's performance, allowing us to evaluate the success of the WWO-based congestion control algorithm in optimizing throughput, reducing packet loss, conserving energy, and minimizing delay. By analysing these metrics, we can determine whether the proposed approach effectively improves QoS in WSNs.

### 5.3 Comparative Algorithms

**CODA (Congestion Detection and Avoidance)** is one of the earliest congestion control protocols in Wireless Sensor Networks (WSNs). It detects congestion using event-driven notifications and employs hop-by-hop backpressure mechanisms to adjust data rates. While CODA is effective at congestion detection and prevention, it has limitations when it comes to optimizing multiple Quality of Service (QoS) parameters like throughput, energy consumption, and packet loss. Additionally, CODA struggles to adapt to dynamic network conditions and topology changes, making it less effective in highly variable environments.

**PSO-based Routing (Particle Swarm Optimization)** is a nature-inspired algorithm that uses particles to search for optimal routing paths based on parameters such as energy consumption and delay. PSO can simultaneously optimize multiple parameters and often provides better performance compared to traditional methods. However, a significant drawback of PSO is its tendency to experience premature convergence, meaning the algorithm may settle on suboptimal solutions too quickly, especially in dynamic WSN environments with frequent changes in network conditions.

**The proposed WWO-based Routing algorithm** introduces a novel approach to congestion control by simulating the behaviour of water waves. It dynamically explores and adapts routes through propagation, refraction, and breaking, which allows for continuous adjustment in response to network congestion, node failures, and topology changes. This method provides a balanced solution to optimizing throughput, reducing packet loss, and conserving energy, making it ore robust and adaptable than both CODA and PSO-based methods. However, further testing in real-world deployment scenarios is needed to validate its effectiveness under practical conditions.

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### 5.4 Results

| Metric | CODA | PSO | WWO (Proposed) |
|---|---|---|---|
| Throughput (kbps) | 120 | 150 | 180 |
| Packet Loss (%) | 18% | 12% | 6% |
| Residual Energy (J) | 0.45 | 0.60 | 0.75 |
| End-to-End Delay (ms) | 280 | 230 | 200 |

**Observations**:
Throughput improved by 20% over PSO.
Packet Loss reduced by 50% compared to CODA.
Residual Energy higher, leading to prolonged network lifetime.
Delay slightly reduced, enhancing real-time performance.

## VI. CONCLUSION AND FUTURE WORK

This paper introduced a novel routing protocol for congestion control in Wireless Sensor Networks (WSNs) based on the Water Wave Optimization (WWO) algorithm. The proposed approach effectively optimizes an objective function that combines key Quality of Service (QoS) parameters such as throughput, residual energy, and packet loss.

The unique characteristics of the WWO algorithm, inspired by the natural behaviour of water waves, enable dynamic adaptation to varying network conditions, leading to more efficient congestion control and improved overall network performance. The simulation results demonstrate that the WWO-based protocol significantly outperforms traditional congestion control techniques such as CODA and PSO-based routing in several critical aspects. Specifically, WWO achieved superior performance in terms of throughput, packet loss reduction, and energy conservation. This indicates that WWO is an effective solution for improving the reliability and longevity of WSNs, especially in scenarios with high congestion and resource constraints.

**Future Work**
Looking ahead, several potential directions can be explored to further enhance the applicability and performance of the WWO-based protocol:

1. **Heterogeneous WSNs:** Future research will focus on extending the WWO model to accommodate heterogeneous WSNs, where nodes have different capabilities (e.g., energy levels, processing power, or communication range). This will help optimize the protocol for more diverse and real-world networks.
2. **Mobility Support:** Incorporating mobility support for dynamic environments is another key area of interest. In mobile WSNs, nodes may change their positions, requiring constant adaptation of routing paths to maintain network performance. Future work will explore how WWO can efficiently handle mobility and ensure stable communication in such dynamic scenarios.
3. **Real-World Testing**: While the simulation results are promising, future research will involve real-world deployment of the WWO-based routing protocol to validate its performance under practical conditions. This will help identify any potential challenges in the actual deployment and offer insights into further improvements.

By addressing these challenges, the WWO-based protocol could be adapted for more complex, dynamic, and heterogeneous WSN environments, leading to more robust and efficient solutions for congestion control and QoS improvement in WSNs.

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