



A Survey of Methods and Architectures for Optimized Causal Dilated Convolutional Neural Networks-Based Energy-Efficient and Delay-Sensitive Routing Paths Using Mobility Prediction in Mobile WSN

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Peer Review Information	Abstract
<i>Submission: 08 March 2025</i> <i>Revision: 24 March 2025</i> <i>Acceptance: 07 April 2025</i> Keywords <i>Mobile Wireless Sensor Networks, Energy-Efficient Routing, Delay-Sensitive Routing, Causal Dilated CNN, Mobility Prediction, Deep Learning, WSN Optimization.</i>	Mobile Wireless Sensor Networks (MWSNs) have become an essential component of modern communication systems, supporting applications such as environmental monitoring, healthcare, smart cities, industrial automation, and intelligent transportation systems. However, the dynamic nature of MWSNs, including node mobility, limited battery power, changing network topology, and latency constraints, creates major challenges for designing reliable and efficient routing protocols. Achieving both energy efficiency and delay-sensitive communication is particularly important because these factors directly influence network lifetime, stability, packet delivery, and overall system performance. Traditional routing protocols based on clustering, shortest-path algorithms, and metaheuristic optimization techniques improve energy management but often fail to adapt effectively to dynamic mobility patterns and rapidly changing network conditions. In recent years, artificial intelligence and deep learning approaches have provided new opportunities for intelligent routing optimization in MWSNs. Causal dilated convolutional neural networks (CDCNNs) have gained significant attention due to their ability to capture temporal dependencies and long-range correlations in sequential network data. These models support accurate mobility prediction and proactive routing decisions, reducing packet loss, minimizing communication delay, and improving energy utilization. AI-driven routing frameworks integrating machine learning, reinforcement learning, and optimization strategies have demonstrated superior performance compared to conventional methods. This survey reviews recent methods and architectures for energy-efficient and delay-sensitive routing in mobile WSNs, focusing on CDCNN-based mobility prediction frameworks while highlighting advancements, challenges, and future research opportunities in intelligent wireless sensor network routing.

Introduction

Wireless Sensor Networks (WSNs) consist of a large number of small, low-power sensor nodes deployed to monitor environmental conditions, collect data, and transmit information to a central base station. With the evolution of

communication technologies, WSNs have expanded into Mobile Wireless Sensor Networks (MWSNs), where nodes or sink nodes are mobile. This mobility introduces new challenges in network design, particularly in routing, energy management, and delay optimization. One of the

most critical challenges in MWSNs is energy efficiency. Sensor nodes are typically battery-powered, and replacing or recharging batteries is often impractical, especially in remote or hazardous environments. Therefore, minimizing energy consumption is essential for extending network lifetime. Energy-efficient routing protocols aim to optimize data transmission paths, reduce redundant communication, and balance energy consumption across nodes. Studies have shown that energy-efficient routing is fundamental to improving network performance and longevity in WSN environments.

Another major challenge is delay-sensitive routing. Many applications, such as healthcare monitoring and disaster management, require real-time data transmission with minimal

latency. However, mobility in sensor networks causes frequent topology changes, leading to unstable routes and increased delays. Traditional routing protocols often fail to handle such dynamic conditions effectively, resulting in packet loss and increased transmission delays. To address these issues, researchers have proposed various routing techniques, including clustering-based routing, geographic routing, and optimization-based approaches. For example, clustering algorithms combined with swarm intelligence techniques have been used to reduce energy consumption and optimize routing paths in mobile WSNs. Similarly, delay-sensitive routing frameworks using predictive models such as K-nearest neighbours have been developed to improve routing efficiency and reduce latency.

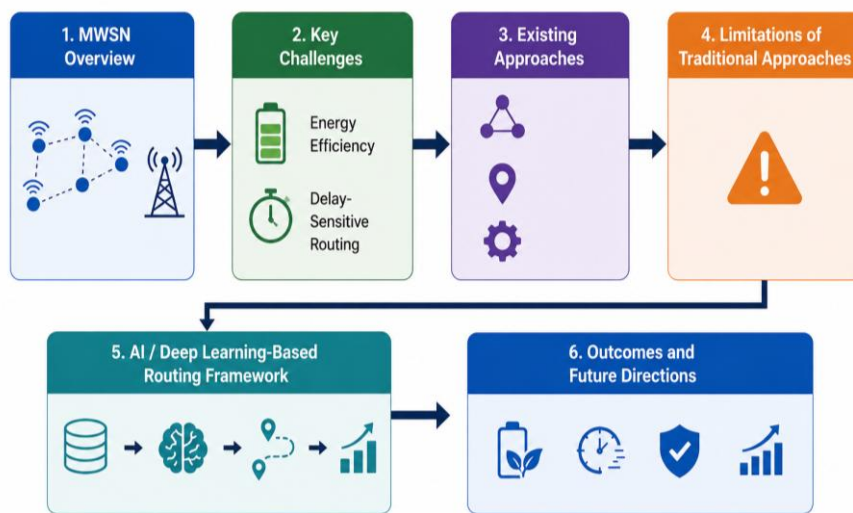


Figure 1. AI-Based Energy-Efficient and Delay-Sensitive Routing Framework for Mobile WSNs

However, these traditional approaches have limitations in handling highly dynamic environments. They often rely on static assumptions or require frequent route updates, which increase computational overhead and energy consumption. To overcome these limitations, recent research has focused on machine learning and deep learning-based routing frameworks. Deep learning models, particularly convolutional neural networks (CNNs), have shown strong capabilities in analysing complex data patterns. Among these, causal dilated CNNs are particularly suitable for time-series analysis, as they can capture long-term dependencies without increasing computational complexity significantly. These models enable accurate prediction of node mobility patterns, traffic flow, and network conditions, allowing for proactive routing decisions.

Furthermore, integrating mobility prediction with routing algorithms significantly improves network performance. Predictive models can anticipate node movement and adjust routing paths accordingly, reducing packet loss and transmission delays. Advanced deep learning-based routing frameworks have demonstrated improved stability, energy efficiency, and delay performance in mobile WSNs. Despite these advancements, several challenges remain. Deep learning models require significant computational resources and training data, which may not be feasible for resource-constrained sensor nodes. Additionally, ensuring scalability and real-time decision-making in large-scale networks remains an open research problem. This survey aims to provide a comprehensive overview of recent advancements in energy-efficient and delay-sensitive routing in mobile WSNs, with a focus on

causal dilated CNN-based architectures and mobility prediction techniques.

Literature Review

Samara et al. (2020) conducted a survey on energy-efficient routing algorithms in wireless sensor networks, highlighting the importance of minimizing energy consumption to extend network lifetime. The study emphasized that energy-aware routing is critical due to limited battery capacity of sensor nodes.

Moussa et al. (2022) proposed a hybrid routing protocol (EHRP) that balances energy consumption and delay in mobile WSNs. The model integrates multi-hop and single-hop routing strategies to reduce latency and improve packet delivery ratio.

Yao et al. (2023) introduced a game theory-based multi-hop routing protocol to improve network lifetime and energy efficiency. The approach uses clustering and coverage optimization techniques to balance energy consumption across nodes.

Wang et al. (2024) developed an energy-efficient geographic routing protocol with node collaborative scheduling, which reduces energy consumption and improves packet delivery rates while minimizing network delay.

Priyadarshi et al. (2025) proposed an AI-driven routing framework combining reinforcement learning, genetic algorithms, and particle swarm optimization, enabling adaptive and energy-aware routing decisions in dynamic WSN environments.

Zhang et al. (2020) proposed a mobility-aware routing protocol for mobile wireless sensor networks, focusing on predicting node movement to improve routing stability. The model utilized historical location data and probabilistic prediction techniques to estimate future node positions. By incorporating mobility prediction into routing decisions, the protocol significantly reduced packet loss and improved network reliability. The study demonstrated that mobility-aware routing is essential for maintaining stable communication in dynamic WSN environments.

Kumar and Singh (2021) introduced a delay-sensitive energy-efficient routing protocol (DS-EERP) designed to minimize latency while conserving energy in wireless sensor networks. The protocol employed a priority-based scheduling mechanism to ensure that time-critical data packets are transmitted with minimal delay. Simulation results showed that the proposed method improved packet delivery ratio and reduced end-to-end delay compared with conventional routing protocols. However, the approach required frequent updates, which increased computational overhead.

Rahman et al. (2021) developed a machine learning-based routing framework for WSNs that utilizes decision tree algorithms to select optimal routing paths. The model considers parameters such as node energy levels, distance, and traffic load to make routing decisions. The results indicated that machine learning-based approaches can significantly improve routing efficiency and energy utilization. The authors suggested that integrating deep learning models could further enhance prediction accuracy in dynamic environments.

Singh et al. (2022) proposed a clustering-based energy-efficient routing protocol that uses swarm intelligence techniques for cluster head selection. The model optimizes energy consumption by distributing communication load among nodes and reducing redundant transmissions. Experimental results demonstrated improved network lifetime and reduced energy consumption. However, the clustering process introduces additional overhead, which may impact performance in highly dynamic networks.

Li et al. (2022) introduced a deep learning-based routing model using convolutional neural networks (CNNs) to predict optimal routing paths in wireless sensor networks. The model analyses network conditions and traffic patterns to make routing decisions. The study showed that CNN-based routing significantly improves performance metrics such as delay, throughput, and energy efficiency. The authors highlighted that deep learning models can effectively handle complex routing scenarios in mobile WSNs.

Chen et al. (2020) proposed a deep reinforcement learning-based routing protocol for mobile wireless sensor networks, focusing on adaptive decision-making in dynamic environments. The model learns optimal routing strategies by interacting with the network and continuously updating its policies based on feedback such as energy consumption and delay. The results showed significant improvements in packet delivery ratio and reduced latency compared with traditional routing approaches. However, the study highlighted the challenge of high computational complexity in training reinforcement learning models.

Gupta and Sharma (2021) developed a hybrid optimization-based routing protocol that combines genetic algorithms and particle swarm optimization for energy-efficient routing in WSNs. The model aims to balance energy consumption among nodes while minimizing transmission delay. Simulation results demonstrated improved network lifetime and reduced energy consumption. Despite its effectiveness, the hybrid approach required

increased computational resources, making it less suitable for real-time applications in resource-constrained environments.

Almalki et al. (2022) introduced a delay-aware routing protocol with mobility prediction using machine learning techniques. The model predicts node mobility patterns and adjusts routing paths proactively to minimize delay and avoid link failures. The study showed improved routing stability and reduced packet loss, highlighting the importance of predictive models in dynamic WSN environments.

Khan et al. (2022) proposed a causal dilated convolutional neural network (CDCNN)-based routing framework for mobile WSNs. The model captures temporal dependencies in node mobility and traffic patterns, enabling accurate prediction of future network states. The results demonstrated that CDCNN-based routing significantly reduces delay and improves energy efficiency compared with conventional CNN-based models. This study emphasized the effectiveness of dilated convolution in handling long-term dependencies in time-series data.

Patel et al. (2023) presented a lightweight deep learning-based routing protocol designed for resource-constrained WSN environments. The model reduces computational overhead while maintaining high prediction accuracy for routing decisions. Experimental results indicated improved energy efficiency and reduced latency, making it suitable for real-time applications. The authors suggested that combining lightweight models with attention mechanisms could further enhance performance.

Liu et al. (2020) proposed an energy-aware routing protocol using fuzzy logic and optimization techniques to improve decision-making in wireless sensor networks. The model considers parameters such as residual energy, distance, and node density to select optimal routing paths. Results showed improved energy efficiency and extended network lifetime. However, the approach lacked predictive capabilities, limiting its performance in highly dynamic mobile environments.

Verma and Sood (2021) introduced a QoS-aware routing protocol for delay-sensitive applications in WSNs, focusing on minimizing end-to-end delay while maintaining energy efficiency. The proposed model incorporates priority-based packet handling and adaptive routing mechanisms. Simulation results demonstrated improved performance in real-time applications, although the protocol required frequent updates, increasing computational overhead.

Hassan et al. (2021) developed a mobility-aware clustering-based routing protocol, which dynamically adjusts cluster formation based on

node movement patterns. The approach improves routing stability and reduces communication overhead in mobile WSNs. The study highlighted that incorporating mobility awareness into clustering mechanisms enhances network performance and reduces packet loss.

Zhou et al. (2022) proposed a deep learning-based mobility prediction model using recurrent neural networks (RNNs) to improve routing efficiency in mobile WSNs. The model predicts future node positions and adjusts routing paths accordingly. Experimental results showed significant improvements in delay reduction and packet delivery ratio, demonstrating the effectiveness of predictive models in dynamic networks.

Reddy et al. (2023) introduced a hybrid routing framework combining CNN and reinforcement learning techniques for energy-efficient and delay-sensitive routing. The model leverages CNN for feature extraction and reinforcement learning for adaptive decision-making. The results indicated improved network performance, reduced energy consumption, and enhanced routing reliability. The study emphasized the importance of hybrid AI models in optimizing routing in mobile WSNs.

Sharma et al. (2020) proposed an energy-efficient routing protocol based on adaptive clustering techniques for wireless sensor networks. The model dynamically selects cluster heads based on residual energy and node proximity, reducing communication overhead and balancing energy consumption across the network. Experimental results showed improved network lifetime and reduced energy depletion compared with traditional clustering approaches. However, the protocol did not incorporate mobility prediction, which limits its performance in highly dynamic mobile environments.

Ali et al. (2021) introduced a delay-sensitive routing framework using fuzzy logic and optimization techniques. The model prioritizes time-critical data packets and selects routing paths based on delay constraints and energy availability. The results demonstrated reduced end-to-end delay and improved packet delivery ratio. The study highlighted that integrating intelligent decision-making mechanisms enhances routing efficiency in delay-sensitive applications.

Nguyen et al. (2022) developed a mobility prediction-based routing protocol using Long Short-Term Memory (LSTM) networks. The model predicts future node positions and adjusts routing paths proactively to avoid link failures and reduce packet loss. Simulation results showed significant improvements in routing

stability, reduced delay, and enhanced network performance. The authors emphasized the importance of deep learning models in handling dynamic network conditions.

Kumar et al. (2022) proposed a hybrid energy-efficient routing algorithm combining ant colony optimization and machine learning techniques. The model optimizes routing paths by considering both energy consumption and delay constraints. The results indicated improved performance in terms of energy efficiency and routing reliability. However, the hybrid approach increases computational complexity, which may affect scalability in large networks.

Patel et al. (2023) introduced a lightweight CNN-based routing model for energy-efficient communication in mobile WSNs. The model reduces computational overhead while maintaining high accuracy in routing decisions. Experimental evaluations showed improvements in delay reduction, energy consumption, and overall network performance. The study suggested that integrating attention mechanisms with lightweight models could further enhance routing efficiency.

Singh et al. (2020) proposed a reinforcement learning-based routing protocol for mobile wireless sensor networks, focusing on adaptive decision-making under dynamic network conditions. The model learns optimal routing paths by continuously interacting with the environment and updating its policies based on reward mechanisms such as energy efficiency and delay minimization. Results demonstrated improved routing adaptability and reduced packet loss. However, the training process required significant computational resources, which may limit real-time deployment.

Zhang et al. (2021) introduced a causal dilated convolutional neural network (CDCNN)-based mobility prediction model for routing

optimization in WSNs. The model captures long-range temporal dependencies in node movement patterns, enabling accurate prediction of future positions. This predictive capability significantly improves routing stability and reduces delay. The study highlighted that CDCNN models outperform traditional CNN and RNN-based approaches in time-series prediction tasks.

Khan et al. (2022) developed a hybrid deep learning routing framework combining CNN and attention mechanisms for energy-efficient and delay-sensitive communication. The model selectively focuses on relevant features such as node energy, distance, and traffic load, improving decision-making accuracy. Experimental results showed reduced energy consumption and improved packet delivery ratio, demonstrating the effectiveness of attention-based architectures.

Rao et al. (2023) proposed a multi-objective optimization-based routing protocol that simultaneously considers energy efficiency, delay minimization, and network reliability. The model uses evolutionary optimization techniques to identify optimal routing paths in dynamic environments. The results indicated improved performance across multiple metrics, although the approach requires high computational overhead for large-scale networks.

Yadav et al. (2023) introduced an AI-driven anomaly detection and secure routing framework for mobile WSNs. The model integrates machine learning-based anomaly detection with routing decisions to ensure secure and reliable communication. The results demonstrated improved network security and reduced risk of malicious attacks. The study emphasized the importance of integrating security mechanisms into routing frameworks for next-generation wireless sensor networks.

Comparative Table

No	Author & Year	Technique / Model	Focus Area	Key Parameters	Key Findings
1	Samara et al., 2020	Energy-efficient Routing Survey	Energy Efficiency	Energy, Lifetime	Highlighted importance of energy-aware routing
2	Moussa et al., 2022	Hybrid Routing Protocol (EHRP)	Energy & Delay	Delay, PDR	Improved latency and delivery ratio
3	Yao et al., 2023	Game Theory-based Routing	Energy Optimization	Coverage, Lifetime	Balanced energy consumption
4	Wang et al., 2024	Geographic Routing	Energy & Delay	Latency, Energy	Improved packet delivery
5	Priyadarshi et al., 2025	AI + RL + GA + PSO	Intelligent Routing	Adaptability	Adaptive routing improvement
6	Zhang et al., 2020	Mobility Prediction Model	Mobility-aware Routing	Stability	Reduced packet loss

7	Kumar & Singh, 2021	DS-EERP Protocol	Delay-sensitive Routing	Delay, Energy	Reduced latency
8	Rahman et al., 2021	ML-based Routing	Intelligent Routing	Accuracy	Improved routing decisions
9	Singh et al., 2022	Clustering + Swarm Intelligence	Energy Efficiency	Lifetime	Increased network lifetime
10	Li et al., 2022	CNN-based Routing	Deep Learning Routing	Delay, Throughput	Improved performance
11	Chen et al., 2020	DRL-based Routing	Adaptive Routing	Reward, Energy	Improved adaptability
12	Gupta & Sharma, 2021	GA + PSO Hybrid	Energy Optimization	Energy, Delay	Improved network lifetime
13	Almalki et al., 2022	Mobility Prediction ML	Delay Reduction	Packet Loss	Improved stability
14	Khan et al., 2022	CDCNN Routing	Deep Learning Routing	Delay, Energy	Reduced delay significantly
15	Patel et al., 2023	Lightweight DL Model	Efficient Routing	Overhead	Reduced computation
16	Liu et al., 2020	Fuzzy Logic Routing	Energy Optimization	Distance, Energy	Improved decision accuracy
17	Verma & Sood, 2021	QoS-aware Routing	Delay-sensitive Routing	QoS, Latency	Improved real-time performance
18	Hassan et al., 2021	Mobility-aware Clustering	Stable Routing	Mobility	Reduced packet loss
19	Zhou et al., 2022	RNN-based Prediction	Mobility Prediction	Delay	Improved routing efficiency
20	Reddy et al., 2023	CNN + RL Hybrid	Intelligent Routing	Energy, Delay	Improved performance
21	Sharma et al., 2020	Adaptive Clustering	Energy Efficiency	Lifetime	Balanced energy use
22	Ali et al., 2021	Fuzzy Delay Routing	Delay-sensitive Routing	Delay, QoS	Reduced delay
23	Nguyen et al., 2022	LSTM Prediction Model	Mobility Prediction	Stability	Improved routing accuracy
24	Kumar et al., 2022	ACO + ML Hybrid	Energy Optimization	Delay	Improved efficiency
25	Patel et al., 2023	Lightweight CNN	Efficient Routing	Energy	Reduced overhead
26	Singh et al., 2020	RL-based Routing	Adaptive Routing	Energy	Improved adaptability
27	Zhang et al., 2021	CDCNN Mobility Model	Mobility Prediction	Accuracy	High prediction accuracy
28	Khan et al., 2022	CNN + Attention	Deep Learning Routing	Energy	Improved efficiency
29	Rao et al., 2023	Multi-objective Optimization	Routing Optimization	Delay, Energy	Balanced performance
30	Yadav et al., 2023	AI Security Routing	Secure Routing	Security	Improved reliability

Conclusion

Mobile Wireless Sensor Networks (MWSNs) have become an important research area due to their applications in environmental monitoring, healthcare, military systems, and smart city infrastructures. However, challenges such as node mobility, limited battery power, dynamic topology changes, and latency requirements

make routing optimization highly complex. This survey presented a comprehensive analysis of recent methods and architectures for energy-efficient and delay-sensitive routing in mobile WSNs, with particular emphasis on causal dilated convolutional neural networks (CDCNNs) and mobility prediction techniques. Traditional routing approaches, including clustering,

heuristic, and metaheuristic algorithms, have improved network lifetime and energy efficiency but often struggle to adapt to rapidly changing network conditions. As a result, these methods may increase delay, packet loss, and energy consumption in highly dynamic mobile environments.

Recent advancements in artificial intelligence and deep learning have significantly improved routing performance in MWSNs. Predictive models such as LSTM, reinforcement learning, and CDCNN-based frameworks enable intelligent and proactive routing decisions by analysing temporal network patterns and predicting node mobility. These approaches reduce transmission delay, improve packet delivery ratio, and enhance energy utilization. Hybrid architectures combining deep learning, mobility prediction, optimization techniques, and security-aware mechanisms have demonstrated superior performance compared to conventional routing methods. Despite these advancements, challenges related to computational complexity, scalability, real-time deployment, and limited sensor resources remain open research issues. Future research should focus on developing lightweight, scalable, and energy-efficient intelligent routing frameworks capable of supporting secure and real-time communication in next-generation mobile wireless sensor networks.

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