"A Study on Quality of Service Improvement in Wireless Sensor Networks Using Combined Hardware and Software Approaches"

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Abstract — Wireless Sensor Networks (WSNs) have emerged as a critical technology for applications such as environmental monitoring, industrial automation, healthcare systems, and smart communication networks. Despite their widespread adoption, ensuring Quality of Service (QoS) in WSNs remains a significant challenge due to constraints such as limited energy resources, node failures, network congestion, transmission delays, and inefficient routing mechanisms.This paper presents a Hybrid QoS Improvement Approach for Wireless Sensor Networks that combines both hardware and software-based techniques. The proposed framework integrates an Enhanced LEACH Routing Protocol, Crawling Pattern Technique, and Authoritative Sensor Node (ASN) identification mechanism to improve network performance by reducing communication delay, optimizing energy utilization, and enhancing network reliability.The system is evaluated through simulations using MATLAB and NS-2 Simulator, complemented by a real-time hardware testbed incorporating temperature, humidity, and light sensors for environmental monitoring applications. Quality of Service is assessed using key Reliability, Availability, and Serviceability (RAS) metrics through both mathematical modeling and experimental validation.The obtained results demonstrate significant improvements in network coverage, routing efficiency, energy management, and delay reduction. Furthermore, the proposed hybrid framework achieves superior QoS performance compared to conventional WSN approaches, making it a viable solution for reliable and efficient sensor network deployments.

Keywords: Wireless Sensor Networks (WSNs), Quality of Service (QoS), Enhanced LEACH Protocol, Hybrid Approach, MATLAB, NS-2 Simulator, Reliability, Availability, Serviceability (RAS), Crawling Pattern Technique, Authoritative Sensor Node (ASN).

INTRODUCTION

Wireless Sensor Networks (WSNs) have become an essential technology for monitoring, sensing, and data acquisition across diverse application domains, including environmental surveillance, healthcare monitoring, industrial automation, and smart city infrastructures. A typical WSN comprises numerous sensor nodes distributed over a target area to collect, process, and transmit information to a central monitoring system.

Node density is a critical factor influencing the overall performance and reliability of a WSN. Increasing the number of sensor nodes generally enhances network coverage, connectivity, and fault tolerance by providing multiple communication paths and improving data collection accuracy. However, excessive node density may result in increased channel contention, packet collisions, network congestion, and higher energy consumption, thereby adversely affecting network efficiency.

Transmission range is another important parameter that directly impacts communication performance within a WSN. A shorter transmission range minimizes energy consumption and prolongs sensor node lifetime but often requires multi-hop communication, which can increase routing complexity and end-to-end delay. Conversely, a larger transmission range reduces the number of communication hops and improves network connectivity; however, it leads to greater energy expenditure and increased signal interference. Therefore, optimizing both node density and transmission range is essential for achieving efficient and reliable network operation.

Wireless communication in WSNs is also susceptible to noise, interference, and signal distortion, which can degrade data quality, reduce throughput, and increase packet loss rates. These challenges necessitate the implementation of robust signal processing techniques to ensure reliable communication and accurate data transmission.

To address these issues, the Adaptive Beamforming Least Mean Square (BF-LMS) algorithm is employed to enhance signal estimation and communication quality. The algorithm continuously updates its filter coefficients based on the error between the desired and received signals, enabling it to adapt effectively to dynamic network conditions. This adaptive capability makes the BF-LMS algorithm particularly suitable for WSN environments characterized by varying node densities, changing transmission ranges, and fluctuating environmental conditions. By mitigating noise and reducing transmission errors, the algorithm significantly improves network reliability and overall performance.

This paper presents the design and implementation of a Wireless Sensor Network operating under varying node density and transmission range conditions using the Adaptive BF-LMS algorithm. Simulation and performance analysis demonstrate that the integration of adaptive filtering techniques enhances signal quality, reduces communication errors, and improves the robustness, efficiency, and reliability of WSNs in dynamic operating environments.

I. PROBLEM STATEMENT

Wireless Sensor Networks (WSNs) have emerged as a vital technology for real-time sensing, monitoring, and communication across a wide range of applications, including environmental monitoring, healthcare services, industrial automation, military operations, smart agriculture, and Internet of Things (IoT) systems. A WSN typically consists of numerous sensor nodes deployed within a specific area to collect, process, and transmit data wirelessly to a central base station. Despite their advantages, such as cost-effective deployment, scalability, and flexibility, ensuring consistent Quality of Service (QoS) remains a significant challenge due to resource constraints and the dynamic characteristics of wireless communication environments.

A critical issue affecting the performance of Wireless Sensor Networks is transmission delay. As network size and traffic load increase, sensor nodes encounter higher levels of congestion, packet collisions, channel contention, and communication overhead. These factors contribute to increased end-to-end delay, reduced throughput, and degraded overall network performance. The impact of delay is particularly significant in time-sensitive and mission-critical applications where accurate and timely data delivery is essential for effective decision-making.

Furthermore, conventional routing protocols often struggle to efficiently manage large-scale data traffic and rapidly changing network conditions. Their limitations in handling congestion and optimizing communication paths can result in inefficient resource utilization, increased latency, and reduced QoS. Therefore, developing advanced routing and network management techniques that minimize transmission delay while maintaining reliability and energy efficiency is crucial for enhancing the overall performance of Wireless Sensor Networks.

II. OBJECTIVE

• Analyze and evaluate sensor data in MATLAB using the Profiler Tool to assess computational performance and processing efficiency.

• Identify and compare suitable algorithms capable of delivering improved performance and enhanced Quality of Service (QoS) metrics when applied to realistic sensor datasets.

• Design, implement, and evaluate various crawling pattern techniques for sensor nodes to facilitate the identification of the Authoritative Sensor Node (ASN) using the NS-2 Simulator.

• Develop a hybrid testbed environment to test, measure, and validate key Quality of Service parameters under real-time operating conditions.

• Assess and justify the QoS metrics of Reliability, Availability, and Serviceability (RAS) through mathematical analysis, simulation results, and experimental validation.

• Evaluate the effectiveness of the proposed hybrid approach in improving network performance, routing efficiency, and overall system reliability.

III. LITERATURE SURVEY

1. *An Enhancement Approach for Reducing Energy Consumption in Wireless Sensor Networks*

Authors: Mohamed Elshrkawey

Summary:

In this study, Mohamed Elshrkawey presented an enhanced approach for reducing energy consumption in Wireless Sensor Networks (WSNs). The proposed method focuses on an efficient cluster-head selection mechanism to minimize energy utilization among sensor nodes. By reducing energy consumption, the network lifetime is significantly extended, thereby improving overall network performance. The paper also highlights various challenges associated with sensor node deployment and discusses critical issues affecting energy-efficient operation in WSN environments.

2. *A Scalable Multitasking Wireless Sensor Network Testbed for Monitoring Indoor Human Comfort*

Authors: Emanuele Lattanzi

Summary:

Emanuele Lattanzi proposed a scalable Wireless Sensor Network testbed designed for monitoring indoor environmental conditions related to human comfort. The proposed framework employs sensor nodes capable of performing multiple tasks simultaneously, thereby enhancing system flexibility and operational efficiency. Experimental evaluations demonstrate the effectiveness of the testbed in supporting diverse monitoring applications while contributing to improved Quality of Service (QoS) within the network.

3. *QoS in Wireless Sensor Networks*

Authors: Nathalie Mitton

Summary:
In this paper, Nathalie Mitton examined the growing demand for Wireless Sensor Networks that can provide enhanced Quality of Service. The study particularly focuses on the application of WSNs in urban healthcare monitoring systems. Various challenges affecting QoS, including unreliable wireless communication, network dynamics, and hardware resource limitations, are discussed in detail. The paper emphasizes the need for robust solutions to overcome these constraints and ensure reliable service delivery in sensor network applications.

4. Joint Hybrid Transmission and Adaptive Routing for Lifetime Extension of WSNs

Authors: Chih-Min

Summary:
This research introduces a hybrid transmission strategy that combines both single-hop and multi-hop communication techniques with adaptive routing mechanisms to extend the operational lifetime of Wireless Sensor Networks. The proposed approach incorporates a systematic decision-making model consisting of multiple functional modules that evaluate network conditions and determine the optimal transmission probability for each sensor node. The results demonstrate improved energy efficiency, balanced network load, and prolonged network lifetime compared to conventional routing approaches.

IV. PROPOSED SYSTEM

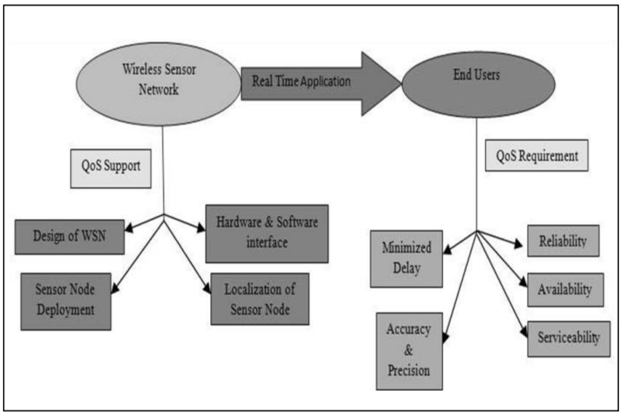


Fig 1: Block Diagram

IV. PROPOSED SYSTEM

a) Software-Based Design of Wireless Sensor Networks

The software-based design of Wireless Sensor Networks (WSNs) offers a flexible and cost-effective environment for modeling, monitoring, and evaluating network operations. Simulation platforms enable researchers to analyze the behavior of sensor nodes during data sensing, processing, transmission, and reception. These tools provide graphical and statistical representations of network performance, facilitating the assessment of Quality of Service (QoS) metrics under various operating conditions.

b) Simulation and Protocol-Oriented Algorithms

The proposed WSN framework utilizes protocol-oriented simulation algorithms to evaluate network performance. These algorithms consider critical parameters such as sensor node density, cluster-head selection, routing strategies, transmission rounds, and packet delivery probability. Simulation environments enable comprehensive performance analysis without requiring physical deployment, thereby reducing development costs and accelerating system evaluation for real-time applications.

c) Clustering and Routing Strategy

Efficient clustering and routing mechanisms are essential for effective WSN operation. In the proposed system, sensor nodes are organized into clusters to improve network scalability and energy efficiency. Routing protocols are employed to establish optimized communication paths between sensor nodes and the base station while minimizing bandwidth utilization and energy consumption. These mechanisms also enhance fault tolerance, network stability, and communication reliability, ensuring efficient data transmission throughout the network.

d) Challenges of Software-Based WSN Modeling

Although software simulation provides valuable insights into network behavior, it cannot fully replicate real-world operating environments. Practical issues such as hardware failures, sensor inaccuracies, wireless interference, environmental disturbances, and deployment constraints are difficult to model accurately in a purely virtual environment. Consequently, simulation-based analysis alone may not provide a complete representation of actual network performance.

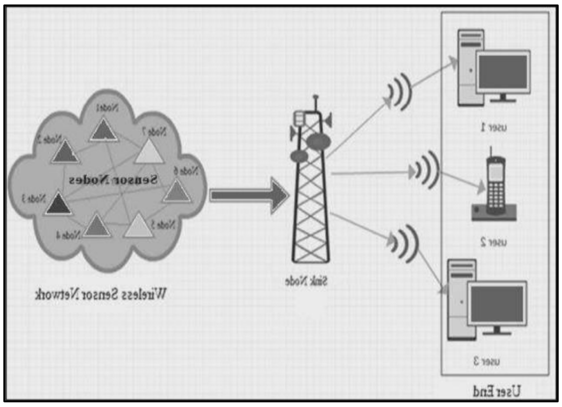
e) Hybrid Framework for Wireless Sensor Networks

To address the limitations of standalone hardware and software approaches, a Hybrid Framework is proposed for Wireless Sensor Network design and evaluation. The hybrid model combines software simulation with hardware implementation, enabling both theoretical analysis and practical validation. This integrated approach enhances system accuracy and reliability while overcoming constraints related to power consumption, memory capacity, communication bandwidth, and network lifetime. Furthermore, it bridges the gap between virtual simulation results and real-world deployment scenarios.

f) QoS Assessment Using the Hybrid Framework

The proposed Hybrid Framework facilitates comprehensive evaluation of both static and dynamic network characteristics. The static component includes hardware elements such as sensor modules, processing units, wireless communication interfaces, and Printed Circuit Board (PCB) assemblies. The dynamic component consists of software-based simulations that generate graphical and statistical analyses of network behavior. By combining these two perspectives, the framework enables accurate measurement of key Quality of Service parameters, including Reliability, Availability, and Serviceability (RAS). The results demonstrate improved network efficiency, enhanced operational reliability, and reduced performance degradation in real-time Wireless Sensor Network applications.

V. SYSTEM DESIGN



a) Overall Architecture of the Wireless Sensor Network

The proposed Wireless Sensor Network (WSN) is developed using a hybrid framework that integrates both hardware and software components to enhance Quality of Service (QoS). The architecture comprises sensor nodes, communication modules, routing mechanisms, a base station, and a monitoring platform. Sensor nodes are deployed across the target area to collect environmental data such as temperature, humidity, and light intensity. The acquired data is transmitted to the Base Station (BS) through optimized communication routes. The architecture is designed to improve network reliability, reduce transmission delay, and optimize energy utilization while ensuring efficient data delivery.

b) Sensor Node Architecture

The sensor node serves as the fundamental component of the Wireless Sensor Network. Each node consists of sensing devices, a microcontroller unit, memory resources, a power management system, and a wireless communication interface. Environmental sensors continuously monitor physical parameters and generate data that is processed by the microcontroller. The processed information is then transmitted either to neighboring nodes or directly to the base station. The sensor node architecture is optimized to achieve low power consumption, reliable communication, and accurate data acquisition.

c) Cluster Formation and Routing Strategy

To improve communication efficiency and network lifetime, the proposed system employs an Enhanced LEACH (Low-Energy Adaptive Clustering Hierarchy) Protocol for cluster formation and routing. Sensor nodes are organized into clusters, with a Cluster Head (CH) selected based on factors such as residual energy and communication capability. The Cluster Head aggregates data received from cluster members and forwards it to the base station. This approach reduces communication overhead, balances energy consumption across the network, and extends operational lifetime. Additionally, a Crawling Pattern Routing mechanism is incorporated to optimize data transmission paths and alleviate network congestion.

d) Authoritative Sensor Node (ASN) Selection

An important feature of the proposed design is the identification of an Authoritative Sensor Node (ASN), which represents the most efficient and reliable node within the network. The ASN is selected using performance parameters such as coverage area, transmission delay, communication speed, residual energy, and routing efficiency. An optimized path selection algorithm determines the most suitable communication routes through the ASN, resulting in improved data transmission efficiency, reduced latency, and enhanced overall network performance.

e) Integration of Hardware and Software Components

The proposed system combines physical hardware implementation with software-based simulation to achieve comprehensive performance evaluation. The hardware platform includes environmental sensors, microcontroller units, Wi-Fi communication modules, relay circuits, LCD displays, and Printed Circuit Board (PCB) assemblies. The software environment utilizes MATLAB and NS-2 Simulator for network modeling, routing analysis, data visualization, and performance assessment. This integrated framework enables accurate monitoring and validation of network behavior under realistic operating conditions.

f) QoS Monitoring and Performance Assessment

The primary objective of the system design is to evaluate and enhance key Quality of Service parameters, namely Reliability, Availability, and Serviceability (RAS). Throughout network operation, critical performance metrics such as node failures, transmission delay, packet delivery efficiency, energy consumption, and communication reliability are continuously monitored. Mathematical modeling, simulation studies, and experimental analysis are employed to quantify QoS performance. The hybrid testbed generates both graphical and statistical results, enabling comprehensive validation of the proposed framework. The findings demonstrate improved network efficiency, enhanced service quality, and greater suitability for real-time Wireless Sensor Network applications.

VI. RESULT

1. ***Graph 1: Node Density vs. Packet Delivery Ratio (PDR)***

This graph presents the impact of node density on the Packet Delivery Ratio (PDR) in the Wireless Sensor Network. The results indicate that as the number of sensor nodes increases from a low to a moderate level, the PDR improves considerably due to enhanced network connectivity and the availability of multiple routing paths for data transmission. Improved connectivity increases the likelihood of successful packet delivery and strengthens overall network reliability.

However, when node density exceeds the optimal level (approximately 30 nodes), a slight reduction in PDR is observed. This decrease can be attributed to higher levels of channel contention, packet collisions, signal interference, and network congestion caused by the large number of communicating nodes. Consequently, excessive node deployment may adversely affect communication efficiency and packet delivery performance.

The analysis highlights the importance of maintaining an optimal node density to achieve a balance between network connectivity and communication efficiency, thereby maximizing Packet Delivery Ratio and overall Quality of Service (QoS).

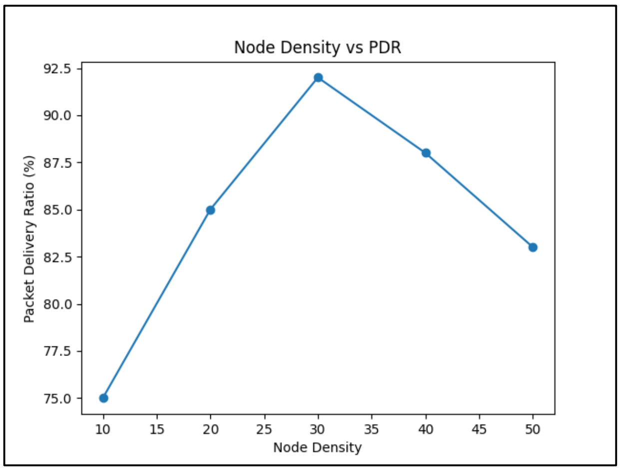


Fig 2: Graph1

Node Density	PDR (%)
10	75
20	85
30	92
40	88
50	83

Graph 2: Transmission Range vs Throughput

This graph shows the effect of transmission range on network throughput. As the transmission range increases, throughput initially improves due to reduced multi-hop communication and better connectivity between nodes. The peak throughput is achieved at an optimal range (around 150 meters). Beyond this point, throughput begins to decrease slightly due to higher interference, signal attenuation, and increased energy consumption. This result highlights the importance of selecting an appropriate transmission range to balance communication efficiency and network stability.

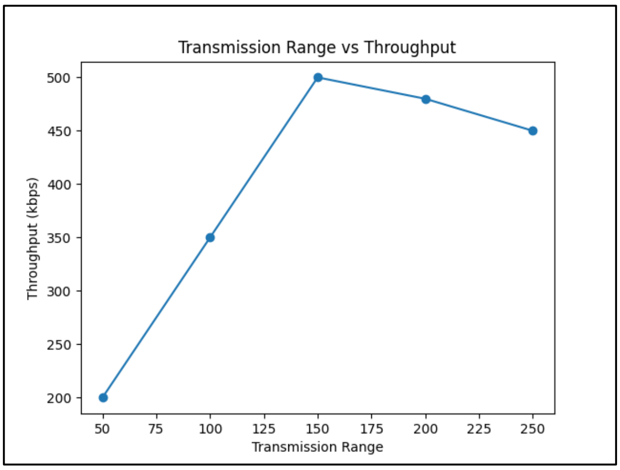


Fig 3: Graph 2

Transmission Range	Throughput (kbps)
50	200
100	350
150	500
200	480
250	450

Graph 3: Node Density vs Energy Consumption

This graph represents how energy consumption varies with node density. As the number of nodes increases, overall energy consumption rises steadily. This is due to increased communication overhead, frequent transmissions, and higher chances of collisions requiring retransmissions. In dense networks, nodes consume more energy for maintaining connectivity and handling interference. The results indicate that energy efficiency decreases with higher node density, emphasizing the need for optimization techniques such as adaptive algorithms to prolong network lifetime.

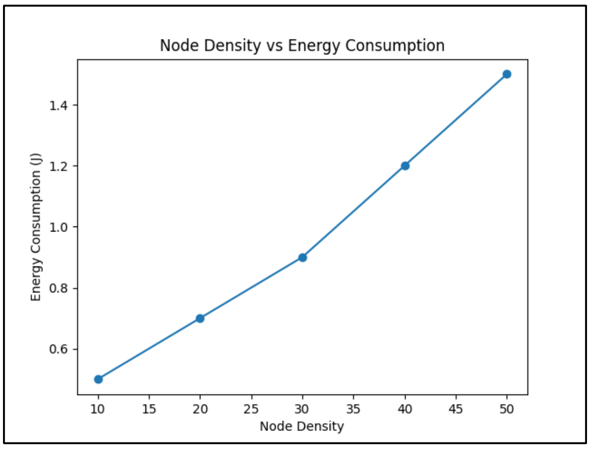


Fig 4: Graph 3

Node Density	Energy Consumption (J)
10	0.5
20	0.7
30	0.9
40	1.2
50	1.5

VII. CONCLUSION

Wireless Sensor Networks (WSNs) have emerged as a fundamental technology for real-time sensing, monitoring, and data communication across a wide range of applications, including environmental surveillance, healthcare systems, industrial automation, smart agriculture, and Internet of Things (IoT) environments. Despite their extensive adoption, ensuring consistent Quality of Service (QoS) remains a significant challenge due to factors such as excessive energy consumption, transmission delays, node failures, limited bandwidth availability, and inefficient routing mechanisms. These challenges can adversely affect network performance, reliability, scalability, and operational lifetime.

The proposed research aims to enhance the Quality of Service of Wireless Sensor Networks through a Hybrid Approach that integrates both hardware and software methodologies. The framework incorporates an Enhanced LEACH Protocol, Crawling Pattern Routing Technique, and Authoritative Sensor Node (ASN) identification mechanism to improve communication efficiency and optimize resource utilization. MATLAB and NS-2 Simulator are employed to model network behavior, evaluate routing performance, analyze energy efficiency, and assess key QoS parameters under varying network conditions. The proposed approach is intended to improve network reliability, reduce communication delay, enhance routing effectiveness, and extend the overall lifetime of the Wireless Sensor Network.

VIII. FUTURE SCOPE

The proposed Hybrid Approach for enhancing Quality of Service (QoS) in Wireless Sensor Networks establishes a strong foundation for future advancements in intelligent and efficient communication systems. While the current research primarily focuses on reducing transmission delay, optimizing energy utilization, and improving key QoS parameters such as Reliability, Availability, and Serviceability (RAS), there remains significant scope for further enhancement in terms of network intelligence, scalability, security, and autonomous operation.

Future research can explore the integration of Artificial Intelligence (AI) and Machine Learning (ML) techniques into Wireless Sensor Networks to enable intelligent routing, predictive analysis, and automated decision-making. AI-driven algorithms can be utilized to predict network congestion, identify potential node failures, and estimate energy depletion levels, allowing proactive network management and improved service continuity. Similarly, machine learning models can support adaptive cluster-head selection, dynamic routing optimization, and efficient resource allocation based on changing network conditions.

The proposed framework can also be extended to support advanced Internet of Things (IoT) applications, including smart cities, healthcare monitoring systems, precision agriculture, industrial automation, and environmental surveillance. The integration of cloud computing and edge computing technologies with WSNs can significantly enhance data processing capabilities, enable large-scale remote monitoring, and improve real-time communication efficiency. Furthermore, future developments may focus on incorporating secure communication mechanisms, energy-harvesting technologies, and next-generation wireless communication standards to further improve network sustainability, reliability, and performance in complex deployment environments.

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