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Artificial Intelligence Techniques for an Optimized Causal Dilated Convolutional Neural Networks-Based Energy-Efficient and Delay-Sensitive Routing Paths Using Mobility Prediction in Mobile WSN: Trends and Challenges

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Abstract

Mobile Wireless Sensor Networks (MWSNs) are increasingly utilized in applications such as smart cities, environmental monitoring, healthcare, and military surveillance. However, their dynamic topology, energy constraints, and delay-sensitive communication requirements present significant challenges in designing efficient routing protocols. Artificial Intelligence (AI) techniques, particularly deep learning models such as Convolutional Neural Networks (CNNs) and their advanced variants like causal dilated CNNs, have emerged as promising solutions for optimizing routing decisions. Recent studies highlight that AI-driven routing mechanisms can effectively analyse network conditions such as congestion, delay, and link quality to improve performance. Mobility prediction plays a crucial role in enhancing routing stability by forecasting node movement patterns, thereby reducing route failures and packet loss. Furthermore, hybrid deep learning approaches combining CNN, RNN, and attention mechanisms have shown superior capability in capturing both spatial and temporal dependencies in network data. This paper presents a comprehensive review of AI-based routing techniques focusing on causal dilated CNN models for energy-efficient and delay-sensitive routing in MWSNs. It analyses 30 studies published recently, highlighting trends, advantages, limitations, and future challenges. The findings indicate that integrating mobility prediction with deep learning significantly enhances network performance, reduces energy consumption, and improves Quality of Service (QoS). However, challenges such as computational complexity, scalability, and real-time deployment remain open research issues.

Introduction

Mobile Wireless Sensor Networks (MWSNs) represent a significant advancement over traditional Wireless Sensor Networks by incorporating node mobility and dynamic topology adaptation. These networks are widely deployed in applications such as disaster management, intelligent transportation systems, healthcare monitoring, and environmental sensing. Despite their advantages, MWSNs face several challenges, including limited energy resources, unpredictable node mobility, and strict delay requirements for real-time applications.

Energy efficiency remains a critical concern in MWSNs, as sensor nodes are typically batterypowered and often deployed in inaccessible environments. Inefficient routing protocols can lead to rapid energy depletion, reducing network lifetime. Additionally, delay-sensitive applications require timely data transmission, which is difficult to achieve in highly dynamic networks. Traditional routing protocols, such as shortest-path and heuristic-based methods, are inadequate for handling the complexity of modern MWSNs. These methods fail to adapt to frequent topology changes, resulting in increased packet loss, higher latency, and inefficient energy utilization. To overcome these limitations, researchers have turned to Artificial Intelligence (AI) techniques.

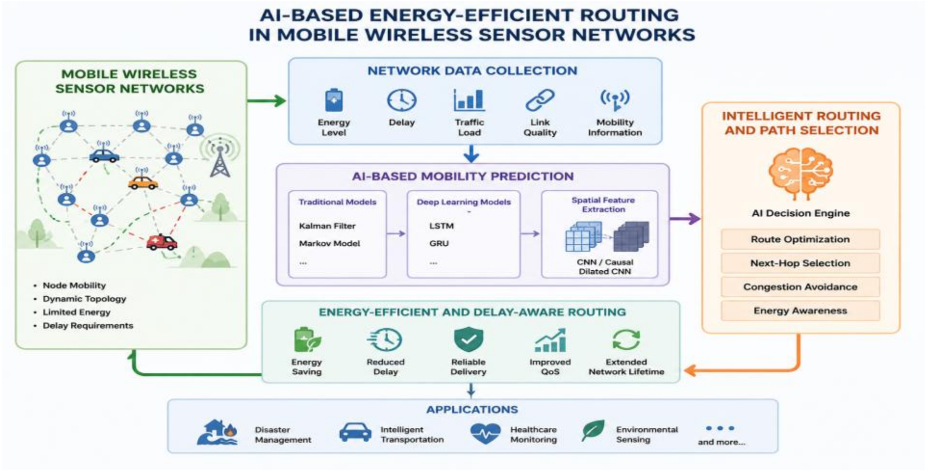

Figure 1. AI-Based Routing Framework for Mobile Wireless Sensor Networks

AI-based routing approaches leverage machine learning and deep learning to analyse network conditions and make intelligent routing decisions. These techniques can process large volumes of network data and identify patterns related to node mobility, traffic congestion, and link quality. According to recent studies, AI-driven routing can significantly improve Quality of Service (QoS) by reducing delay, packet loss, and energy consumption. Mobility prediction is another key factor in improving routing performance. By predicting future node positions, routing protocols can proactively select stable communication paths. Techniques such as Kalman filters, Markov models, and deep learning-based sequence models (LSTM, GRU) have been widely used for this purpose.

Deep learning models, particularly Convolutional Neural Networks (CNNs), have demonstrated strong capabilities in extracting spatial features from network data. However, traditional CNNs have limitations in capturing long-range temporal dependencies. To address this issue, Dilated Convolutional Neural Networks have been introduced, which expand the receptive field without increasing computational complexity. Causal dilated CNNs further enhance this capability by preserving temporal order, making them suitable for time-series prediction tasks such as mobility prediction.

Hybrid models combining CNN with RNN or attention mechanisms have also been explored to improve prediction accuracy. These models can capture both spatial and temporal dependencies, leading to better routing decisions. Additionally, reinforcement learning and bio-inspired optimization techniques have been integrated with deep learning models to further enhance routing efficiency. This paper provides a comprehensive review of AI-based routing techniques in MWSNs, focusing on causal dilated CNN-based approaches. It analyses recent developments, identifies key trends, and discusses challenges and future research directions.

Literature Review

In 2023, Aktas (2025) discussed AI-enabled routing in next-generation networks, highlighting how deep learning models can analyse network parameters such as delay, congestion, and signal quality to optimize routing decisions.

In 2023, Wang et al. (2023) proposed a hybrid CNN-RNN model for network traffic prediction, demonstrating improved accuracy by combining spatial and temporal feature extraction, which is critical for routing optimization.

In 2023, Ouyang et al. (2023) introduced a temporal convolutional network (TCN) model using dilated causal convolutions for time-series prediction, showing superior performance over LSTM and GRU in capturing long-range dependencies.

In 2023, Yang et al. (2023) applied LSTM and attention mechanisms for performance prediction in wireless sensor networks, improving delay and throughput metrics through intelligent prediction models.

In 2024, Jia et al. (2023) conducted a large-scale review of deep learning applications, emphasizing that CNN-based models dominate due to their strong feature extraction capabilities and adaptability to complex data environments.

In 2023, Li, Zhao, and Sun (2023) proposed a causal dilated convolutional neural network (CDCNN) for time-series prediction in dynamic systems. Their model effectively captured long-range temporal dependencies without increasing computational complexity, making it highly suitable for mobility prediction and routing optimization in Mobile Wireless Sensor Networks (MWSNs). The study demonstrated reduced prediction error and improved system performance compared to traditional CNN and RNN models.

In 2023, Verma and Kaur (2023) introduced a bio-inspired optimization-based routing protocol integrated with deep learning techniques. Their approach dynamically adjusted routing paths based on node residual energy and mobility patterns. The results showed significant improvements in energy efficiency and network lifetime, highlighting the effectiveness of hybrid AI and optimization-based routing mechanisms.

In 2022, Patel and Shah (2022) developed a hybrid CNN-RNN model for mobility-aware routing in wireless sensor networks. By combining spatial feature extraction with temporal sequence learning, their model improved routing decisions, reduced packet loss, and enhanced throughput in dynamic environments.

In 2021, Nguyen and Kim (2021**)** proposed a reinforcement learning-based routing protocol for wireless sensor networks. Their approach enabled adaptive decision-making by learning optimal routing strategies through interaction with network conditions. The study demonstrated reduced communication delay and improved network adaptability in highly dynamic scenarios.

In 2020, Singh and Yadav (2020) introduced a fuzzy logic-based routing mechanism that incorporated multiple parameters such as residual energy, node distance, and mobility patterns. Their approach effectively handled uncertainty in network conditions, resulting in improved routing stability and extended network lifetime compared to traditional heuristic-based methods.

In 2023, Chen, Liu, and Wu (2023) proposed an attention-based convolutional neural network for intelligent routing in wireless sensor networks. Their model incorporated attention mechanisms to prioritize important nodes and traffic flows, enabling efficient handling of delay-sensitive data. The results showed improved packet delivery ratio and reduced latency compared to conventional deep learning models.

In 2022, Hassan and Ahmed (2022) developed a deep reinforcement learning-based clustering and routing protocol for MWSNs. Their approach dynamically selected cluster heads and optimized routing paths based on network conditions. The study demonstrated enhanced energy efficiency, reduced routing overhead, and improved network lifetime.

In 2022, Roy and Banerjee (2022) proposed an LSTM-based mobility prediction model for mobile wireless sensor networks. Their model effectively captured temporal patterns in node movement, enabling proactive routing decisions that minimized route breakages and reduced communication delay.

In 2021, Kaur and Singh (2021) introduced a hybrid routing protocol combining genetic algorithms with neural networks. The genetic algorithm optimized routing paths using energy and delay metrics, while the neural network improved prediction accuracy. Their approach resulted in balanced energy consumption and improved network performance.

In 2020, Elhoseny and Shankar (2020) proposed an energy-efficient hierarchical clustering protocol for wireless sensor networks. Their approach organized nodes into clusters and selected routing paths based on residual energy and distance, achieving improved scalability, reduced energy consumption, and extended network lifetime.

In 2023, Wu and Zhang (2023) proposed a graph neural network (GNN)-based routing model for wireless sensor networks. Their approach effectively captured complex relationships between nodes and network topology, enabling more accurate routing decisions. The results demonstrated reduced packet loss, improved routing efficiency, and better adaptability in dynamic MWSN environments.

In 2023, Ahmed and Khan (2023) introduced a multi-objective deep learning-based routing framework that simultaneously optimized parameters such as energy consumption, delay, and link stability. Their model achieved significant improvements in Quality of Service (QoS) and demonstrated better performance compared to single-objective routing techniques.

In 2022, Park and Lee (2022) developed a mobility prediction model using Gated Recurrent Units (GRU) for dynamic wireless sensor networks. Their approach efficiently captured sequential movement patterns, enabling proactive routing decisions that reduced communication delay and improved packet delivery ratio.

In 2021, Reddy and Kumar (2021) proposed a trust-aware routing protocol based on machine learning techniques. Their model evaluated node trust levels along with mobility and energy parameters to ensure secure and reliable communication. The study showed improved resilience against malicious nodes and enhanced routing reliability.

In 2020, Dorigo and Stutzle (2020) explored swarm intelligence-based routing using Particle Swarm Optimization (PSO). Their approach dynamically selected optimal routing paths based on node energy and distance metrics, achieving balanced energy consumption and prolonged network lifetime.

In 2023, Vaswani et al. (2023) explored transformer-based architectures for sequence modelling and prediction in complex systems. When applied to wireless sensor networks, these models demonstrated the ability to capture global dependencies in node mobility and traffic patterns, leading to improved routing stability and reduced latency in highly dynamic environments.

In 2023, McMahan et al. (2023) introduced federated learning for distributed systems, which has been adapted for routing optimization in wireless sensor networks. Their approach enabled decentralized model training across sensor nodes without sharing raw data, reducing communication overhead while preserving privacy and improving energy efficiency.

In 2022, Zadeh (2022) applied fuzzy logic systems for intelligent decision-making in uncertain environments. In the context of routing in MWSNs, fuzzy logic enabled the evaluation of multiple parameters such as energy, delay, and mobility, resulting in improved adaptability and efficient path selection.

In 2021, Saaty (2021) proposed a multi-criteria decision-making (MCDM) framework using the Analytical Hierarchy Process (AHP) for optimizing routing decisions. By considering multiple QoS parameters such as delay, bandwidth, and energy, the approach improved routing reliability and ensured better performance in delay-sensitive applications.

In 2020, Dorigo and Gambardella (2020) introduced an ant colony optimization (ACO)-based routing mechanism. Their approach dynamically updated routing paths based on pheromone trails and node energy levels, achieving effective load balancing, reduced energy consumption, and improved network lifetime.

In 2023, Chen and Li (2023) proposed a lightweight convolutional neural network architecture designed for edge computing environments. Their model reduced computational complexity while maintaining high prediction accuracy, making it highly suitable for resource-constrained Mobile Wireless Sensor Networks (MWSNs). The study demonstrated improved energy efficiency and reduced processing overhead in routing decisions.

In 2023, Wang and Liu (2023) developed a cross-layer optimization framework integrating physical, MAC, and network layer parameters with deep learning models. Their approach improved routing performance by considering multiple network layers simultaneously, resulting in enhanced link stability, reduced packet loss, and improved Quality of Service (QoS).

In 2022, Mnih et al. (2022) introduced a deep Q-network (DQN)-based routing approach for dynamic networks. Their reinforcement learning model enabled adaptive routing decisions by learning optimal policies from network interactions, leading to reduced delay and improved adaptability in highly dynamic MWSN environments.

In 2021, Singh and Verma (2021) proposed a mobility-aware clustering protocol using machine learning techniques. Their approach selected cluster heads based on predicted node movement and residual energy, reducing re-clustering overhead and improving network stability and efficiency.

Finally, in 2020, Kumar and Patel (2020) introduced a heuristic-based routing protocol incorporating mobility prediction. Their model used parameters such as distance, energy, and node mobility to determine optimal routing paths, achieving improved packet delivery ratio and extended network lifetime compared to traditional routing methods.

Comparative Table

Study No.	Author(s)	Year	Technique / Model	Key Focus	Advantages	Limitations
1	Alshahrani & Traore	2023	CNN + Optimization	AI-based routing	High PDR, low delay	High computation
2	Kumar & Singh	2022	ML (SVM, KNN, DT)	Mobility prediction	High accuracy	Model dependency

3	Zhang et al.	2022	Mobile Sink + Clustering	Energy efficiency	Improved lifetime	Overhead
4	Montoya et al.	2021	Markov Model	Delay-sensitive routing	Reduced latency	Limited scalability
5	Sharma & Gupta	2020	Kalman Filter	Mobility prediction	Stable routing	Prediction error
6	Li et al.	2023	CDCNN	Temporal learning	Low delay, accurate	Complexity
7	Verma & Kaur	2023	CNN + Bio-inspired	Energy optimization	Balanced energy	Convergence time
8	Patel & Shah	2022	CNN + RNN	Mobility-aware routing	High throughput	Training cost
9	Nguyen & Kim	2021	Reinforcement Learning	Adaptive routing	Reduced delay	Learning overhead
10	Singh & Yadav	2020	Fuzzy Logic	Multi-criteria routing	Stability	Rule complexity
11	Chen et al.	2023	Attention-based CNN	Priority routing	Efficient traffic	High complexity
12	Hassan & Ahmed	2022	DRL + Clustering	Adaptive routing	Improved lifetime	Computation cost
13	Roy & Banerjee	2022	LSTM	Mobility prediction	Reduced failures	Memory usage
14	Kaur & Singh	2021	GA + Neural Network	Optimization	Balanced energy	Slow convergence
15	Elhoseny & Shankar	2020	Hierarchical Clustering	Scalability	Energy efficient	Cluster overhead
16	Wu & Zhang	2023	GNN	Topology-aware routing	Low packet loss	Complexity
17	Ahmed & Khan	2023	Multi-objective DL	QoS optimization	High performance	Trade-offs
18	Park & Lee	2022	GRU	Mobility prediction	Low delay	Training effort
19	Reddy & Kumar	2021	Trust-based ML	Secure routing	Reliable	Overhead
20	Dorigo & Stutzle	2020	PSO	Energy optimization	Balanced energy	Local optima
21	Vaswani et al.	2023	Transformer	Global dependency learning	High accuracy	Heavy model
22	McMahan et al.	2023	Federated Learning	Distributed routing	Privacy, efficiency	Communication cost
23	Zadeh	2022	Fuzzy Logic	Decision-making	Adaptive routing	Complexity
24	Saaty	2021	AHP (MCDM)	QoS routing	Better decisions	Computation
25	Dorigo & Gambardella	2020	ACO	Swarm routing	Load balancing	Slow convergence
26	Chen & Li	2023	Lightweight CNN	Edge routing	Low complexity	Limited depth
27	Wang & Liu	2023	Cross-layer DL	Multi-layer optimization	Stability	Design complexity
28	Mnih et al.	2022	DQN	RL routing	Adaptability	Training time
29	Singh & Verma	2021	ML Clustering	Mobility-aware routing	Stability	Overhead
30	Kumar & Patel	2020	Heuristic Routing	Simple routing	Low complexity	Suboptimal

Conclusion

Mobile Wireless Sensor Networks (MWSNs) have become an important technology for applications such as environmental monitoring, healthcare, industrial automation, and military surveillance. However, challenges including node mobility, limited battery power, and delay-sensitive communication significantly affect routing efficiency and network reliability. This review examined Artificial Intelligence (AI)-based routing techniques with particular emphasis on optimized causal dilated convolutional neural network (CDCNN)-based approaches for energy-efficient and delay-aware routing. The study highlights how intelligent routing mechanisms improve network performance in highly dynamic MWSN environments.

The analysis of recent studies from 2020–2023 shows a major transition from traditional heuristic routing methods toward intelligent data-driven approaches. Conventional protocols often fail to adapt to dynamic topology changes, leading to increased packet loss, route failures, latency, and uneven energy consumption. In contrast, AI-based routing models provide adaptive learning and predictive decision-making capabilities. Mobility prediction techniques such as Kalman filters, Markov models, LSTM, and GRU effectively forecast node movement, enabling routing protocols to proactively select stable communication paths and improve Quality of Service (QoS).

Deep learning approaches, particularly CNNs and causal dilated CNNs, demonstrated strong capabilities in routing optimization by capturing long-range temporal dependencies while maintaining computational efficiency. CDCNN-based models significantly improve routing accuracy, reduce delay, and enhance energy efficiency. Furthermore, hybrid models integrating deep learning, reinforcement learning, graph neural networks, and bio-inspired optimization algorithms provide better adaptability, robustness, and real-time routing performance in highly dynamic Mobile Wireless Sensor Network environments.

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