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Ultra-Low Latency Emergency Event Detection Using Cloud Integrated Teen Sensor Architecture

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ABSTRACT

WSNs (WSNs) play a critical role in environmental monitoring, industrial automation, and real-time event detection by enabling large-scale data collection through energy-constrained sensor nodes. However, efficient data transmission remains a major challenge due to limited battery power, dynamic network topology, and increasing communication overhead. Traditional routing approaches in WSNs primarily rely on hop-based shortest path routing, where data packets are forwarded through the minimum-hop route without considering node energy levels or sensing conditions. While simple to implement, such methods often lead to uneven energy consumption, increased latency, higher error rates, and premature node failures, thereby reducing overall network lifetime and reliability. To address these challenges, this research focuses on the design and analysis of an energy-aware routing mechanism inspired by the Threshold Sensitive Energy Efficient Network (TEEN) concept. The proposed system models an optimized routing strategy that emphasizes efficient path selection using weighted links and adaptive routing behavior, aiming to reduce unnecessary transmissions and improve communication performance. A simulation-based framework is developed using graph-based network modeling to compare the proposed TEEN routing approach and traditional hop-based routing. Performance evaluation is carried out using key metrics such as latency, mean square error (MSE), bit error rate (BER), hop count, and path length. Experimental results demonstrate that the proposed approach significantly outperforms traditional hop-based routing in terms of reduced latency, lower error rates, and improved routing efficiency. The proposed system highlights the importance of energy-aware routing strategies in enhancing the performance, scalability, and sustainability of WSNs.

Key words: Wireless Sensor Networks (WSNs), Energy-Aware Routing, Threshold Sensitive Energy Efficient Network (TEEN), Routing Performance Evaluation.

1.INTRODUCTION

The rapid evolution of wireless communication technologies has significantly transformed global connectivity, enabling faster data transmission, broader network coverage, and support for an increasing number of intelligent applications. With the deployment of fifth-generation (5G) cellular networks, communication systems are expected to provide not only higher bandwidth but also Ultra-Reliable Low-Latency Communications (uRLLC), which are essential for mission-critical and real-time applications [1]. Conventional communication networks typically provide end-to-end latency of around 20 milliseconds or higher, which is sufficient for traditional internet services but inadequate for emerging applications that demand near-instantaneous communication. Consequently, the development of next-generation communication technologies has focused on minimizing transmission delays while improving network reliability, scalability, and overall Quality of Service (QoS) to satisfy the growing requirements of modern digital ecosystems.

The continuous advancement from earlier cellular generations to 5G has introduced substantial improvements in network performance, security, privacy, spectral efficiency, and service flexibility. Unlike

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previous generations that primarily focused on enhancing mobile broadband services, 5G standardizes its capabilities into three major service categories: Enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communications (uRLLC), and Massive Machine-Type Communications (mMTC) [2]. Among these service classes, uRLLC has emerged as one of the most important technologies for supporting latency-sensitive applications by enabling highly reliable communication with minimal transmission delays [3]. These capabilities allow communication networks to efficiently support intelligent automation, industrial control systems, autonomous vehicles, smart factories, and various mission-critical applications that require uninterrupted connectivity and rapid response.

Many modern applications require end-to-end communication latency within one millisecond or even sub-millisecond levels to operate efficiently. Advanced technologies such as industrial automation, holographic communication, remote robotic control, and the Tactile Internet depend on extremely low-latency communication for real-time interaction and accurate synchronization [4]. Furthermore, emerging applications including Augmented Reality (AR), Virtual Reality (VR), autonomous systems, haptic communications, and remote telesurgery demand communication delays of no more than 5 milliseconds, while certain healthcare and industrial control applications require latency approaching one millisecond to ensure safe and reliable operation [5]. These stringent performance requirements highlight the necessity for intelligent network architectures, optimized resource allocation, and advanced communication technologies capable of delivering highly reliable, ultra-low-latency services for future 5G and sixth-generation (6G) communication networks.

2.LITERATURE SURVEY

Nakas, et al. [6] presented a comprehensive and up-to-date survey of routing protocols developed for Wireless Sensor Networks (WSNs), providing a systematic classification based on network architecture, data transmission mechanisms, location awareness, Quality of Service (QoS) support, and multipath routing capabilities. The study compared both traditional and modern routing protocols using several performance metrics, including latency, energy efficiency, scalability, reliability, and packet delivery performance. Furthermore, the advantages and limitations of each routing strategy were thoroughly analysed, providing valuable insights into protocol selection for different wireless communication scenarios. Iqbal, et al. [7] proposed an energy-aware Ultra-Reliable Low-Latency Communication (uRLLC) framework specifically designed for healthcare applications requiring reliable and time-sensitive data transmission. The proposed architecture integrated a priority-aware packet scheduler, adaptive transmission control, and edge-computing-based reliability management to dynamically prioritize critical healthcare traffic. Extensive Monte Carlo simulations under varying network loads and edge computing delays demonstrated improvements in latency, throughput, reliability, energy consumption, delay violation rate, and Jain's fairness index, confirming the effectiveness of the proposed framework for next-generation healthcare communication systems. Al-Zabin, et al. [8] proposed a collaborative event detection framework that incorporated fuzzy logic at the fusion center to improve event detection accuracy in wireless sensor environments. The proposed Probabilistic Collaborative Event Detection (PCED) mechanism was evaluated using MATLAB simulations and compared with existing event detection approaches. Experimental results demonstrated higher detection probability and significantly lower false alarm rates, indicating the effectiveness of fuzzy logic in enhancing

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collaborative sensing performance. Gu, et al. [9] proposed two neighbor discovery protocols, Panacea-NCD and Panacea-WCD, to reduce discovery latency in wireless networks with and without collision detection capabilities. The proposed protocols achieved latency bounded by (O(n \cdot \ln n)) regardless of the duty cycle, demonstrating efficient neighbor discovery performance even in large-scale wireless communication environments.

Kilius, et al. [10] investigated synchronization techniques for Wireless Sensor Networks operating in industrial environments, where precise timing is essential for reliable communication. The study evaluated low-cost sensor network topologies by measuring communication delays and analysing network jitter under different modulation schemes and transmission bitrates. Experimental results provided a quantitative assessment of propagation delays across various hardware implementations, contributing valuable knowledge toward improving synchronization accuracy in industrial wireless sensor deployments. Noorwali, et al. [11] proposed an Industrial Internet of Things (IIoT) communication model integrating LoRa-based mesh networking, Voronoi-based spatial coverage optimization, and a Neural Route Mapping Protocol (NRMP). The framework combined Signal-to-Interference-plus-Noise Ratio (SINR) optimization, queueing-theory-based delay modelling, and multi-objective routing optimization to minimize communication latency, reduce network interference, maximize throughput, and extend network lifetime. The proposed analytical model demonstrated improved communication efficiency and energy-aware routing performance in large-scale industrial IoT environments. Manjeshwar, et al. [12] introduced a formal classification of Wireless Sensor Networks into proactive and reactive architectures while proposing the Threshold-sensitive Energy Efficient sensor Network (TEEN) routing protocol for reactive applications. Unlike proactive networks that periodically transmit sensed information, the TEEN protocol immediately responds to significant changes in monitored parameters, reducing unnecessary data transmissions and improving energy efficiency. The protocol significantly extended network lifetime while supporting time-critical monitoring applications. Ge, et al. [13] further enhanced the TEEN routing protocol by introducing the Advanced Threshold-sensitive Energy Efficient sensor Network (A-TEEN) protocol for Cognitive Wireless Sensor Networks. The proposed optimization improved routing stability, spectrum utilization, and overall energy efficiency by incorporating cognitive radio capabilities, thereby extending network lifetime while maintaining stable communication performance.

El-Sayed, et al. [14] proposed the IoT-TEEN protocol to address the energy hole problem commonly encountered in Wireless Sensor Networks. The proposed framework combined multiple energy optimization techniques, including a sleep-awake scheduling mechanism and adaptive cluster-head selection based on dynamic power-level switching among sensor nodes. Experimental results demonstrated a significant increase in network lifetime, extending the number of operational rounds to approximately 3,500 while improving packet delivery performance to more than 2,500 successful transmissions to the base station. Bhattacharyya, et al. [15] analysed the rapid evolution of micro-sensor technologies and their impact on the development of modern Wireless Sensor Network protocols. The study highlighted that advances in miniature sensing devices have enabled the deployment of large-scale sensor networks consisting of hundreds or thousands of sensor nodes capable of continuously monitoring unattended environments. These networks efficiently collect environmental information and transmit the gathered data to centralized users for applications including environmental

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monitoring, industrial automation, healthcare, and smart city infrastructure. The research emphasized the growing importance of designing scalable, energy-efficient, and reliable communication protocols capable of supporting increasingly complex wireless sensor network applications.

4.PROPOSED METHODOLOGY

This research implements a cloud-integrated wireless sensor network architecture. The system models sensor nodes as a network graph and evaluates routing behavior under time-critical conditions. The TEEN protocol is employed as the proposed routing algorithm, where cost-based optimal path selection is used to enable faster data delivery during emergency events. A Traditional Hop-Based Routing approach is used as the existing system for comparative analysis. Network behavior and routing paths are computed using graph-based algorithms implemented with the NetworkX library. The application is developed using the Flask framework to provide an interactive web-based simulation and visualization interface. Simulation results and routing performance data are stored using TinyDB, a lightweight NoSQL database as illustrated in Fig. 1. The system supports dynamic network generation, path computation, and performance evaluation within a cloud-supported analytical environment.

Sensor Network Initialization: Sensor nodes are initialized with predefined energy levels and spatial positions within the monitoring area. Each node is represented as a graph vertex to model communication behavior. Network topology is established before routing begins.

Network Graph Construction: Connections between sensor nodes are created based on communication range and distance constraints. Link weights are assigned to represent transmission cost. This graph structure forms the basis for routing and path computation.

Emergency Event Simulation: An emergency event is simulated by selecting a source sensor node that generates high-priority data. The event data must be forwarded to the sink node with minimal delay. Normal background transmissions are not emphasized during this stage

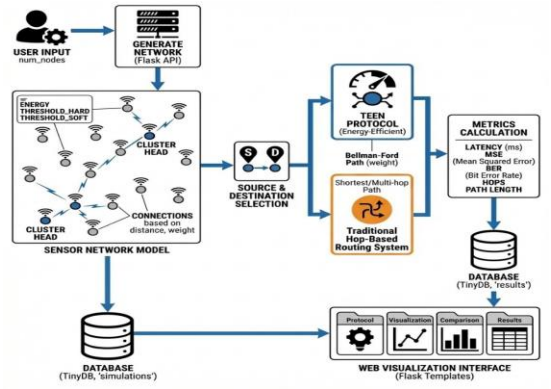


Fig. 1: Proposed system Architecture

TEEN Protocol Path Selection: The TEEN protocol computes an optimized routing path using cost-based shortest path selection. The routing process minimizes hop count and link cost to reduce transmission latency. This path represents the proposed routing behavior.

Traditional Hop-Based Routing Path Selection: A traditional hop-based routing approach forwards data through neighboring nodes based on hop progression. Routing decisions are made locally without global path optimization. This path serves as the existing system for comparison.

Performance Metric Computation: Routing paths obtained from both approaches are analyzed to calculate latency, hop count, mean square error, and bit error rate. These metrics are used to evaluate communication efficiency. The comparison highlights performance differences under emergency conditions.

Data Storage and Management: Simulation configurations and routing results are stored using TinyDB. The database maintains records of network parameters, selected paths, and computed metrics. This enables result retrieval and historical analysis.

Web-Based Visualization: The Flask framework provides a web interface for network visualization and interaction. Users can generate networks, select source and

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destination nodes, and observe routing paths. Performance results are displayed dynamically for analysis.

3.2 Proposed TEEN Routing Protocol

The proposed TEEN protocol as shown in Fig. 2 operates as an energy-aware and latency-optimized routing mechanism for emergency event detection in WSNs. The protocol organizes sensor nodes into clusters to manage communication efficiently. Continuous environmental sensing is performed at each node, while data transmission is triggered only when threshold conditions are satisfied. Event data is aggregated at cluster heads to reduce redundancy. Optimized routing paths are computed to minimize hop count and transmission delay. Priority data forwarding ensures faster delivery to the sink or cloud node. Performance metrics are evaluated to assess routing efficiency.

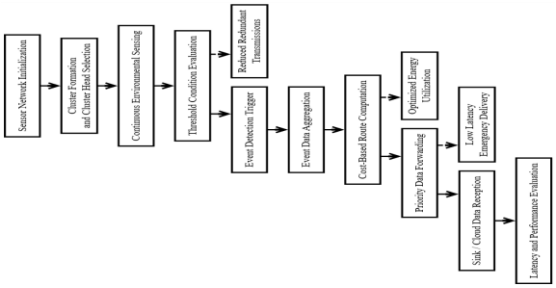


Fig. 2 Internal Workflow of TEEN Routing Protocol

Network Initialization and Clustering: Sensor nodes are deployed within the monitoring region and interconnected based on communication range. Nodes are organized into clusters to reduce routing overhead. Cluster heads are selected to coordinate data collection and forwarding.

Continuous Environmental Sensing: Each sensor node continuously monitors environmental parameters. Sensing is performed locally without initiating data transmission. This minimizes unnecessary communication during normal conditions.

Threshold Condition Evaluation: Hard and soft threshold values are evaluated at each sensor node. Data transmission is triggered only when the sensed value crosses the defined threshold. This ensures event-driven communication.

Event Detection Trigger: When threshold conditions are met, an emergency event is detected. The sensor node prepares event data for transmission. This triggers the routing process within the network.

Event Data Aggregation: Detected event data is forwarded to the corresponding cluster head. Cluster heads aggregate data from multiple sensor nodes. This reduces redundant transmissions and network congestion.

Cost-Based Route Computation: Cluster heads compute an optimized routing path toward the sink or cloud node. Routing decisions consider link cost and hop count. The selected path minimizes transmission delay.

Priority Data Forwarding: Emergency data is forwarded through the optimized route with priority handling. Intermediate nodes relay data without additional processing. This ensures rapid delivery of critical information.

Sink and Performance Evaluation: The sink or cloud node receives the transmitted data for analysis. Performance metrics such as latency and efficiency are computed. These metrics are used for protocol evaluation and comparison

4. RESULTS AND DISCUSSION

Fig. 3 depicts the network generation process after specifying the number of sensor nodes within the simulation environment. The figure illustrates the automatically constructed sensor topology representing node placement and connectivity relationships across the network. It demonstrates how the system dynamically organizes nodes to form a communication structure suitable for routing experiments. The generated topology serves as the foundation for protocol execution and comparative analysis.

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Fig. 3: Network Generation Screen



(a)



(b)

Fig. 4: Performance Comparison Metrics of (a) Event Detection Latency & Mean Square Error (b) Bit Error Rate & Path Length Comparison

Fig. 4 depicts the comparative performance evaluation of the proposed TEEN protocol and the existing protocol using multiple quantitative metrics to validate routing efficiency. Subfigure (a) illustrates Event Detection Latency and Mean Square Error, where the TEEN protocol achieves approximately 93.3% lower latency and 97.5% improvement in signal accuracy compared to the existing protocol, indicating faster event response and reduced signal degradation. Subfigure (b) presents Bit Error Rate and Path Length comparison results, showing nearly 99.2% reduction in transmission errors along with a significant decrease in routing hops. The TEEN protocol reduces the path length from 11 hops to 2 hops, representing about 81.8% improvement in routing efficiency.

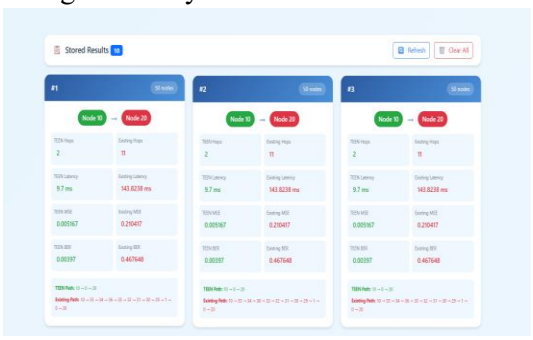


Fig. 5: Simulation Results History Screen

Fig. 5 illustrates the simulation results history interface that stores previously executed experiment outcomes for analysis and reference. The figure depicts recorded experimental results containing routing metrics, latency values, and error measurements across multiple simulations. It reflects the system's capability to maintain experiment consistency and enable comparative tracking over time. The stored results support reproducibility and systematic evaluation of protocol performance.

5. CONCLUSION

This research designed and implemented a Flask-based wireless sensor network routing simulation framework for ULLEED. The system integrated network modeling, routing execution, performance metric evaluation, data persistence, and visualization into a unified platform. By comparing traditional hop-based routing with the TEEN protocol, the study demonstrated clear performance improvements in latency reduction, hop count optimization, and efficient data transmission during emergency conditions. The threshold-based communication mechanism of the TEEN protocol significantly reduced redundant transmissions, leading to improved routing efficiency and better utilization of network resources. The use of graph-based modeling and controlled simulation ensured consistent, repeatable, and analyzable results.

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