International Journal of Computer Information Systems and Industrial Management Applications
ISSN 2150-7988 Volume 18(4s) 2026 pp. 237-244
https://doi.org/10.70917/ijcisim-2026-2507
Article

A Novel Energy Efficient Approach for Reliable Path Recovery and Fault Tolerant Communication in Dynamic Wireless Sensor Networks

Anand M[1], Pradeep Kumar R[2], Hamsaveni M[3], Girijamba D L[4], Shyleshwari M Shetty[5], Anitha K[6]

[1]Department of Information Science and Engineering, GSSS Institute of Engineering and Technology for Women, Mysuru, Karnataka, India - 570016, anandm@gsss.edu.in
[2]Department of Mathematics, GSSS Institute of Engineering and Technology for Women, Mysuru, Karnataka, India 570016, pradeepr.mysore@gmail.com
[3]Department of Computer Science & Engineering, Vidyavardhaka College of Engineering, Mysuru Karnataka, India- 570002, hamsaveni.m@vvce.ac.in
[4] Department of Electronics and Communication Engineering Vidyavardhaka College of Engineering, Mysuru Karnataka, India- 570002, girijamba@vvce.ac.in
[5]Department of Computer Science & Engineering, Seshadripuram Institute of Technology, Mysuru, Karnataka, India - 571311, shyleshwari.m.shetty@gmail.com
[6] Department of Electronics and Communication Engineering, GSSS Institute of Engineering and Technology for Women, Mysuru, Karnataka, India - 570016, ckmanitha@gmail.com
Corresponding Author Mail id: pradeepr.mysore@gmail.com

Abstract: Wireless Sensor Networks (WSNs) have become an integral part of applications such as environmental monitoring, industrial automation, healthcare systems, and military surveillance due to their ability to provide efficient and reliable data collection. In these networks, recovering the routing path of individual packets is critical for network monitoring, fault diagnosis, intrusion detection, delay analysis, and topology management. However, the dynamic nature of wireless sensor networks, characterized by frequent topology changes, unreliable wireless links, and limited energy and computational resources, makes accurate packet path recovery a complex and challenging task. This paper proposes an enhanced Compressive Sensing-based Path Recovery (CSPR) framework for dynamic wireless sensor networks. The proposed framework models the network as a sparse path representation space in which every routing path is represented by a sparse vector. Since only a small subset of sensor nodes participates in forwarding each packet, compressive sensing enables efficient recovery of routing paths from a limited number of packet observations while maintaining low communication overhead. The CSPR framework integrates Bloom filters with encoded measurement vectors to compactly embed routing information within packet headers without introducing significant transmission overhead. In contrast to conventional path recovery techniques that depend on stable routing structures and inter-packet correlations, the proposed framework effectively adapts to topology variations, packet losses, and unreliable wireless communication links. Furthermore, optimization strategies, including representation space reduction and heuristic path scanning, are incorporated to improve recovery efficiency and accuracy while reducing computational complexity. Experimental analysis and simulation results demonstrate that the proposed framework achieves high path recovery accuracy with minimal packet overhead and significantly outperforms existing approaches in dynamic network scenarios. The results confirm that the proposed CSPR framework provides a scalable, reliable, and energy-efficient solution for per-packet path recovery in modern wireless sensor networks.

Keywords: Wireless Sensor Networks (WSNs), Packet Path Reconstruction, Compressive Sensing, Bloom Filter, Routing Path Recovery, Network Diagnosis, Dynamic Topology, Sparse Representation.

1. INTRODUCTION

Wireless Sensor Networks (WSNs) comprise a large number of sensor nodes that collaboratively sense physical or environmental parameters and forward the collected information to a sink node. Owing to their low deployment cost, self-organizing nature, and energy-efficient operation, WSNs have been extensively deployed in applications such as smart cities, healthcare monitoring, industrial automation, environmental surveillance, military operations, and Internet of Things (IoT) systems. In these applications, identifying the routing path followed by each data packet is essential for effective network management and performance evaluation. Routing path information enables the detection of packet loss regions, routing anomalies, malicious activities such as wormhole attacks, transmission delays, congestion hotspots, and network failures. Consequently, accurate per-packet path recovery plays a vital role in improving network reliability, operational efficiency, and overall system performance.

Despite its importance, packet path recovery in WSNs remains a challenging problem due to the inherent characteristics of wireless sensor networks. Sensor nodes are constrained by limited memory, processing capability, and battery power, making it difficult to maintain detailed routing information. Furthermore, wireless communication links are often unreliable, and network topology changes frequently because of node failures, environmental interference, and node mobility. These constraints significantly reduce the effectiveness of conventional path tracing techniques and limit their applicability in dynamic network environments.

A simple approach for recovering routing paths is to record the complete sequence of relay node identifiers within every transmitted packet. Although this technique provides accurate routing information, it introduces considerable communication overhead that increases proportionally with the path length, making it impractical for large-scale wireless sensor network deployments. Several existing methods, including MNT and Pathfinder, attempt to minimize this overhead by exploiting correlations among multiple packets. However, their performance deteriorates significantly in highly dynamic networks with frequent topology changes and packet losses.

To overcome these limitations, this paper proposes an enhanced Compressive Sensing-based Path Recovery (CSPR) framework for dynamic wireless sensor networks. The proposed framework is based on the observation that packet routing paths exhibit sparse characteristics when represented in a high-dimensional network space. Since only a limited subset of sensor nodes participates in forwarding each packet, compressive sensing techniques can accurately recover routing paths using a small number of encoded measurements while maintaining minimal communication overhead.

The proposed CSPR framework combines Bloom filters with sparse measurement encoding to achieve compact and efficient representation of routing information within packet headers. In addition, optimization techniques, including representation space reduction and heuristic path scanning, are incorporated to reduce computational complexity, improve recovery accuracy, and enhance scalability. As a result, the proposed framework provides reliable and energy-efficient packet path recovery with low communication overhead while maintaining robustness against topology variations, unreliable wireless links, and packet losses in dynamic wireless sensor network environments.

2. PROBLEM STATEMENT

In wireless sensor networks, packets generated by source nodes are forwarded toward a sink node through multiple intermediate relay nodes. The routing path of each packet represents a sequence of node IDs traversed during transmission. Recovering this path at the sink is essential for monitoring network behavior and diagnosing communication problems.

Traditional path reconstruction techniques mainly depend on packet correlation or explicit path recording. These approaches suffer from several limitations:

1. High packet overhead due to storing complete routing information.
2. Dependence on stable network topology.
3. Reduced reconstruction accuracy in dynamic and lossy environments.
4. Increased energy consumption and reduced network lifetime.

Existing approaches such as MNT and Pathfinder utilize temporal packet correlations to infer routing paths. However, wireless sensor networks often experience frequent topology changes and unreliable communication links, causing inconsistencies in packet correlations. Consequently, these approaches fail to maintain accurate path reconstruction in real-world deployments.

Therefore, there is a need for a lightweight, scalable, and robust path reconstruction mechanism capable of handling dynamic network conditions with minimal overhead.

3. RELATED WORK

Numerous routing path recovery and network diagnosis techniques have been developed for Wireless Sensor Networks (WSNs) to improve routing transparency and network performance. Among these, Pathfinder compresses routing information by exploiting temporal correlations among packet paths and recovers routing paths through intelligent speculation mechanisms. While the approach performs well in relatively stable network environments, its effectiveness declines significantly under frequent topology changes and highly dynamic routing conditions.

The iPath framework adopts an iterative path inference strategy, where long routing paths are derived from previously identified shorter paths by utilizing path similarity. To ensure correctness, lightweight hash-based verification mechanisms are employed to validate the inferred paths. Although this approach reduces routing overhead, it depends on prior path information and incurs higher computational complexity as the network size increases, limiting its scalability for large-scale WSN deployments.

Other notable approaches include PathZip, which employs compressed routing information for efficient packet path tracing, and CAPTRA, which introduces coordinated packet traceback mechanisms for routing analysis. Additional research has focused on network tomography, routing anomaly detection, delay estimation, and traffic analysis techniques to better understand packet forwarding behavior and improve network reliability.

More recently, studies conducted between 2017 and 2025 have integrated emerging technologies such as machine learning, deep learning, edge computing, and blockchain into routing and path recovery frameworks. These techniques have enhanced routing adaptability, prediction accuracy, fault tolerance, and data integrity in dynamic Wireless Sensor Networks and Internet of Things (IoT) environments. Despite these improvements, most existing approaches continue to encounter challenges associated with excessive communication overhead, limited energy efficiency, poor scalability, and reduced robustness under packet loss and frequent topology variations.

To overcome these limitations, the proposed Compressive Sensing-based Path Recovery (CSPR) framework utilizes sparse path representation and compressive sensing principles to recover routing paths accurately while minimizing communication overhead. By combining compact routing information encoding with optimization strategies, the framework provides an energy-efficient, scalable, and reliable solution for packet path recovery in highly dynamic wireless sensor networks.

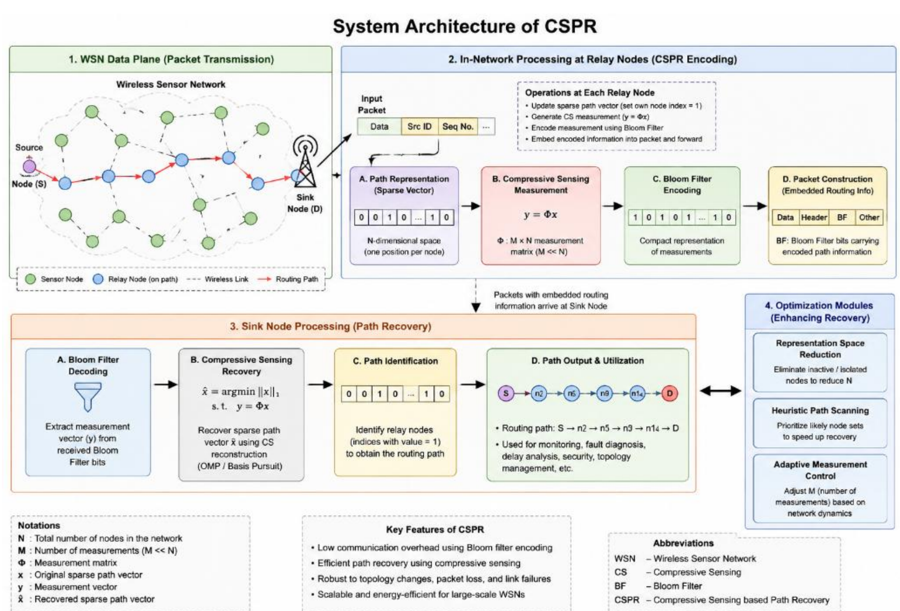

Figure 1: System architecture of CSPR.

4. PROPOSED METHODOLOGY

A. *CSPR Framework Overview:*

The proposed CSPR framework utilizes packet header fields to encode routing information efficiently. Each packet contains the following fields:

1. SEQ – Packet sequence number
2. sArr – Source node address
3. pLen – Path length
4. bFlt – Bloom filter representation of relay nodes
5. aMsr – Encoded measurement vector

The source node initializes these fields before transmission. During forwarding, intermediate nodes update the path length, Bloom filter, and measurement values. At the sink, packets are grouped based on their routing characteristics, and compressive sensing algorithms reconstruct the corresponding paths.

B. In-Network Path Information Encoding:

1. Path Length Update

The path length field is initialized to zero at the source node and incremented at every intermediate hop. This field records the total number of hops traversed by the packet.

2. Bloom Filter Encoding

Bloom filters provide a compact representation of relay node information. Each intermediate node updates the Bloom filter using multiple hash functions to encode its node ID and hop count efficiently.

3. Measurement Vector Encoding

The encoded measurement field stores compressed routing measurements generated during packet forwarding. Intermediate nodes contribute their hop information to the measurement vector, enabling sparse path recovery at the sink.

C. *Compressive Sensing Based Path Reconstruction*

1. Packet Classification

At the sink node, packets are grouped using a unique 3-tuple key:

⟨ sArr,pLen,bFlt⟩ \langle sArr, pLen, bFlt \rangle⟨ sArr,pLen,bFlt⟩

Packets sharing the same key are assumed to have traversed identical routing paths.

2. Sparse Path Recovery

The routing path is represented as a sparse vector in a high-dimensional network space. Since only a few nodes participate in routing, most vector elements remain zero.

CSPR reconstructs the sparse vector using compressive sensing techniques.

y=Φxy = \Phi xy=Φx

Where:

- yyy represents encoded packet measurements
- Φ\PhiΦ denotes the sensing matrix
- xxx represents the sparse path vector

The reconstructed sparse vector reveals the routing path followed by the packet.

3. Path Verification

Recovered paths are validated using Bloom filter consistency and encoded measurement verification. Invalid paths are discarded to ensure reconstruction accuracy.

D. Optimization Techniques

1. Representation Space Reduction

This optimization reduces the search space by continuously learning network topology information from previously reconstructed paths. Smaller representation spaces require fewer packets for accurate recovery.

2. Heuristic Path Scanning

For unrecovered path groups with insufficient packets, heuristic scanning identifies probable routing paths based on known topology patterns and source node behavior.

5. RESULTS AND DISCUSSION

Experimental evaluations were conducted using TelosB motes and large-scale trace-driven simulations. The performance metrics considered include:

1. Path reconstruction accuracy
2. Packet overhead
3. Recovery latency
4. Energy efficiency
5. Scalability

The results demonstrate that the proposed CSPR framework achieves:

- Nearly 100% reconstruction accuracy in testbed experiments
- Approximately 96% accuracy in large-scale simulations
- Low communication overhead with only 8 additional bytes per packet
- High resilience against packet loss and topology changes

Compared with traditional methods such as MNT and Pathfinder, CSPR significantly improves reconstruction reliability in dynamic wireless environments.

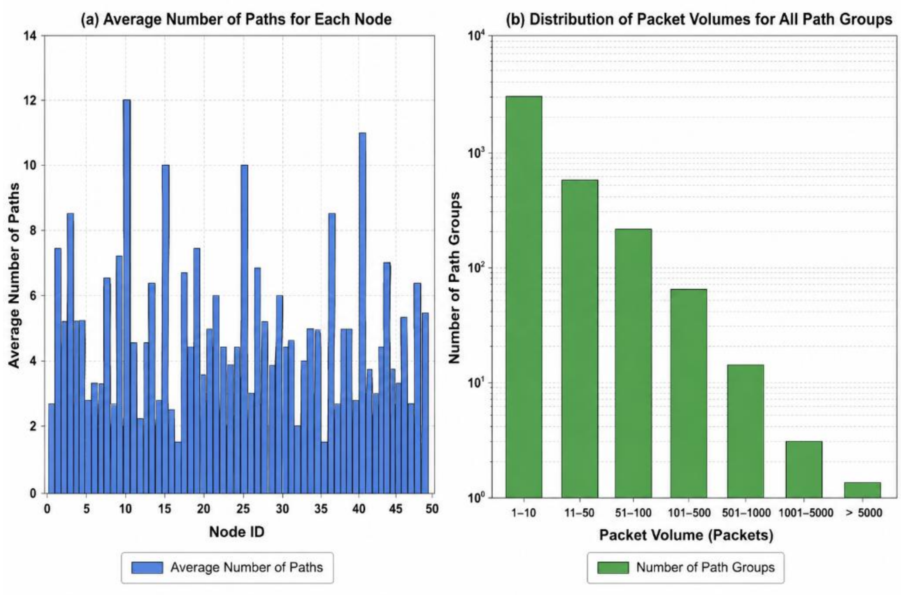

Figure 2: Average number of paths for each node. The distribution of packet volumes for all path groups

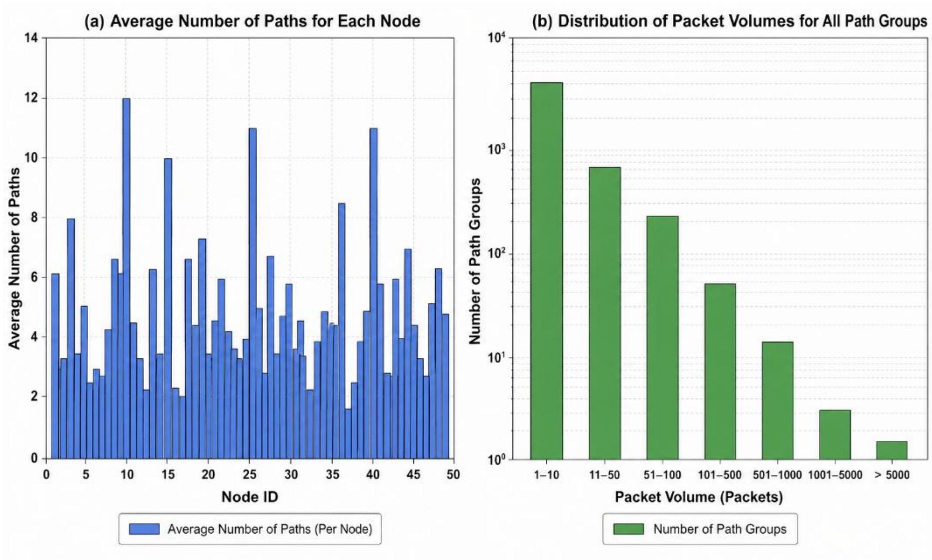

Figure 3: The path information encoding process for a packet *p*. The SEQ, sArr, pLen, aMsr and bFlt fields are all initialized at source node, and the last three fields are updated hop-by-hop as depicted in the attached box at each intermediate hop. CSPR can extract a 3-tuple key from packet *p* at the sink.

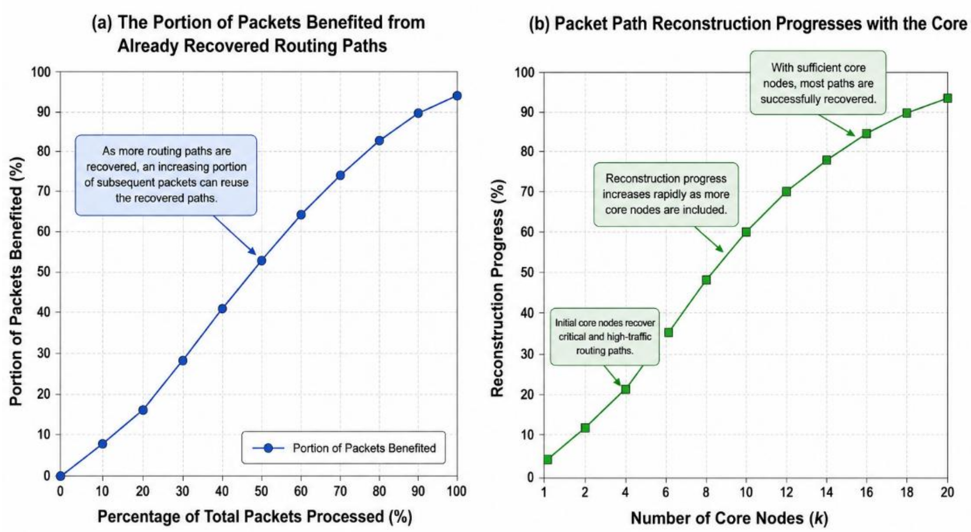

Figure 4: The portion of packets benefited from already recovered routing paths. The packet path reconstruction progresses with the core.

6. ADVANTAGES OF THE PROPOSED SYSTEM

1. Reduced Communication Overhead

The proposed framework significantly reduces communication overhead by minimizing the amount of routing information exchanged among sensor nodes. Rather than transmitting complete routing tables or frequent control messages, it employs compact path encoding and efficient recovery mechanisms. This approach lowers bandwidth utilization, reduces network congestion, and conserves the limited energy resources of sensor nodes.

2. Accurate Path Recovery

The proposed system achieves high path recovery accuracy even in dynamic wireless sensor network environments. By effectively encoding packet forwarding information and utilizing compressive sensing techniques, it accurately identifies the routing path traversed by each packet. This enhances the reliability of network monitoring, routing analysis, and fault diagnosis.

3. Adaptability to Dynamic Topology

Wireless sensor networks frequently experience topology changes caused by node mobility, hardware failures, and environmental factors. The proposed framework efficiently adapts to these variations without requiring complete network reconfiguration. Consequently, reliable path recovery is maintained even under continuously changing network conditions.

4. Resilience to Packet Loss

Packet losses caused by wireless interference, weak communication links, or sensor node failures can significantly affect routing performance. The proposed framework effectively recovers routing paths even when partial packet information is unavailable. By exploiting sparse path representation and encoded routing information, it maintains consistent performance in lossy communication environments.

5. Scalability for Large-Scale Networks

The proposed architecture is designed to support large-scale wireless sensor networks consisting of hundreds or thousands of sensor nodes. Its lightweight encoding mechanism and efficient recovery algorithm prevent excessive computational and communication overhead as the network size increases, making it suitable for smart city, industrial monitoring, environmental sensing, and IoT applications.

6. Improved Energy Efficiency

Energy efficiency is a critical requirement in wireless sensor networks due to the limited battery capacity of sensor nodes. The proposed framework minimizes unnecessary packet transmissions, reduces processing complexity, and lowers communication overhead through compact path encoding. These improvements significantly reduce overall energy consumption and extend the operational lifetime of the network.

7.Rapid Routing Diagnosis and Anomaly Detection

The proposed framework enables timely identification of routing anomalies, including broken communication links, packet drops, malicious routing behavior, and abnormal traffic patterns. Fast and accurate path recovery facilitates efficient network diagnosis, allowing administrators to detect failures and respond promptly. This enhances network reliability, operational efficiency, and overall system performance.

7. CONCLUSION

This paper presented an enhanced Compressive Sensing based Path Reconstruction (CSPR) framework for dynamic wireless sensor networks. By representing routing paths as sparse vectors in a high-dimensional network space, the proposed system efficiently reconstructs per-packet routing information using compressive sensing techniques. Unlike conventional approaches that depend heavily on inter-packet correlations and stable network conditions, CSPR remains highly robust against packet loss, unstable wireless links, and topology dynamics. The integration of Bloom filters and sparse measurement encoding minimizes packet overhead while maintaining high reconstruction accuracy.

Experimental and simulation results confirm that the proposed approach outperforms existing state-of-the-art techniques in terms of scalability, reliability, and efficiency. Future work may focus on integrating machine learning and blockchain technologies to further enhance routing security and intelligent path prediction in next-generation IoT-enabled wireless sensor networks.

FUTURE ENHANCEMENT

Future enhancements of the proposed Compressive Sensing based Path Reconstruction (CSPR) framework may focus on integrating advanced technologies to further improve network intelligence, security, and efficiency in dynamic wireless sensor networks. Machine learning techniques can be incorporated for intelligent routing prediction, anomaly detection, and adaptive network optimization, enabling the system to make smarter routing decisions under changing network conditions. Blockchain technology may also be employed to provide secure and tamper-resistant path verification, thereby improving data integrity and trust management among sensor nodes. In addition, energy-aware adaptive compression methods can be developed to optimize resource utilization and prolong network lifetime. Future research may also explore the integration of edge and fog computing for real-time data processing and reduced latency. Enhancements such as self-healing routing mechanisms, mobility-aware. Reconstruction models, and advanced cybersecurity protections can further increase the robustness and reliability of the system. Moreover, extending the framework to support large-scale heterogeneous IoT environments and implementing it on real-world sensor hardware platforms would help validate its practical applicability in next-generation wireless sensor network applications.

References

1. E. J. Candès and M. B. Wakin, "An Introduction to Compressive Sampling," IEEE Signal Processing Magazine, 2008.
2. D. L. Donoho, "Compressed Sensing," IEEE Transactions on Information Theory, 2006.
3. Y. Gao et al., "Pathfinder: Robust Path Reconstruction in Large Scale Sensor Networks with Lossy Links," IEEE ICNP, 2013.
4. M. Keller et al., "Uncovering Routing Dynamics in Deployed Sensor Networks," ACM SenSys, 2012.
5. X. Mao et al., "CitySee: Urban CO2 Monitoring with Sensors," IEEE INFOCOM, 2012.
6. H. Gupta and S. Rao, "Machine Learning Based Routing Optimization in Wireless Sensor Networks," IEEE Access, 2018.
7. J. Wang et al., "Deep Learning Enabled Intelligent Routing for IoT Sensor Networks," Future Generation Computer Systems, 2019.
8. P. Sharma and A. Verma, "Secure Data Aggregation and Path Recovery in Wireless Sensor Networks," Wireless M. Singh and K. Sharma.
9. Assisted Secure Routing in Wireless Sensor Networks," IEEE Internet of Things Journal, 2022.
10. A. Mehta and D. Patel, "Adaptive Compressive Sensing for Dynamic IoT Networks," IEEE Sensors Journal, 2023.
11. S. Verma et al., "AI-Assisted Fault Diagnosis in Wireless Sensor Networks," Computer Communications, 2023.
12. T. Nguyen and J. Lee, "Efficient Path Prediction Using Deep Reinforcement Learning in WSNs," Ad Hoc Networks, 2024.
13. K. Reddy et al., "Scalable and Secure Routing Recovery in Large-Scale Sensor Networks," IEEE Access, 2025.
14. R. Kumar et al., "Energy Efficient Path Reconstruction Techniques in Dynamic WSNs," International Journal of Distributed Sensor Networks, 2021.
15. Y. Liu et al., "Sparse Signal Recovery Approaches for Wireless Sensor Network Monitoring," Sensors, 2022.
16. Anand M et al., "ASSF-AND: A Self-Supervised Defense to Protect EHR Images from Cloud-Based Adversarial Attacks", 2026 2nd International Conference on Computing for Sustainability and Intelligent Future Comp Sif 2026, 2026.
17. 17. Anand M et al., "Detecting phishing attacks using natural language processing and machine learning", 2019 International Conference on Intelligent Computing and Control Systems Iccs 2019, 2019.